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SMOKE FACTOR MEASUREMENTS WITH REMOTE SENSING DEVICE TECHNOLOGY

RECOMMENDED PRACTICE

By

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1 SCOPE

This recommended practice applies to vehicle exhaust Smoke Factor (SF) measurements made using the Remote Sensing Device (RSD) technology manufactured by Environmental Systems Products (ESP). It assumes familiarity with basic RSD set-up and operation described elsewhere in the ESP Operators Manual (RSD-MAN 1160 Edition 4). This document introduces the SF, compares it to measurements made with smoke meters (i.e opacity meters) applying the light extinction principle and performed using snap-acceleration and lug-down procedures.

Whereas the traditional snap-acceleration smoke meter test requires the vehicle to be stopped, detained, and intrusively operated by a trained official, the RSD SF test remains a moving vehicle test that unobtrusively measures exhaust as the vehicle is driven past the RSD by its driver. The test is intended to be used on both heavy duty and light duty vehicle. The document discusses factors which affect the RSD SF measurement and recommends practice to ensure good quality SF measurement, with special attention given to elevated-stack exhaust configurations. Unless otherwise noted, the procedures described herein are considered a supplement to the basic set-up and operations procedures described in the RSD Operators Manual.

Testing conducted in accordance with this practice, in combination with reference SF values, is intended to provide an indication of the state of maintenance and/or tampering of the engine and fuel system relative to the parameters which affect exhaust smoke and particulates. The recommended practice is intended to identify high emitters, however, regulatory agencies using this procedure for enforcement must first establish SF pass/fail criteria based on a preceding fleet SF distribution for the subject fleet.

2 INTRODUCTION TO DIESEL VEHICLE EMISSIONS MEASUREMENT AND CONTROL

Controlling motor vehicle emissions is important for improving air quality on urban, regional, and national scales. In response, vehicle emissions standards over the past 35 years have become more stringent, fuel quality has improved, and vehicle emissions inspection and maintenance (I/M) programs have been implemented in areas with air-quality problems in an attempt to ensure that the emissions-control systems developed in response to these more stringent standards remain operating throughout a vehicle's lifetime. Because of I/M's important role in reducing emissions from motor vehicles, the US Congress requested the National Academy of Sciences (NAS) to review these programs. The 2001 NAS report on I/M programs recommended greater focus on identifying, diagnosing, and repairing the 10% of high emitters that contribute more than 50% of the emissions for any given pollutant, along with verification of the repairs. The NAS also recommended remote sensing play a larger role in I/M programs, the identification of high emitters, the evaluation of I/M programs, and measurement of real-world on-road particulate matter (PM) emissions.[1]

Light duty gasoline vehicles have made many great technological advances, leaving diesel engines responsible for a growing fraction of mobile source PM emissions. For example:

- In California heavy duty diesel vehicles (HDDV) represent only 2 percent of the vehicle fleet but contribute about 30 percent of the nitrogen oxides and 65 percent of the particulate emissions from motor vehicles.[2]
- In Beijing, the 2008 truck fleet accounted for only 11 percent of vehicle miles traveled, but it accounted for 39 percent and 49 percent of total mobile source NOx and PM emissions. The bus fleet contributed 2.2 percent of total distance travelled; however, it accounted for 26 percent and 11 percent of PM and NOx emissions, respectively.[3]
- In Mexico City, particulate matter pollution is estimated to cause 4,000 excess deaths and the loss of 2.5 million days from work each year and emissions from diesel-powered buses and trucks have been shown to be a major source of this air pollution.[4]

Diesel exhaust emissions contribute to ground-level ozone (smog), fine particulate pollution, and contain over 40 substances that are considered toxic. Furthermore, over 30 epidemiological studies have linked diesel exhaust to cancer.[5] Today's data show that

[1] National Academy of Sciences; "Evaluating Vehicle Emissions I/M Programs"; 2001: http://www.nap.edu/openbook.php?isbn=0309074460.
[2] California Air Resources Board, 2004 (http://www.arb.ca.gov/msprog/hdvip/hdvip.htm see pampl1-4.pdf)
[3] Havard School of Public Health, 2009 (http://belfercenter.ksg.harvard.edu/publication/19091/inuse_vehicle_emissions_in_china.html), page iv.
[4] Transportation Research Board, 2006 (http://pubsindex.trb.org/view.aspx?type=CO&id=776830).
[5] Farleigh, Kaplan, US PIRG, "Dangers of Diesel"; http://www.pirg.org/reports/enviro/dangerousdiesel/.

diesel exhaust poses a greater risk of cancer than all the other air toxics USEPA tracks combined.[6]

Active strategies to clean up HDDV exhaust include stricter emission standards for new diesel engines, low sulfur diesel fuels, older vehicle retrofit programs, and vehicle emissions I/M programs. However, the I/M programs typically use visible wavelength opacity meters that are considered largely ineffective for PM 2.5.

Existing diesels will last for several decades and although many will be retrofitted with emissions control technologies to reduce their emissions, most of the diesel engines in use in North America today lack particle emissions controls entirely. The situation is no different in Beijing where an effective I/M program that identifies and removes gross emitters among the high-mileage vehicles was identified in a Harvard School of Public Health study as a key control strategy needed for further mobile source emissions reductions. With various diesel emissions reduction strategies being implemented, there is a growing need to monitor emissions from in-use diesel engines to ensure that the reduction strategies perform as expected and to allow additional mitigation measures, including improved diesel I/M programs, to be put in place in a timely manner.

While stricter new vehicle emissions standards for light duty vehicles (LDV) are reflected in lower on-road emissions today, studies show that on-road NOx emissions from HDDVs have remained high over the past two decades despite lower new engine certification limits. Moreover, large particle emissions from older diesels have been replaced by a greater number of finer particles, which pose a greater health risk from today's modern diesels.[7]

In summary, diesel vehicles today are polluting in increasingly greater proportion, have mostly uncontrolled emissions, have defied stricter engine limits with high on-road NOx emissions, and are emitting greater number of the most harmful fine particles.

[6] Bruce Hill, PA Clean Air Task Force senior scientist; Business Wire Incorporated; Feb 22, 2006.

[7] Presentation by Dr. David Kittleson, University of Minnesota, Department of Mechanical Engineering, et al "Chemical & Physical Characteristics of Diesel Aerosol," presented at the 12th Annual CRC Conference, April 15-17, 2002.

3 DIESEL EMISSIONS MEASUREMENT – DEFINITIONS

3.1 SMOKE

Smoke is a general term used to describe the cloudy, hazy, emanations that result from the burning of organic substances. It consists of solid and/or liquid particles or droplets that are so small that they tend to remain suspended in air for extended periods of times varying from seconds to years. Although smoke is often visible to the human eye, much of it is not. The size and content of the particles or droplets comprising smoke very much affect our ability (as well as the ability of optical instruments) to "see" it. A simple example of invisible smoke from everyday experience results from the act of toasting bread. Long before visible smoke is obvious to the eye, the human nose senses the very small particles wafting in the air. It is only later when the toast begins to brown or blacken that the particles grow large enough to be seen as smoke.

3.2 PARTICULATE MATTER (PM)

Particulate Matter (PM) is very similar to smoke in that it consists of small solids and/or liquids suspended in air; however, the sources of the suspended substances are not necessarily the result of burning organic substances. Dust, sand, abraded material from tires and brakes, salt sprays, and even small water droplets like fog are some of the other constituents. PM is usually the terminology used from a regulatory compliance perspective and may be further subdivided into size related classifications such as PM10, PM2.5, etc.

3.3 PM 10

PM10 is a classification of PM representing constituents that are less than 10 microns in diameter (PM less than 10 x10-6 meters in size). Typically, an air sample is passed through a cyclonic sample filter that removes the larger particles. What remain are the PM10 constituents.

3.4 PM 2.5

In a manner similar to the definition of PM10, PM2.5 represents the PM constituents when all particles larger than 2.5 microns are removed. PM2.5 is also commonly referred to as fine particle PM.

3.5 OPACITY

Opacity is a measure of light reduction/loss over a smoke column path usually expressed as a percentage. An opacity of 10% means that 90% of the source light power remains and

10% has been lost after passing through the measurement path. The 90% (0.9) term (the light remaining) is referred to as Transmittance.

3.6 SMOKE DENSITY

Smoke density is a term usually associated with opacity measurements where there is reason to assume that the optical measurement relationships follow the Beer-Lambert exponential laws. The Beer-Lambert Law is usually expressed as T = e-KL where T is transmittance (same as 1-opacity/100), K is the smoke density factor in units of inverse length, and L is path length of the measured smoke sample column. Conceptually, the smoke density term represents the exponential light loss sensitivity per unit length of the smoke column.

3.7 SOOT

Soot is considered by many to be the agglomerated combination of elemental carbon (EC) and organic carbon (OC) in diesel exhaust particulate matter. However, others consider soot to be only the insoluble portion of diesel particulate; hence, elemental carbon.

3.8 SMOKE METER

The term Smoke Meter generally refers to a smoke measuring instrument based on optical property measurements. A wide variety of approaches to such instruments exists. Many measure opacity directly through the smoke column. Others measure opacity through a sampled fraction of the column.

Another measurement class of these instruments samples the exhaust and flows it through a filter membrane, or “paper”. Reflective and/or transmissive optical measurements quantify how “blackened” the filter “paper” has become from the soot content of the smoke. The “blackening” effect is usually considered to be caused by the elemental carbon component of the soot. The classes of instruments that measure the reflective properties are generally called Smoke Meters with their results reported in special units called Smoke Numbers. A variety of such Smoke Number scales have evolved (e.g. Hartridge Smoke Units, Bosch Units, etc.). More sophisticated instruments may measure combinations of reflective and transmissive optical properties. These instruments are usually specially designed and calibrated to measure primarily the elemental carbon and are generally referred to as Black Carbon measurement devices.

With few exceptions smoke meters generally operate with optical frequencies in the visible to near infra-red spectra. The majority use green light (~550 nm) or deep red light (~680 nm) as optical spectral bands for measurement.

3.9 SMOKE NUMBER

Smoke number is a term relating the output of smoke meters (aetholometers) that measure optical properties of smoke on a filter "paper" substrate. A variety of smoke number scales have been developed to relate different instrument measurements to the assumed amount of soot being measured. An underlying assumption for such reporting is that soot is the majority or at least most important constituent of the smoke to be measured. Common reporting scales include Hartridge Smoke Units (HSU), Bosch Smoke Unit (BSU), Filter Smoke Number (FSN), etc.

3.10 SMOKE FACTOR

Smoke Factor (SF) is a term introduced by ESPH to describe its remote sensing measurement of smoke. It represents a ratio of exhaust opacity to the amount of fuel burned at the time of measurement. SF is measured in the UV using frequencies providing the greatest sensitivity to the particulate mass fraction. The amount of fuel burned element of the ratio is formulated by summing measurements of the carbon-based gases of the exhaust. For black diesel smoke, a SF of 1 indicates 1% of fuel by mass is emitted as PM.

4 RSD SMOKE FACTOR – INTERPRETATION AND MEASUREMENT RANGE

ESP developed the SF measurement for remote sensing devices (RSD) in response to the clear need for an effective and unobtrusive measurement of smoke from old and new diesel engines. For a primer on general smoke opacity theory, refer to Appendix A.

4.1 SF MEASUREMENT

While SF is a new term introduced by ESP, the actual measurement is based on a familiar light extinction measurement (i.e. an opacity measurement, but at a much shorter UV wavelength). Those familiar with remote sensing understand that by necessity, remote sensing measurements of vehicle exhaust taken as the vehicle is driven by are not the same as absolute tailpipe measurements, but rather pollutant measurements of the dilute exhaust behind the vehicle ratioed to other measurements of the same dilute exhaust. If the opacity measurement is ratioed to the sum of the carbon-based gases of the exhaust (i.e. CO_2, CO, and HC's), then the result is a fuel specific measurement. This is true because the sum of carbon-based gases represents the quantity of combusted fuel carbon. For ESP smoke factor theory and calculations, refer to Appendix B.

4.1.1 SF INTERPRETATION 1

Where there is reason to believe that the measured exhaust is predominantly elemental carbon (i.e. black soot) as emitted by most diesel engines, the SF can be interpreted and reported as grams of particles per 100 grams of fuel consumed, or SF multiplied by ten as grams of particles per kg of fuel consumed.

4.1.2 SF INTERPRETATION 2

SF can be thought of as the percentage of fuel emitted as smoke for predominantly black carbon soot emissions. For example, a RSD SF measurement of 2.0 means that 2.0% of the mass of fuel being consumed by the vehicle is being emitted as particulate matter. In this case, SF represents the undesirable efficiency with which a vehicle produces PM from fuel.

4.1.3 SF INTERPRETATION 3

When measuring black diesel soot under full engine load conditions, the SF can be converted into a K-value by simply multiplying by 3 (see Appendix C). This is particularly useful when the regulations are K-value based.

4.1.4 SF INTERPRETATION 4

Once the RSD SF is converted to K-Value, if required, it can be converted to HSU as per the standard formulae; HSU = 100 * (1 – exp(-0.43K).

4.2 GENERALLY EXPECTED SMOKE VALUES

4.2.1 VISIBLE SMOKE

From general observations, SF values of 0.60 to 0.80 correspond to the threshold of visual identification of exhaust smoke for moderate (non-idle) exhaust flows. For SF values greater than 0.9 and non-idle flow conditions, black smoke should normally be visible to the human eye when viewed from the proper angle.

4.2.2 GASOLINE FUELED VEHICLES

Properly functioning gasoline vehicles (not direct liquid injection) operating from idle to near full load normally produce very little particulate matter in the exhaust. SF readings should essentially be in the noise band of the instrument (i.e. +/- 0.1). Readings at moderate loads that exceed 0.3 most likely indicate a smoking vehicle (probably oil-based “blue smoke”).

4.2.3 PRE-2007 (USA) DIESEL VEHICLES WITHOUT PM FILTERS

Typical values for well-maintained vehicles operating at moderate loads fall in the range of 0.3 to 0.6.

4.2.4 DIESELS WITH PROPERLY FUNCTIONING PM FILTERS

Typical values should essentially be in the noise band of the instrument (i.e. +/- 0.1).

5 ADVANTAGES OF THE RSD SMOKE FACTOR

The versatile RSD SF measurement has several advantages over the conventional smoke meter (i.e. opacity) measurements that are applied to both LDDVs and HDDVs. California currently applies the SAE J1667 snap-acceleration test for its heavy duty vehicle inspection programs (HDVIP),[8] although CARB was among the most active agencies in the development of recommended practice for RSD SF measurements.

5.1 ENGINE OPERATING RANGE

Because SF is fuel specific, it has a very significant advantage over simple opacity–based measurements. It provides useful information over the entire operating range of the engine, from idle to full load. On the other hand opacity measurements have their primary value at near maximum engine load conditions. The reason for this is that diesel engines by their very nature have huge amounts of excess air along with the combustion products. This excess air dilutes any opacity measurement. But at maximum engine loading air to fuel ratios are generally lowest; hence, less dilution of the particulate effects and maximum opacity sensitivity. The RSD SF is not affected by this dilution effect. Although SF opacity measurement is affected by dilution, so also is the measured fuel. The two dilution effects cancel in the SF calculation.

5.2 TRADITIONAL OPACITY METER CHALLENGES

5.2.1 VARIABILITY

Opacity measurements can vary with ambient air conditions and with placement of the optical beam. Wind, temperature air density and humidity can affect the opacity result, and correction factors may be required if these are outside the procedure's prescribed operating range.[9] However, no correction is available for wind affecting the plume in the sampling zone, or inconsistent instrument placement along the plume centerline.

The SF is not affected by these factors since the measurement is indexed to fuel consumption (i.e., it is fuel-specific). Ambient air density has an effect on the reported measurement. Although these effects are present in the opacity measurement, and they are also present in the carbon-based gas measurements; when the ratio of the opacity to the fuel gases is performed, the error effects cancel.

5.2.2 INSENSITIVITY

When scattering particles are much smaller than the wavelength of the light used to measure them, they are nearly invisible (do not generate much in the way of opacity

[8] ARB HDVIP Program: http://www.arb.ca.gov/enf/hdvip/hdvip.htm
[9] SAE J1667: http://www.arb.ca.gov/enf/hdvip/saej1667.pdf

response). Visible light (e.g. green light (~550nm)) instruments are far less sensitive to the accumulation mode mass particles (centered at ~250nm) emitted by today's modern diesel and are decreasingly sensitive to the finer particles emitted in the greatest numbers.

The SF opacity measurement uses 230 nm UV light with a mass optical extinction response that is 3 times the response of instruments measuring at 550 nm. The UV based opacity measurement has also demonstrated a very strong response to oil-based (blue) smoke; whereas it is generally acknowledged that conventional Smoke Meters have a poor response to blue smoke.

5.2.3 INTERFERENCE

NO_2 absorbs some of the broadband green light, limiting the effectiveness of conventional visible light smoke meters. This interference effect is not significant on diesel engines without after treatment since the exhaust NOx has generally less than 10% NO_2 (the rest being NO); however for diesels equipped with oxidation catalysts the NOx may be as much as 90% NO_2.

The UV based SF measurement is not subject to NO_2 or other interferences.

5.2.4 REAL WORLD OPERATING CONDITIONS ON-ROAD

Another significant advantage of the RSD SF measurement is that it is synchronized with all the other gas measurements and is obtained while the vehicle is driven on the road in real world operating conditions. There is no need to stop, detain vehicles for 15 minutes or more and displace the driver to conduct the test. A hundred SF measurements can be made literally in the time it takes to make one traditional opacity measurement.

6 RSD SMOKE FACTOR MEASUREMENT – RECOMMENDED DEPLOYMENT CONFIGURATIONS

Light duty gasoline and diesel vehicles as well as some heavy duty trucks and buses have one and sometimes two rear exhaust tailpipes located within ~35 cm of the roadway. If there is a single exhaust, it may be on the left or the right side of the vehicle. The tailpipe direction can vary from directly backwards to up to 90 degrees left or right, and the final bend may aim the flow down or parallel to the roadway. For all these exhaust configurations a standard equipment deployment that places the measurement beams at 20-25 cm above the roadway in the middle of the lane in which the vehicle travels works well with excellent overall coverage of this fleet segment. Data are acquired based on blockage and un-blockage of the measurement beams. Ambient gas values are acquired when the front of the vehicle blocks the beams. Exhaust readings are enabled when the rear of the vehicle passes thereby unblocking the measurement beams.

Some heavy duty trucks (primarily European manufactured) have a low exhaust pipe that is located mid truck (or mid-vehicle for some tractor/trailer rigs). Attempts to measure these vehicles with a standard deployment are usually not successful since the plume is already well dispersed at the rear of the vehicle. In order to measure these vehicles the measuring beams must be lowered so as to be able to read the plume under the vehicle. The beams must be lowered so that they are unobstructed by the vehicle undercarriage paraphernalia (typically, lowered to 15-cm). The specialized measurement algorithms used by RSD will measure sensed plume gases in the undercarriage gaps between tires. These lower deployments also continue to work well for measuring the general fleet segment (light duty vehicles) containing low rear exhausts.

It is the high stack heavy duty and bus/truck fleet segments that are the most difficult to measure and no single on-road deployment configuration of RSD will cover the entire high stack fleet segment. Multiple configurations are required!

Some heavy duty buses have high rear exhaust that can be either on the right or left side of the vehicle. These vehicles can be measured by deploying the RSD measuring beams at a fixed height at approximately the level of the exhaust outlet, but low enough so that the top of the bus blocks the beam. The rear of the bus unblocks the measurement beams and normal gas measurement data collection proceeds. Alternatively, the RSD beams can be deployed higher than the bus body. In this case an optional Body Sensor must be used to sense the body of the bus.

High stack exhaust configurations where the exhaust pipe is located directly behind the driver compartment of a tractor pulling a trailer or a truck with a long cargo carrying body require a multiplicity of RSD deployments. A single exhaust pipe configuration may be located left side or right side, the height of the exhaust can vary 1-2 meters depending on the particular make/model, the exhaust flow exit angle can be vertical, backward, or a variety of angles between backward and sideways. In addition the height of the cargo carrying component is a major factor in deployment considerations. Attempts to measure the plume at the rear of the trailer (as described above for buses) have proved unsuccessful

– the plumes are either too dispersed at that distance from the exhaust pipe, or else there is too much uncertainty between the ambient reading at the front of the vehicle and the exhaust readings at the rear.

For these types of vehicle exhaust configurations the measuring beams must be deployed to intercept the exhaust gas while not being blocked by the body of the truck or trailer (for example, above the trailer body). Since the measurement beams do not get blocked, normal signals are not present to identify when to measure ambient and exhaust plume values. For this situation ESP provides an optional sensor (Body Block Sensor) and some specialized triggering logic to synchronize gas measurement. The body sensor when properly aligned with its companion retro-reflector across the roadway is used to sense beam blockage by the front body of the truck crossing its path. When the Body Sensor beam is blocked by the front of the vehicle a simulated blockage of the measurement beams is created that persists for 0.5-seconds. Ambient gas values are read at the beginning of the blockage and plume exhaust readings are enabled at the end of the simulated blockage. The entire process is then inhibited until the Body Block sensor beams remains connected for a fixed time period. Proper spacing between the body sensor beam and RSD measurement beams controls where the measurement widow opens to measure the exhaust plume. Ideally, the window opens at approximately the position of the exhaust pipe. Recommendations for the horizontal spacing of the Body Sensor with respect to the Source/Detector Module (SDM) are shown in the following table. Positive distances represent Body Sensor positions after (downstream of) the SDM.

BODY SENSOR POSITION TABLE

Speed (mph)	Distance(ft) after SDM	Speed (kph) After SDM	Distance (meters)
5-10	12	8-16	3.7
10-15	8	16-24	2.4
15-20	4	24-32	1.2
20-25	0	32-40	0
25-30	-3	40-48	-0.9
30+	-3	48+	-0.9

6.1 RECOMMENDATIONS FOR VERTICALLY AIMED EXHAUST FLOWS (SINGLE OR DUAL EXHAUST PIPES)

Mount the SDM and Corner Cube Mirror (CCM) for approximately level beams at a height above the highest trailer configuration to be measured. Mount the body sensor at a height

that is certain to be blocked by the front of the vehicle. Set its position with respect to the SDM per the BODY SENSOR POSITION.

6.2 RECOMMENDATIONS FOR HIGH STACK SIDE AIMED EXHAUST FLOWS

Side aimed exhausts with high trailers are particularly difficult to measure since the exhaust does not rise above the trailer. Reasonable success has been obtained by deploying the SDM and CCM in a steep angle across the roadway. For example, the SDM can be placed several feet above the level of the highest trailer. It would then be aimed at a downward angle to a transfer mirror that is set up at approximately the height of the exhaust pipe.

7 RSD SMOKE FACTOR MEASUREMENT – AMBIENT CONDITIONS, OPERATING MODE CHALLENGES AND SITE CONFIGURATIONS

How, where, and when to collect remote sensing measurements depends on the vehicles being targeted (gasoline vs. diesel, light duty vs. heavy duty, old vs. new), the goals of the RSD measurement campaign (clean screening, high emitter identification, general fleet emissions characterization/monitoring), and the prevailing site conditions.

Gaseous emission measurements of light duty gasoline vehicles (LDGV) using RSDs have traditionally been collected during low to moderate acceleration. RSDs are set up at on-ramps to highways where vehicles must accelerate to highway speeds in order to merge into traffic. Correlations of on-road LDGV RSD measurements (CO, HC, and NO) to dynamometer I/M measurements were best when the measurements were collected under acceleration, engine loads matched, and the vehicle's mechanical state had not changed between tests. Numerous LDGV demonstration studies were conducted which led to three USEPA guidance documents issued for the three general LDGV applications; clean screening, high emitter identification, and fleet emissions monitoring/characterization.

7.1 AMBIENT CONDITIONS

When to collect quality RSD measurements is less a function of the vehicle and the application, and more a function of the RSD instrument itself and the prevailing ambient conditions at the measurement location. Unless specifically studying a transient state (e.g. cold start), vehicles should be in a warm, stable operating condition at the chosen RSD site. The most critical ambient factors are temperature, moisture, wind, dust and background levels. These are discussed elsewhere in the manual as part of general RSD operating instructions and are only quickly reviewed below:

Vehicle – Warmed-up, stable operation (avoid cold-starts and long extended idle conditions).

Temperature – 30-120° Fahrenheit (white smoke due to freezing exhaust water scatters RSD light and temperatures above 120° F can affect instrument electronics; avoid both extremes).

Moisture – Dry (test under light drizzle as long as equipment is protected and tire spray is minimal; heavy rain and tire spray attenuates RSD light and limits quality measurements and resulting loss of productivity, but not measurement accuracy). Fog conditions will rapidly lower productivity. To avoid condensation/fog on RSD equipment mirrors in high humidity conditions insure that the RSD equipment (SDM and CCM) is warmer than the surrounding air.

Wind – Up to low wind (Moderate wind against the flow of traffic can be tolerated; heavier wind and any cross-winds can disperse exhaust plumes prematurely, preventing complete measurements).

Dust – Avoid site conditions where the roadway is covered by dust, or may be subjected to dust from adjacent areas with wind conditions.

Background Levels – Stable (locate away from heavy vehicular traffic where exhaust from adjacent lanes can mix with the exhausts being measured. Locate away from stationary sources of CO, HC, and NO. Locate where dust is not being entrained by passing vehicles. Stable background levels are easily subtracted. Unstable, changing background levels are difficult to track and compensate for).

7.2 OPERATING MODE CHALLENGES AND SITE CONSIDERATIONS

Where and how to collect RSD SF measurements is most critical when identifying excess repairable emissions (i.e. high emitters). It is generally accepted that if a vehicle registers low emissions in valid RSD measurements even under heavy loads, deceleration, or during transitions (i.e. shifts) when high emissions are entirely possible and expected, the vehicle is certain to be a clean vehicle, therefore, operating modes are less important for clean screening.

When characterizing fleet-wide emissions, and validating inventories, a variety of modes may need to be represented. However, when identifying high emitters, it is important to understand under what operating conditions it may be acceptable for a normal vehicle to have temporarily elevated emissions. For example, US light-duty gasoline vehicles manufactured before 2002 were certified using a test procedure that did not include hard acceleration. Vehicles of this type may have high emissions under heavy acceleration but be functioning as designed. For this reason, recommended practice for light-duty gasoline vehicle high emitter identification has been emissions measurement under low to moderate acceleration.

In general, for high emitter identification the on-road operating condition should be similar to the operating modes found in tests used to certify the vehicles. Where these are transient tests, it still is often the case that one mode dominates the fuel consumption and emissions output. This mode should be selected if only a single mode is to be tested on-road.

7.3 NOX EXCESS EMISSIONS AND IDLE CONDITIONS FOR HEAVY DUTY TRUCKS

Although the total amount of NOx pollutant output may be small at idle conditions, the amount of NOx per unit fuel is quite high for most diesel engines. Readings taken at idle conditions for NOx are therefore likely to skew fleet characterization and excess emissions data and should be avoided.

However, avoiding idle measurements is easier said than done. Gasoline engine coasting (idle) conditions rarely result in a valid RSD measurement since not enough exhaust gas is produced for a valid measurement. However, HD diesels are quite large compared to gasoline engines, so there is a much higher likelihood that RSD measurements will be valid for coasting conditions. It should also be understood that idle fuel conditions also occur for short periods during engine shifting operations.

Where it is important to be able to screen out NOx idle readings for your program campaign, first chose a site with a reasonable grade so that coasting is infrequent, and second, consider deploying multiple, side-by-side RSD measurement stations. Data processing can then rule out most idle records by only accepting records where two stations measure approximately the same value and by placing constraints on the plume size.

Please note that unlike NOx, SF readings at idle conditions are generally small and should not skew fleet characterization or excess emissions data.

7.4 HEAVY DUTY DIESELS AND SHIFTING

The majority of heavy duty vehicles on the road have a primary purpose to carry cargo. The weight of the vehicle when it is carrying no cargo to a full cargo load can vary by tens of thousands of pounds. To handle these weight variations the vehicles are equipped with transmissions that can have anywhere from 8 to 18 gears. In order to accelerate a vehicle carrying heavy cargo, many gear shifting cycles are required. During each shift cycle the engine undergoes a rapid transition from no load (idle fuel) to maximum load. As the vehicle accelerates and the transmission gear number increases, the duration that the engine is at maximum load increases. There is no such thing as quasi-steady state engine operation until cruising speed is reached!

7.5 ROADWAY DUST

Dusty on-road sites should be avoided, but the primary reason is that hit rate will be poor – not so much accuracy.

The IR smoke factor and the UV smoke factor are calculated basically the same way: the time series of the reference channel (rear vehicle readings – the single front of the vehicle reading) are correlated with the time series of exhaust gases ($CO2 + CO + HC$) via a least squares fit. Surface road dust attenuation time series effects are usually increasing with

time while exhaust gases are dissipating with time producing negative correlation result. Therefore, rather than saying that there is no effect on accuracy, a truer statement would be that there is in general no false positive effect. When there is a significant amount of smoke coming out of the tailpipe and we measure in the presence of surface road dust, our readings will normally be low or negative.

Except for some specialized situations there is no reason to expect that the pattern of road dust kicked up by the tires (or draft vacuum) should correlate with the dissipating plume gases. One possible exception might be when measuring under HD trucks where the exhaust pipe terminates a significant distance before the rear of the vehicle. Since the truck carriage tends to trap the exhaust gases, plume dissipation in this situation tends to be slower during the measurement period. Road dust kicked up by the leading tires could also be nearly constant depending on the vehicle speed. Therefore, a positive correlation could occur.

The comments above related to surface road dust -not to wide spread suspended or blowing dust conditions. Surface road dust is kicked up into the plume path from the tires and is "sucked" into the plume path by the vehicle draft vacuum. Wide spread dust conditions are the result of wind maintaining dust in a suspended condition. For the widespread conditions it the attenuation effects at the at the front of the vehicle and the rear of the vehicle are the same; hence, there is a null effect on the final result. This situation would be no different from having accumulated dust on the instrument mirrors or optical windows. When there is accumulated dust on our mirrors or windows the primary noticeable effect is reduced hit rate.

8 RSD SMOKE FACTOR MEASUREMENT – RECOMMENDED TEST PROCEDURE

Early 1990s validation testing for a procedure for smoke opacity testing of diesel vehicles using the traditional smokemeter (i.e. opacity meter) found that acceleration peak opacity was the most effective criterion for detecting high opacity emitters of that age.[10,11]

Several candidate methods were evaluated, including: a quick acceleration in gear, a lug-down in gear (manual transmissions only), stall idle (auto transmissions only), and snap idle. The methods with the heaviest achievable loads (i.e. full fuel flow at the highest engine speed) were favored for detecting high emitters because those conditions mimicked the loading characteristics of the Federal Smoke Certification test cycle specified in SAE J1003.[12]

Today, tampering, mal-maintenance, and many engine and control system failures can result in excess repairable PM emissions during conditions other that the heaviest achievable loads, [13]. Fuel-specific PM emissions as measured by RSD are also more stable across moderate and heavy loads. Therefore, it is not necessary to seek the specific condition of acceleration peak opacity in order to detect high emitters. With RSD, a wider range of conditions from moderate to heavy engine loading is acceptable, which allows measurement under less controlled circumstances, e.g. when vehicles are driving on-road.

Opacity meters have been used for emissions inspection of diesel vehicles for many years, but nearly all of these programs have been aimed primarily at the control of visual smoke. When applying RSD for diesel high emitter screening, we recommend measuring particulate and gaseous emissions using a semi-controlled acceleration test. Both excess repairable particulate and gaseous emissions can be identified under moderate to heavy engine loading at lower vehicle speed accelerations as long as shifting and other transition states can be avoided or identified and eliminated.

Several studies support the use of a moderate- to heavy-load acceleration test for diesel screening:

Vancouver (LDDV) 2003

LDDVs were accelerated from stop past the RSD immediately after a dynamometer IM147 peak opacity test in the 2003 Vancouver study. Vehicles could not be accelerated to governed speed, nevertheless, most RSD results corroborated the IM147 test and some vehicles even exhibited smoke levels not observed during the dynamometer test.

Cross-Border (HDDV) 2005

[10] HDV I/M Study, 1998: http://www.arb.ca.gov/research/apr/past/a4-151-32_3.pdf
[11] Smoke Opacity at High Altitudes and Sea level: http://www.arb.ca.gov/enf/hdvip/sae911671.pdf; CARB, 1999.
[12] Smoke Opacity at High Altitudes and Sea level: http://www.arb.ca.gov/enf/hdvip/sae911671.pdf, CARB, 1999.
[13] On-Road Test of HD Trucks: http://www.arb.ca.gov/research/apr/past/01-340-2007.pdf; CE-CERT, April 2007.

Similarly, HDDVs crossing into the United States in Nogales, Arizona in 2005 accelerated under moderate to heavy loads away from the weigh-in-motion station and past the RSDs. These vehicles were far from full throttle, but independent validation of gaseous emissions with a portable emissions monitoring system (PEMS) on a few HDDVs showed that this acceleration test procedure achieved good correlation and could separate high gaseous emitters from normal vehicles.

CARB (LDGV) 2007

CARB found good correlation to PM mass measurements for several light-duty gasoline vehicles accelerated past the RSD.

Singapore (LDDV & HDDV) 2008

The Singapore study demonstrated good RSD SF correlation to peak lug-down opacity when light- and heavy-duty diesels were accelerated at heavy loads past an RSD just before receiving the dynamometer lug-down test. SF cutpoints to achieve specific enforcement goals were developed for the Singapore National Environmental Agency based on the likelihood the RSD identification would be corroborated by the lug-down test.

CARB ICAT (HDDV) 2009

Finally, an acceleration test was capable of flagging DPF failures within a modern HDDV fleet during the CARB-sponsored Innovative Clean Air Technologies (ICAT) study performed in 2009.

The diesel acceleration test under moderate to heavy load is effective for a broad fleet of diesel vehicles of varying technology and fuel and is our recommended best practice for gaseous and particle measurement screening and characterization of diesel vehicles.

Continuing studies of modern diesels equipped with oxidation catalysts and particle filters may reveal that high-speed cruise is also effective at identifying excess repairable emissions while providing a better mode of operation for general fleet characterization. However, the current recommended practice is:

1) to apply a diesel acceleration test at moderate to heavy load to a captive fleet at a specific site, or
2) identify a site on-road where these operating modes are likely to be observed.

8.1 RECOMMENDED PRACTICE FOR SMOKE FACTOR SCREENING OF A CAPTIVE FLEET

The objective of ESP's first on-going RSD heavy duty vehicle inspection program (HDVIP) at the Massachusetts Bay Transportation Authority (MBTA) was to reduce excess gaseous and particulate emissions as well as visible smoke, by identifying CNG and diesel buses with specific types of problems that result in excess emissions. Prior to the RSD-based

inspection program, the MBTA's fleet of 1000 buses received the periodic SAE J1667 snap-idle opacity meter test recommended by the USEPA for heavy-duty vehicle inspection programs.[14,15,16,17]

When applying the diesel acceleration test at moderate to heavy load to a captive fleet such as the MBTA buses, even greater control of the vehicle operating conditions is possible, and always recommended. This can be done by instructing the bus operators on the proper use of the RSD as a measurement tool. Operators are instructed only to test warm vehicles, preferably immediately after returning to the depot from their duty cycle to eliminate the need for throttle cycles in neutral to blow out entrained soot. From a stopped idle state approximately 1.5 bus-lengths before the RSD beam, the operator is instructed to engage the clutch and start the bus rolling, then up-shift skipping one gear so the bus can remain in constant acceleration and load without another shift until well past the RSD.

Guideline for testing a captive fleet are:

- Brief vehicle operators on RSD basics and on its most-effective use as an emissions measurement tool.
- Operate the RSD device under the stable ambient conditions reviewed above and described in greater detail in the RSD Operator's Manual (RSD-MAN 1160 Edition 4).
- Measure buses (upon their return to the bus depot) under warn stable engine operating conditions to avoid preconditioning.
- Start buses at least 1.5 bus lengths before the RSD and have them accelerate without shifting under constant moderate to heavy load until the exhaust pipe is past the RSD beam.
- Site selection simply comes down to having adequate space to complete the test properly and safely.

8.2 RECOMMENDED PRACTICE FOR CORRELATING WITH FACILITY LUG-DOWN TESTS

When a program design is intended to demonstrate on-road measurement correlation with facility lug–down testing, then it is important to measure the vehicle (the engine) in similar operating conditions as the lug down test. Lug-down conditions are "near peak power/peak load" conditions; therefore, the goal is operate and measure the engine output at "near peak power".

The ideal site for measuring near peak power for cargo-laden heavy duty trucks would be at a steep grade where the vehicles must accelerate from a low speed to a significantly

[14] MBTA Bus I/M Program History: http://www.mbta.com/uploadedFiles/About_the_T/Environment/MBTA%20RSD%20History.pdf

[15] SAE Recommended Cutpoints (40%/50%) for J1667 Procedure: http://www.epa.gov/OMS/highway-diesel/regs/saerep.pdf; November, 1998.

[16] SAE J1667 and Particulate Matter: http://www.arb.ca.gov/enf/hdvip/ccdet/saej1667.htm

[17] USEPA J1667 Guidance to States: http://www.epa.gov/oms/highway-diesel/regs/smokguid.pdf; Feb 1999.

higher speed. It will not be possible to predict where shifting will occur, but the duration of engine operation at maximum power conditions for each gear is longer when climbing a steep grade; hence, less likelihood of measuring during the idle part of the shift.

Where a steep site is not available or feasible, then some alternative approaches can be used. These approaches generally require the driver to be instructed to operate the vehicle under a special protocol; hence, these types of measurements would not be performed in normal traffic. Rather a site such as a dedicated area of a truck stop or a restricted side street would be used. The protocols generally have the following elements: (a) several full throttle cycles in neutral to blow out entrained soot in the exhaust system, (b) at a prescribed starting position from either a complete stop (i.e. a stop sign), or slow roll condition, the driver selects a specified gear and accelerates using full throttle past the RSD measurement station without shifting gear.

9 PROJECT EXAMPLES

Since the incorporation of the UV-Smoke Factor into the RSD4000 series products in 2002 many different studies, analyses, and reports have been undertaken to validate and demonstrate the utility of the measurement. The following excerpts represent some example projects that have been taken to validate the RSD Smoke Factor and to provide correlations to other measurement approaches, all of which have contributed to its commercialization.

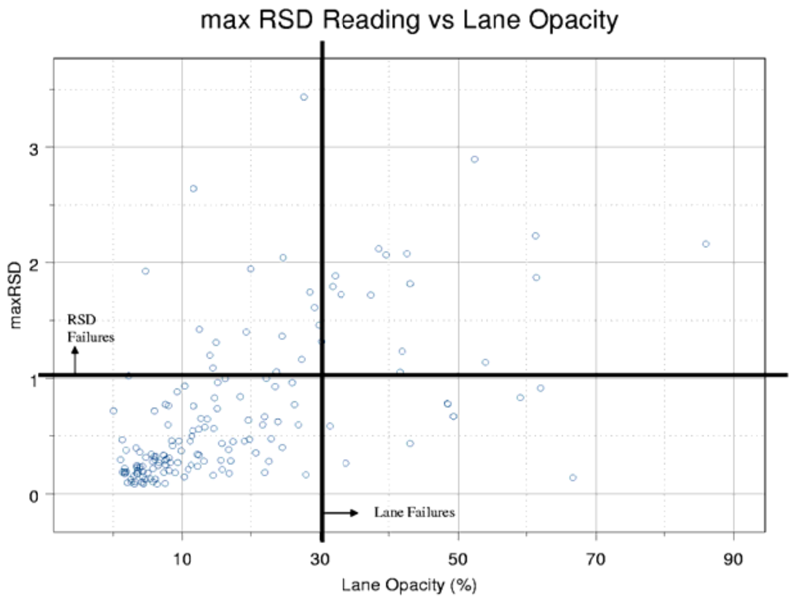
9.1 VANCOUVER STUDY

In the summer of 2003 a study was conducted to compare RSD UV Smoke Factor readings against formal opacity-based test measurements of light duty diesel vehicles at "Air Care" centralized test facilities in Vancouver, British Columbia. The purpose of the comparison can be broadly stated to determine whether the Smoke Factor can be an effective tool to identify diesel smokers.

The Air Care facility performs IM240 tests on light duty gasoline vehicles and a special opacity test on light duty diesel vehicles. The diesel vehicle testing consists of operating the vehicle on a dynamometer with a test cycle consisting of the last half of an IM240 test (IM147 test). During the test cycle opacity is measured with a Wager Smoke Meter. Test

fail determination is based on peak opacity measurement during the test cycle exceeding a 30% value.

An RSD test station was set up in the parking lot of the "Air Care" test facility. Diesel vehicles were recruited immediately after testing in the lane. The lane operator accelerated the vehicle from a standing start past the RSD measurement station three or more times. The highest RSD Smoke Factor value from the multiple passes was then compared to the lane opacity test result.



A total of 156 vehicles were tested with the measurement results shown above. The RSD Smoke Factor is shown on the vertical axis while lane test opacity is shown on the horizontal axis. An arbitrary horizontal RSD cut point line is shown with a value of 1. The lane cut point line is shown with a value of 30%.

A summary of the results is as follows:

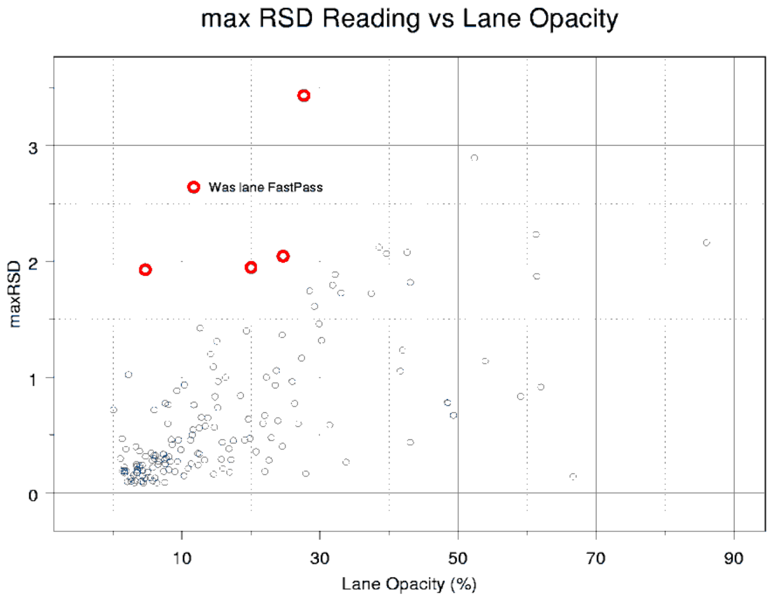
115 out 156 vehicles passed both tests

32 vehicles failed the RSD cut point

25 vehicles failed the lane test

16 of the failures were common

As a general statement the RSD cut point identified more vehicles as “smokers” than did the lane test. But were the additional vehicles identified by RSD really “smokers”?



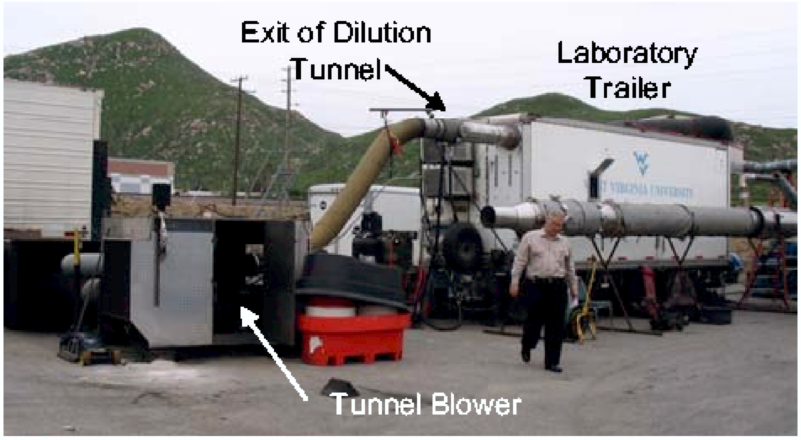
The highlighted values shown above represent the 5 highest reading vehicles from the RSD test set. Since the RSD measurement station also takes pictures of the vehicles when the exhaust is measured, the pictures were reviewed to determine if there was visible smoke present. The pictures that follow demonstrate conclusively that the vehicles produced visible smoke when measured in the parking lot. The fact that the lane test did not fail while the RSD did fail is most likely attributable to higher engine operating load in the parking lot than existed during the lane test.

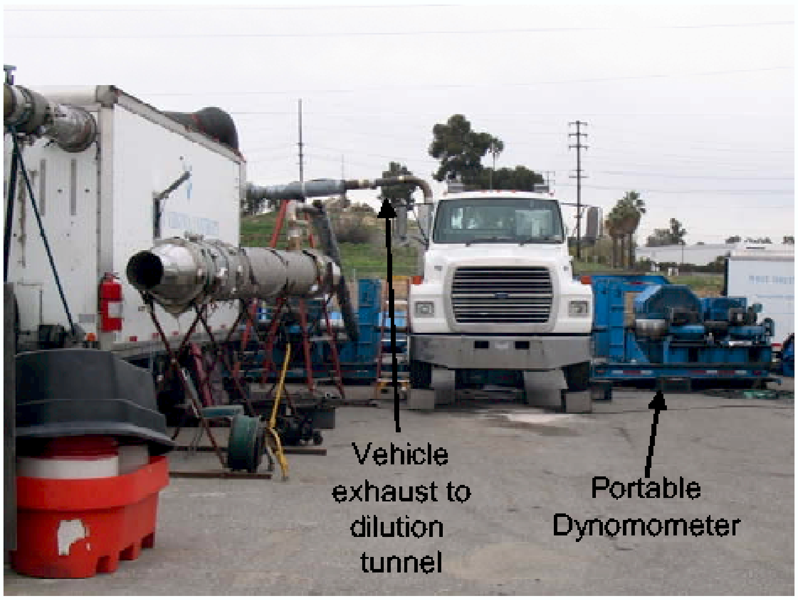

20020530 bclang00160.jpg
SF
0.000 0.000 x 0.44 14.71 797.2 294.50 1.8106 35.92 32 V


20020612 bclang00053.jpg
SF
0.000 0.000 x 1.81 14.28 1578.3 163.25 2.6422 18.80 9 V

The conclusion reached from the study is that the RSD Smoke Factor looks very promising to identify diesel smoking vehicles. Correlation to a formal opacity based inspection test was reasonably good, despite the different measurement techniques and vehicle loading conditions.

9.2 WVU (TEOM) CORRELATION



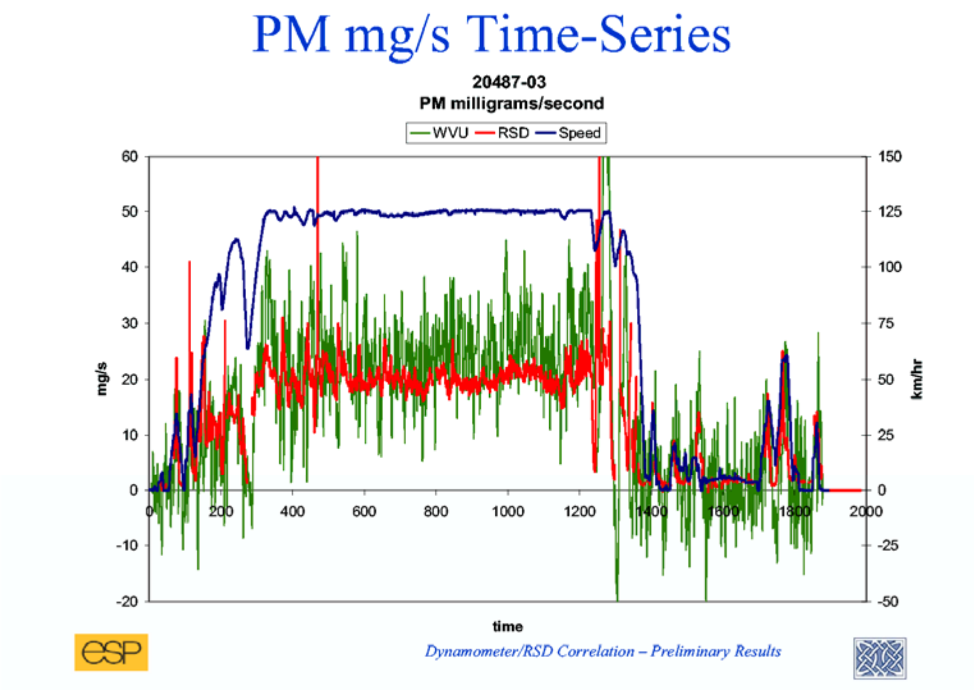


The CRC E55 California Heavy Duty Truck Characterization project was conducted at Riverside, California by West Virginia University (WVU). The project recruited in use heavy duty trucks from the general population and performed a large complement of test measurements over a variety of loaded mode test cycles. The measurements were acquired by an instrumentation suite contained within a mobile trailer that sample the flow from a well controlled CVS dilution tunnel.

One of the measuring instruments contained within the trailer was a TEOM (tapered element oscillating microbalance) instrument. This instrument technology is the basis for the majority of the ambient air monitoring instruments throughout the world. The instrument principle is to flow sampled exhaust onto and around a filter element that is mounted onto the end of a long narrow tapered element. The tapered element is part of an electro-mechanical resonance circuit where the resonant frequency is primarily

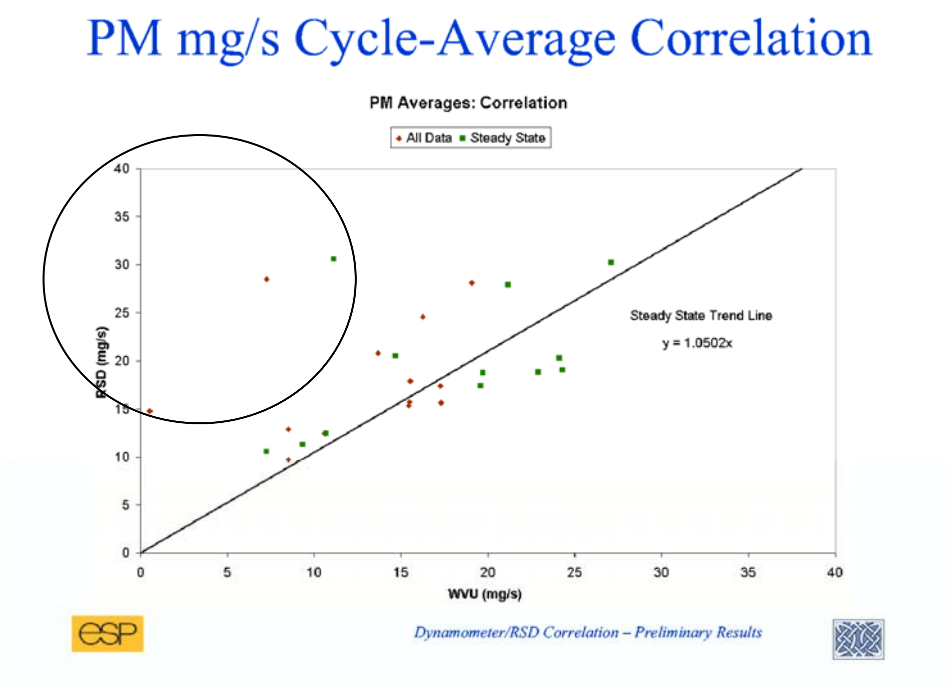
determined by the mass at its end. Particulate is trapped onto the filter element thereby changing the mass. Minute changes in resonant frequency are measured and then translated to change in mass.

ESPH was permitted to set up an RSD instrument at the blower output of the CVS dilution tunnel during testing of several of the heavy duty trucks. The RSD equipment was operated in a special second-by-second data acquisition mode during the same times the trailer instrument package recorded formal test data. Second-by-second test traces from WVU consisting of the TEOM output (milligrams per cm^3), CVS flow rate, and exhaust gas concentrations (CO_2, CO, and HC) provided a basis of comparison.



The primary way in which the instruments were compared was to convert both the RSD UV Smoke Factor output of "grams soot per 100 grams fuel" and the TEOM output of "mg per cubic meter) to a common output of "mg per second". This was accomplished using CVS flow rates and CO_2 concentrations. The above chart shows a time trace of RSD and TEOM mass rates for one of the test cycles. The traces show quite obvious strong correlation for both transient and steady state parts of the test cycle.

However, the traces also show that the TEOM response is quite noisy compared to the RSD measurement. For many of the tests or for portions of tests the TEOM wildly oscillated much more than is shown in the above figure with steady state regions of the test cycle generally more stable. Therefore, the general correlation approach compared cycle integrated averages as well integrated averages for just the steady state regions of the test cycles.

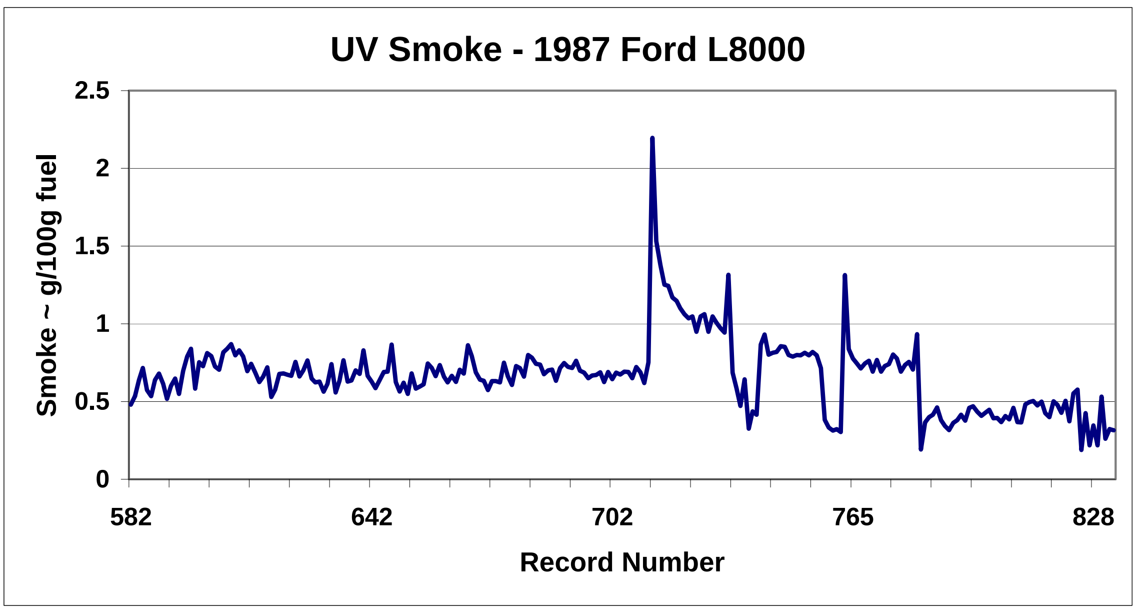


The above chart shows comparisons both ways for 12 different tests of different trucks. The circled area shows the obvious results that skew the correlation; whereas the remainder of the points show fairly good mass correlation. It should be pointed out that no evaluation or classification of the type of smoke (black, blue, white) produced by the vehicle was considered in this comparison.

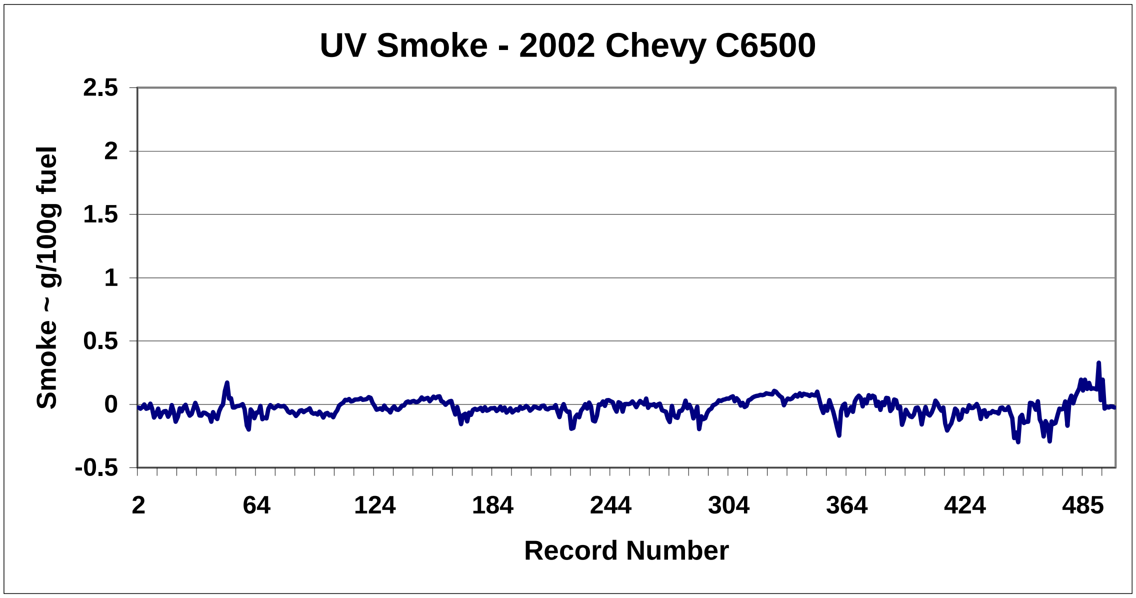
9.3 FREE-ACCELERATION TEST TRACE

On November 12, 2004 as preparation for a study for Raytheon, ESP measured four trucks in different modes of operation at the Raytheon facility in Tucson, Arizona. During idle and snap-idle modes, the RSD unit was run in a continuous measurement mode that reports results every second. Results for two trucks, a 2002 Chevy C6500 and a 1987 Ford L8000 are shown in the figures below. Although there were some set-up and calibration issues to be resolved, the RSD4000 was clearly able to differentiate between the clean 2002 Chevy C6500 and the much smokier 1987 Ford L8000. The characteristics of the traces for all pollutants are consistent with the events of a snap idle procedure; 1) sudden increased fuel, 2) an increase in engine speed with increasing air fuel ratio, and 3) completion of the test by a return to idle condition. The Chevy data show low smoke readings and the snap idle increases are hardly discernable. By contrast the Ford data show three clearly defined snap idle opacity increases. The Ford data also show opacity at the beginning greater than 0.5 and at the end averaging about 0.4. This trace shows how well individual smoke factor readings can see smoking truck exhaust and the rapid variation of same.

Ford L8000 Smoke Measurements



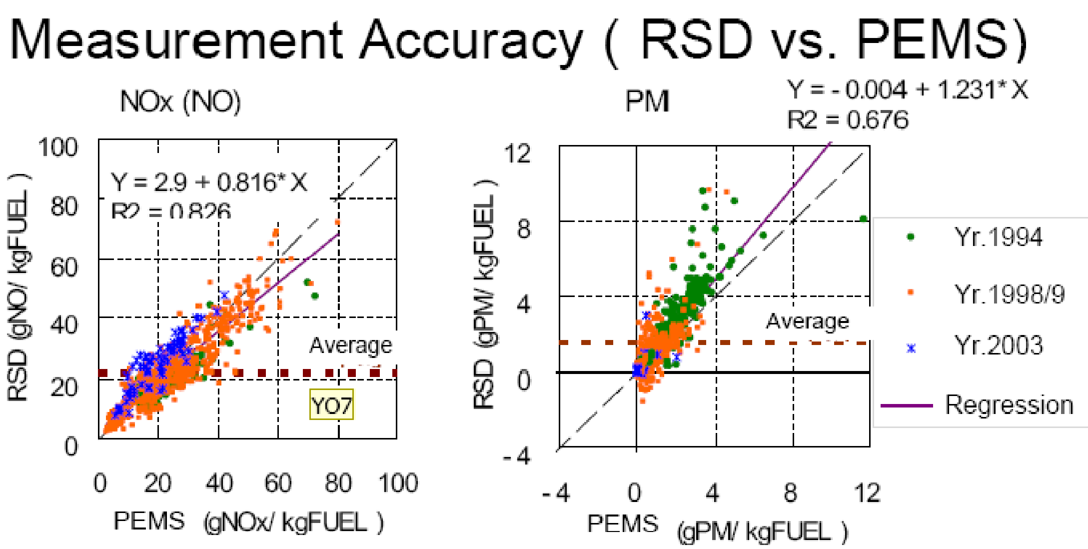
2002 Chevy C6500 Smoke Measurements



9.4 JAPAN PEMS –BASED HORIBA SMOKE CORRELATION

Testing was performed in Japan during 2005 comparing heavy duty truck emissions as measured by RSD to on-board PEMS instrumentation. Testing was conducted on a test course using a fleet of 22 different trucks consisting of different weight classes and age. The PEMS-based PM instrumentation was based on Horiba Micro tunnel flow sampling (DLS-2300) and a MEXA-130S opacity meter. Absorption constant correlations were performed on a chassis dynamometer to provide a mass reference for the Horiba instrumentation.

The following figure compares a large number of RSD readings for both NO and PM to corresponding PEMS readings during many test track operating conditions. The comparison is performed on a fuel specific basis (gNO/kgFUEL and gPM/kgFUEL). The results show excellent correlations for both NO and PM with R^2 values of 0.83 for NO and 0.68 for PM.



n	1274
Coefficent of Determination (r2)	0.83
Standard Error (g/kgFUEL)	5
Standard Error/Mean	0.2

n	1011
Coefficent of Determination (r2)	0.676
Standard Error (g/kgFUEL)	0.9
Standard Error/Mean	0.6

The above figure is from a presentation of the study results titled "Measurement and Analysis of Exhaust Emissions from Diesel Trucks Using Remote Sensing Device" presented at September 7, 2005 at the Annual Meeting of Japan Society for Atmospheric Environment (Nagoya, Japan) by Mr. Yohei Oya, Suuri-Keikaku Co., Ltd.

9.5 CARB LIGHT DUTY GASOLINE VEHICLE CORRELATION AND SHOOT-OUT WITH UV-LIDAR BACKSCATTER

During 2006 and 2007 California Air Resources Board conducted tests on specially recruited **gasoline** light duty "smoking" vehicles. Eight vehicles were recruited one of which was a clean/baseline vehicle while the other seven exhibited at times various degrees and colors of smoke (from barely perceptible visible smoke to obviously smoking vehicles). The vehicles were subjected to repeated dynamometer tests (UC test cycle) to characterize their gaseous pollutant output and gravimetric PM output. Results of the PM measurements are shown in the table below "Vehicle Identification".

Next, the vehicles were repeatedly run past RSD measuring stations set up in a side by side arrangement in a large empty parking lot area. The remote sensing equipment was provided by ESP and DRI (Desert Research Institute). The ESP instrument was a RSD4600 equipped with a UV Smoke Factor measurement channel, while the DRI instrument was a RSD3000 equipped with a laser light backscattering measurement channel. The vehicles were run past the RSD's in alternating left to right and then right to left directions. Operation of the vehicles was as follows: The vehicle was idled for a time period in a stopped condition 25-feet from the RSD stations. It was then accelerated through the station. This process was repeated for several measurement cycles. Next, the start position was set to 50-feet and the sequence is repeated. Additional sequences at starting positions of 75-feet, 100-feet, 150-feet, and 200-feet comprised the testing methodology.

The photograph below shows one of the test vehicles passing through RSD stations. Visible blue exhaust smoke is clear.


200607264518CACECE00179.jpg
Blue Smoke
16.733 8.617 V 5.84 10.69 4396.1 1239.83 2.0455 119.39 48 V
ESP Smoke Factor

California Environmental Protection Agency
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Vehicle Identification

#	MY	OEM	Model	Type	Disp (L)	Mileage	Smoke Type	Target PM (mg/mi)	UC PM Rate (mg/mi)
1	1997	Ford	Escort	PC	2.0	25,598	Normal emitter (no smoke)	< 5	1.51 ±1.12
2	1985	Toyota	Camry	PC	2.0	268,423	Light Black (invisible)	25 to 75	25.24 ±12.06
3	1991	GMC	Sonoma	LDT	4.3	171,487	Light Blue (invisible)	25 to 75	6.86 ±2.97
4	1981	Toyota	Pickup	LDT	2.4	119, 728	Moderate Blue	50 to 500	863.16
5	1995	Dodge	Dakota	LDT	2.5	123,974	Moderate Black	50 to 500	216.07 ±100.30
6	1963	Studebaker	Avanti	PC	4.6	high	Heavy Blue	50 to 500	1718.21 ±1647.26
7	1998	Toyota	Camry	PC	3.0	82,704	Heavy Black	50 to 500	60.38 ±2.80
8	1986	Mitsubishi	Max	LDT	2.0	163,913	Gray	50 to 500	69.61 ±11.35

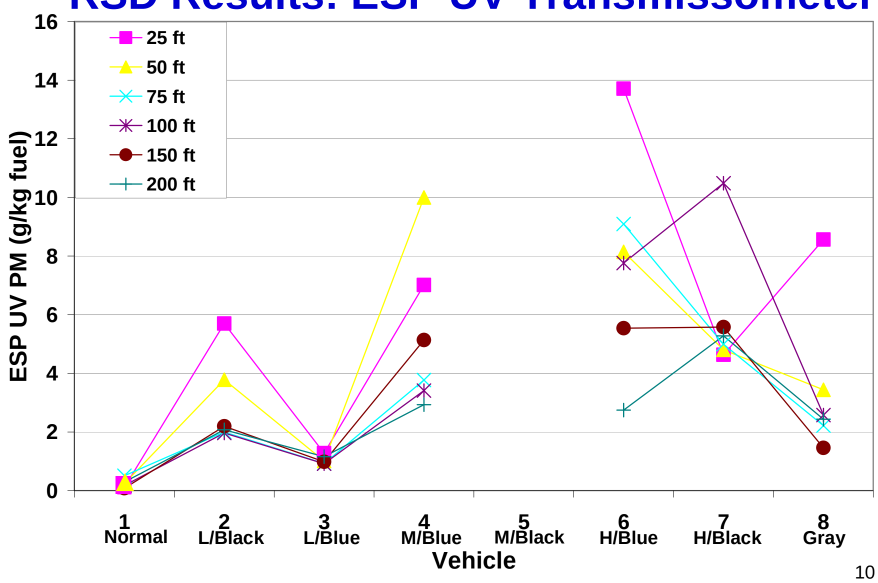
*PC = Passenger Car; LDT = Light-Duty Truck.

Note: this fleet distribution was chosen in order to evaluate the RSD PM measurement equipment over a full range of emissions. The fleet was not designed to be representative of the on road vehicle fleet, other than to include as broad a range as possible.

7

California Environmental Protection Agency
AIR RESOURCES BOARD

RSD Results: ESP UV Transmissometer



10

The CARB Study concluded that (a) the state of PM measurement technology is significantly improved over that evaluated in 2002 via the CRC E56 study; (b) the ESPH UV Smoke Factor shows great promise to classify the on road gasoline fleet into low/medium/high

PM emitters; (c) low speed hard to medium acceleration vehicle conditions are best suited to reveal smokers; and (d) a follow-up study is anticipated to obtain further cut point and emission rate information.

The general testing report for the Light Duty Gasoline Project is published in SAE paper 2007-01-1113.

9.6 SINGAPORE: ON-ROAD SCREENING DEMONSTRATION FOR ENFORCEMENT OF SMOKY VEHICLES

This remote sensing device (RSD) heavy-duty vehicle pilot program was a joint project between National Environment Agency (NEA), Environmental Systems Products (ESP) and VICOM as a subcontractor.

One of the goals was to establish the RSD UV Smoke Factor and operating conditions that will fail the same % of heavy-duty diesel vehicles as fail the Free Acceleration Simulation (FAS) test at an HSU standard of 50% recognizing that two tests were not expected to fail identically the same group of vehicles due to the differences between the opacity measurement and the smoke factor measurement discussed in section 5.

9.6.1 SUMMARY

The phase 3 goal was to demonstrate the RSD measurement of trucks in an on-road environment and establish the RSD cutpoint that would fail the same percentage of vehicles that are failed by the Free Acceleration Simulation (FAS), which is currently used for testing trucks coming from Malaysia.

Two RSD units were deployed on Marsiling Road close to the border crossing and near to where the Free Acceleration Simulation (FAS) testing is conducted. Phase 3 testing started on November 10th starting with training at the site and continued through mid April.

Heavy-duty vehicles selected at the border for FAS testing were directed to the location where two RSD units, one high and one low, were mounted on a scaffold tower. Heavy-duty vehicle drivers were instructed on how they should drive past the RSD system. The protocol developed in phase 2 was used to test the heavy-duty trucks. From a stop, in the lowest gear, trucks were accelerated through the RSD station at full throttle.

An additional video camera was used to capture an exhaust-view of the vehicles being tested while the primary RSD camera captured their license plate.

The RSD fail rate was monitored and compared to the FAS fail rate in order to establish the best cutpoint for RSD.

Just over 50% of vehicles failed the FAS test with greater than 50 HSU. Over 900 vehicles were measured using RSD and the distributions of emissions results from the FAS test and RSD were compared to establish an RSD cutpoint of 0.7 uv Smoke factor that results in the same number of failures using RSD as using the FAS test. The RSD Smoke Factor of 0.7 is equivalent to 7grams diesel soot per kilogram of diesel fuel.

9.6.2 EQUIPMENT SET-UP AND OPERATION

Equipment was mounted on 5 meter towers shown in Figure 9.7-1. Initially one unit was mounted at 5M to measure vertical exhaust and one at ground level in order to measure exhaust from trucks with low exhaust. Figure 9.7-2 shows a typical truck passing the RSD system. A video camera was used to monitor the operation and was

helpful for off-site engineers to see the various truck configurations and the timing of the measurements. Some adjustments to the RSD system operation were required to obtain measurements on most of the trucks. Figures 9.7-3 diagrams the equipment layout plan and Figure 9.7-4 the initial equipment elevation plan.

FIGURE 9.7-1: MARSILING ROAD RSD TOWER

FIGURE 9.7-2: MARSILING ROAD TRUCK MEASUREMENT

Initially the automatic truck sensor used to trigger the RSD measurement was thought to be malfunctioning and the RSD was manually triggered.

For trucks the RSD system is normally triggered by the presence of a vehicle blocking the beam. The actual emissions measurement starts when a significant level of emissions or CO2 are detected. The time window from trigger time to initiation of RSD emissions measurement has a time limit set to ensure the two events relate to the same vehicle. To allow for variability in the manual trigger and for the different truck geometries and relatively slow speed, the window was extended from 1 second to 3 seconds. This was a safe adjustment for an environment where trucks were moving slowly past the RSD system.

With a ground level exhaust, the RSD system is generally able to measure the exhaust independent of whether the exhaust is directed to the side or to the rear of the vehicle. For exhaust at ground level the RSD system is able to measure the exhaust plume either under the truck or behind the truck once it passes.

The vertical exhausts on Malaysian trucks had several different configurations. Ideally the exhaust would disperse vertically and be visible to the RSD system across the top of the truck. This was not always the case. The heights of the exhausts and the heights of the trailer or truck load were variable. Adjustments were made to the level of the higher RSD system to make sure it cleared the tops of nearly all the trucks.

In addition, instead of venting directly upward, some vertical exhausts were curved at the end in order to direct the exhaust in a particular direction; either horizontally to the rear, or to the side at an angle. In these cases the exhaust might not rise above the truck and a measurement was missed on about 20-25% of vehicles.

To capture these trucks, starting in March a trial was performed using both RSD systems operating in the crossing pattern illustrated in Figure 9.7-5. The higher SDM was mounted on a 4 meter platform and the second SDM was mounted 0.6meters lower. With this arrangement, 80% of the vertical exhaust trucks were successfully measured.

FIGURE 9.7-3: SCHEMATIC OF EQUIPMENT SET-UP PLAN

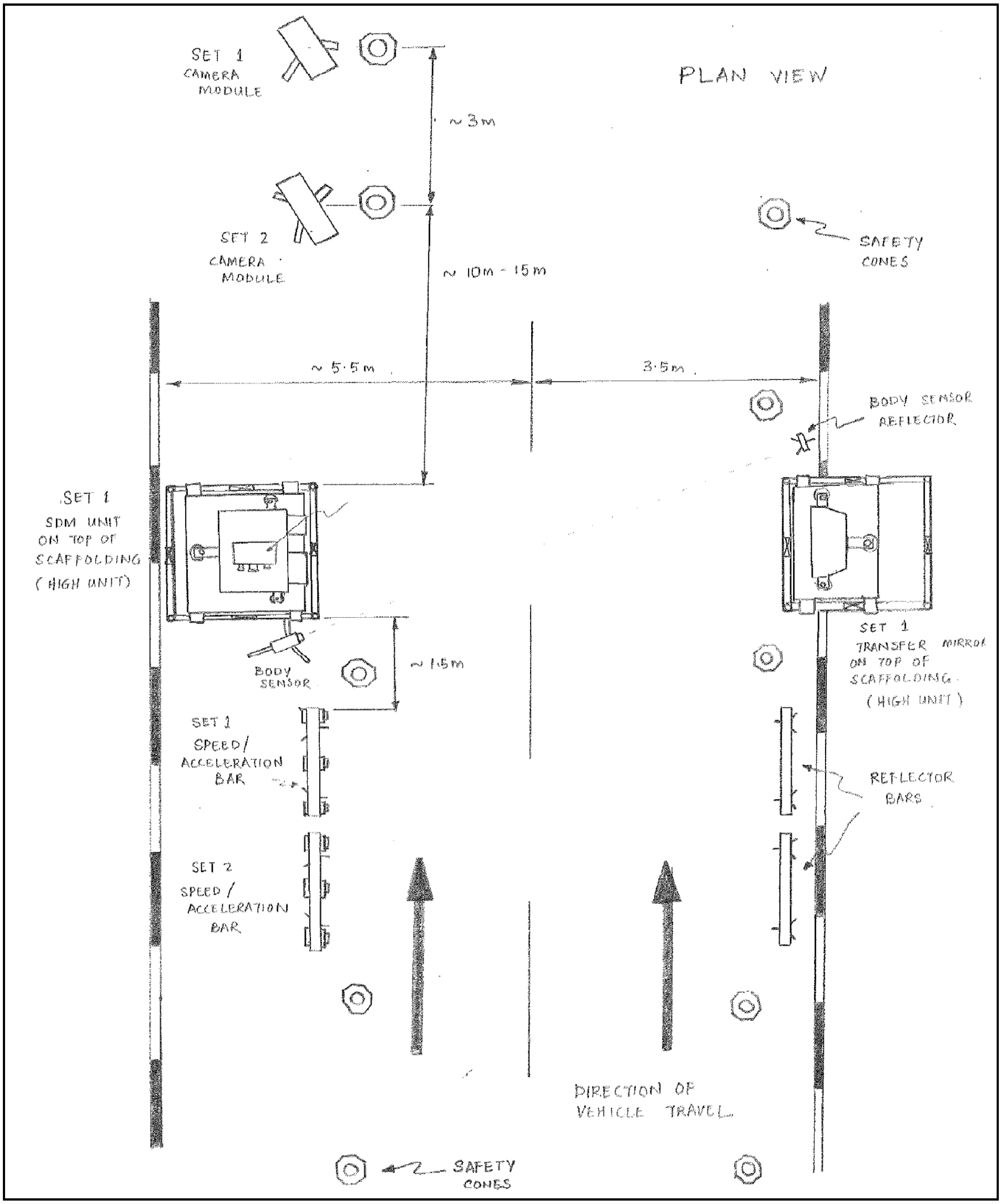


FIGURE 9.7-4: SCHEMATIC OF INITIAL EQUIPMENT ELEVATION

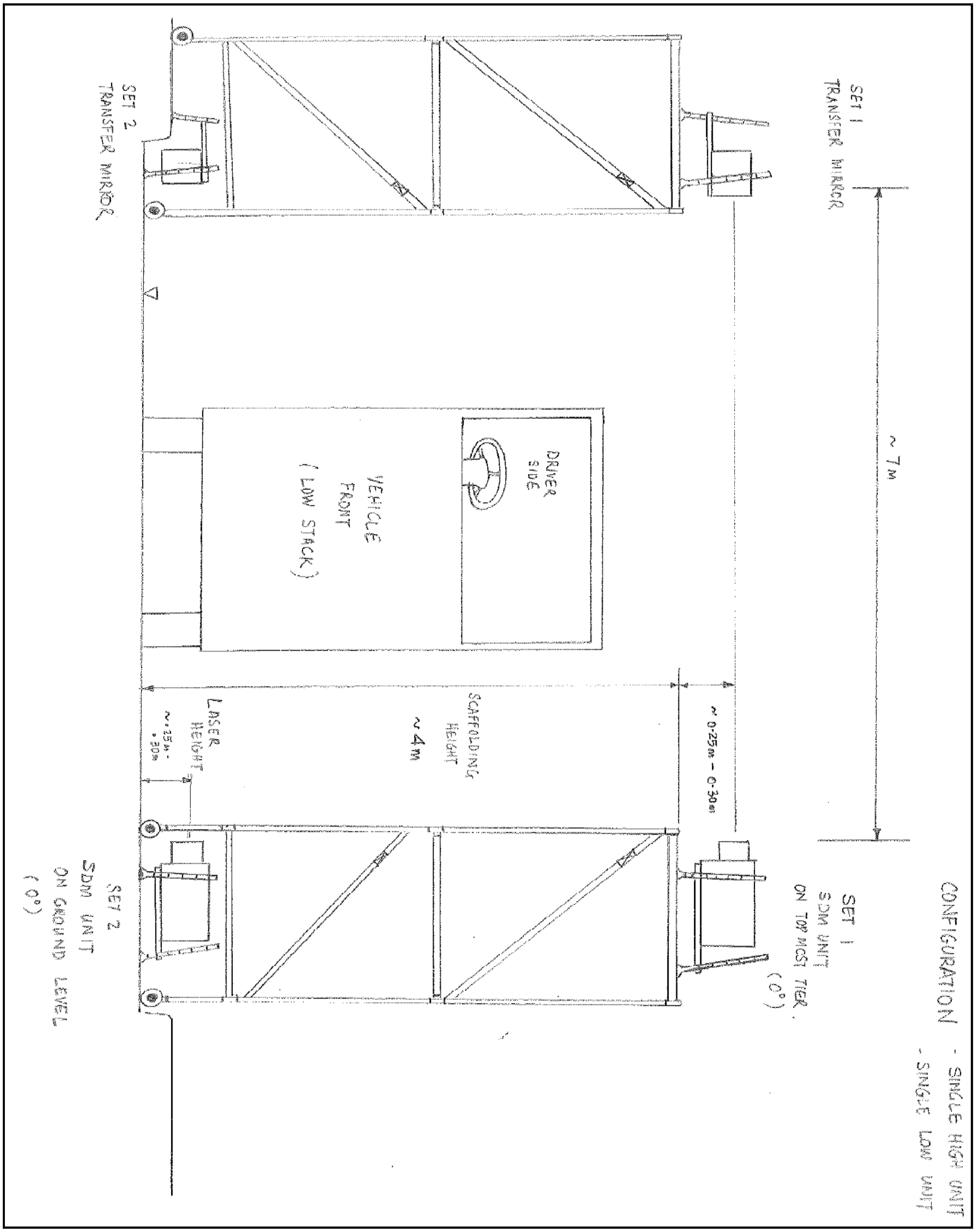
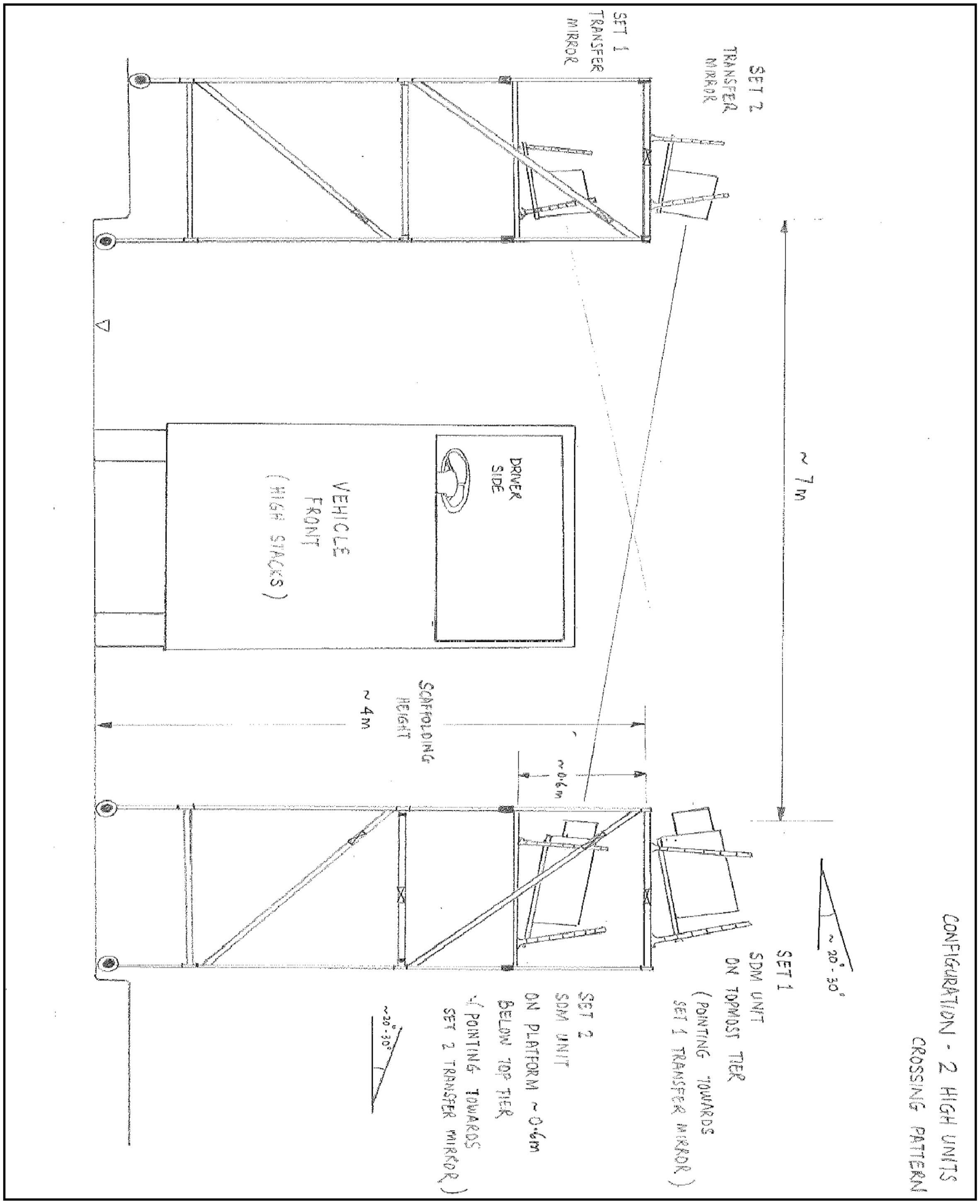


FIGURE 9.7-5: DUAL RSD SET-UP FOR VARIABLE VERTICAL EXHAUSTS



9.6.3 RESULTS

Table 9.7-1 summarizes the trucks measured:

- 1,185 trucks had FAS tests;
- 910 trucks were measured using RSD, and
- 847 trucks had both FAS and RSD measurements.

The capture rate improved over time from an initial 54% to over 80%

Table 9.7-1 Trucks Measured with FAS and RSD

Year	Month	FAS Vehicles	RSD Vehicles	RSD and FAS	RSD Capture Rate
2008	November	67	38	36	54%
	December	333	203	193	58%
2009	January	300	273	236	79%
	February	228	191	178	78%
	March	164	129	128	78%
	April	93	76	76	82%
Total		1,185	910	847	71%

When two RSD units were used and two measurements were obtained there was good correlation between the measurements (see Figure 9.7-6). This confirms the two RSD systems were consistent with each other in their measurement of the exhaust plume.

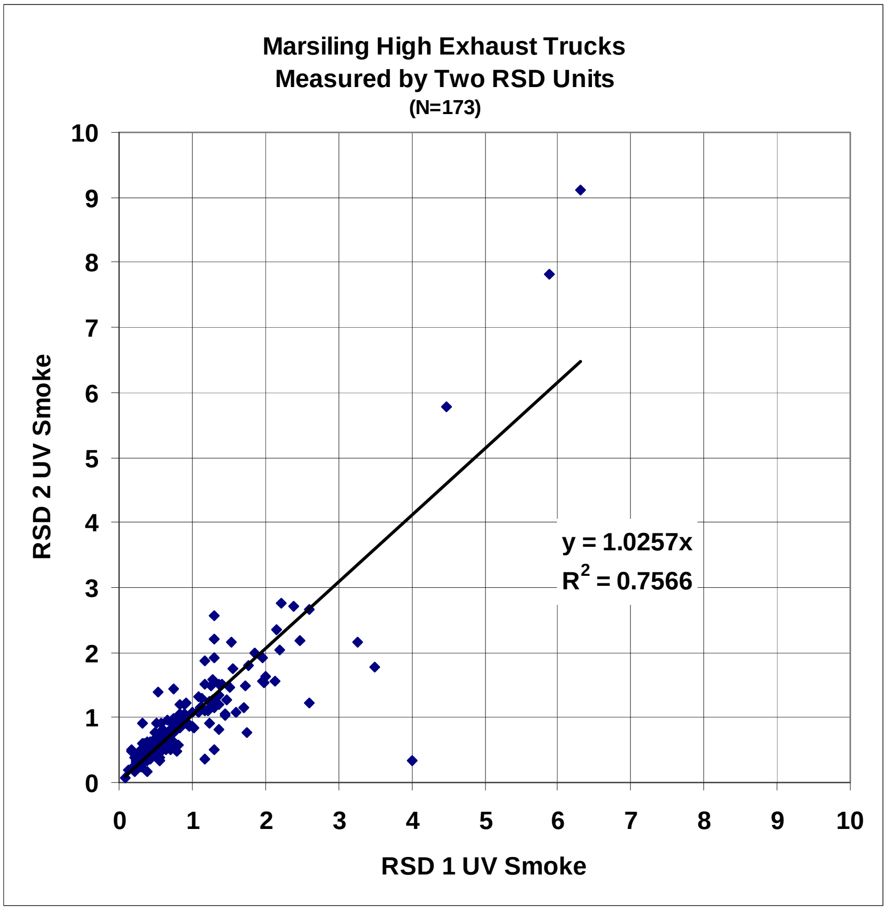
Figure 9.7-7 shows the distribution of the FAS HSU values. Almost exactly half of the trucks failed the FAS standard of 50% HSU.

Figure 9.7-8 shows the distribution of the RSD Smoke Factor values. Almost exactly half of the trucks exceeded an RSD value of 0.7 Smoke Factor.

The distributions of the HSU and RSD values in Figures 9.7-7 and 9.7-8 have different shapes. The RSD Smoke Factor values increase sharply for a small percentage of the dirtiest trucks. The HSU distribution appears more linear.

In fact, the RSD scale is linear with respect to the mass of particulates. The HSU scale, which is a measure of opacity, is compressed at the upper end for the trucks emitting the most particulates.

FIGURE 4-6: RSD CORRELATION FOR TRUCKS WITH TWO MEASUREMENTS



RSD Smoke Factor is calibrated as grams of particulate per 100 grams of fuel, which corresponds to a particular volume of combustion gases. This is similar to a measure called Optical Density which is used to convert opacity measurements of exhausts with measured flow rates to measurements of particle mass. Optical Density is defined as the log to the base 10 of the reciprocal of the transmittance, which is equal to $-\log_{10}$ (1-Opacity).

Optical density, D, is directly proportional to particle concentration in g/m^3 times path length[18]:

$$D = A_E . c . l / 2.303$$

Where, A_E is the specific mass extinction in m^2/g that is a function of the particle characteristics.

For a given path length, optical density is proportional to the mass of particles in g/m^3. Therefore, for measurements made under similar exhaust flow conditions, one could expect the RSD Smoke Factor and Optical Density to be proportional.

[18] Jahnke J, "Continuous Emissions Monitoring", John Wiley & Sons, 2000.

Diesel engines, however, dilute the fuel/air mixture with excess air. This dilution reduces the density of particles in the exhaust and therefore affects a measurement of Optical Density.

In the case of RSD, the measured exhaust particulates are divided by the engine combustion products that are measured simultaneously. Dilution of the exhaust by excess air dilutes the particulates and combustion gases equally. Therefore, the RSD measurement is unaffected by exhaust dilution. This is one reason ESP believes Smoke Factor is a better measurement than HSU.

To illustrate that the RSD and HSU distributions of trucks emissions are actually similar, Figure 9.7-9 shows the distributions of the FAS and RSD measurements using an HSU scale with RSD measurements expressed as Opacity, where:

$$\text{RSD opacity} = 1 - 10^{(-RSDSF/2.303)}$$

Figure 9.7-10 shows the distributions of the FAS and RSD measurements using an RSD Smoke Factor scale with FAS HSU values expressed as optical density. In this case FAS smoke factor is calculated as:

$$\text{FAS Smoke Factor} = 2.303 \times (-\log_{10}(1\text{-Opacity}))$$

In both charts the FAS and RSD distributions now look similar. This might indicate that the excess air is limited during the portion of the FAS test where particulates are highest. It is the highest values measured during the FAS test that are reported.

FIGURE 9.7-7: DISTRIBUTION OF FAS HSU VALUES

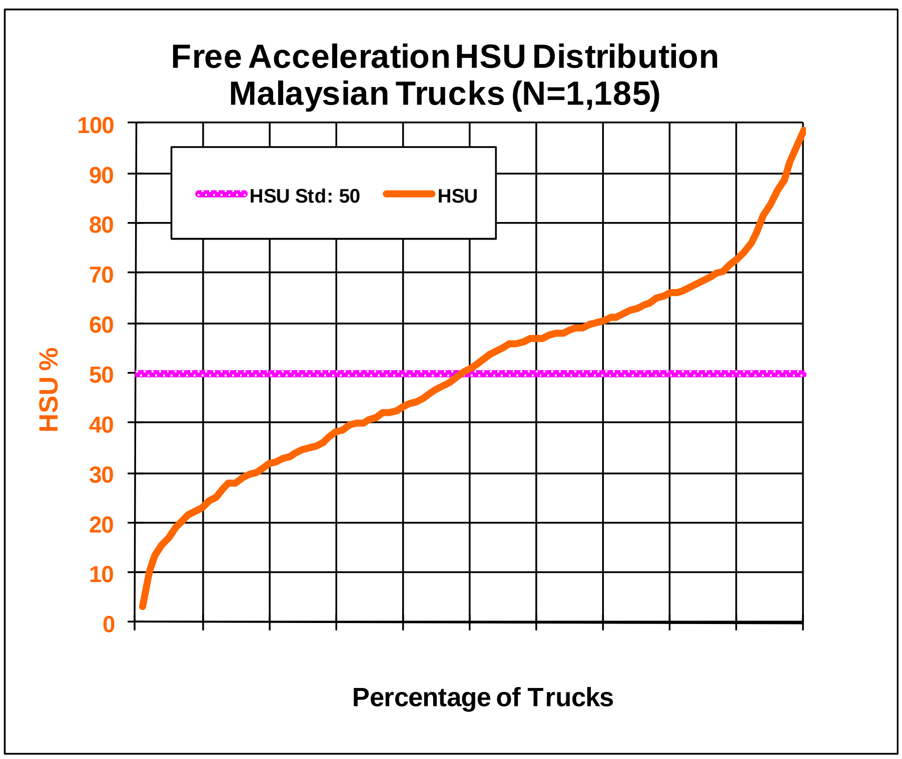


FIGURE 9.7-8: DISTRIBUTION OF RSD SMOKE FACTOR VALUES

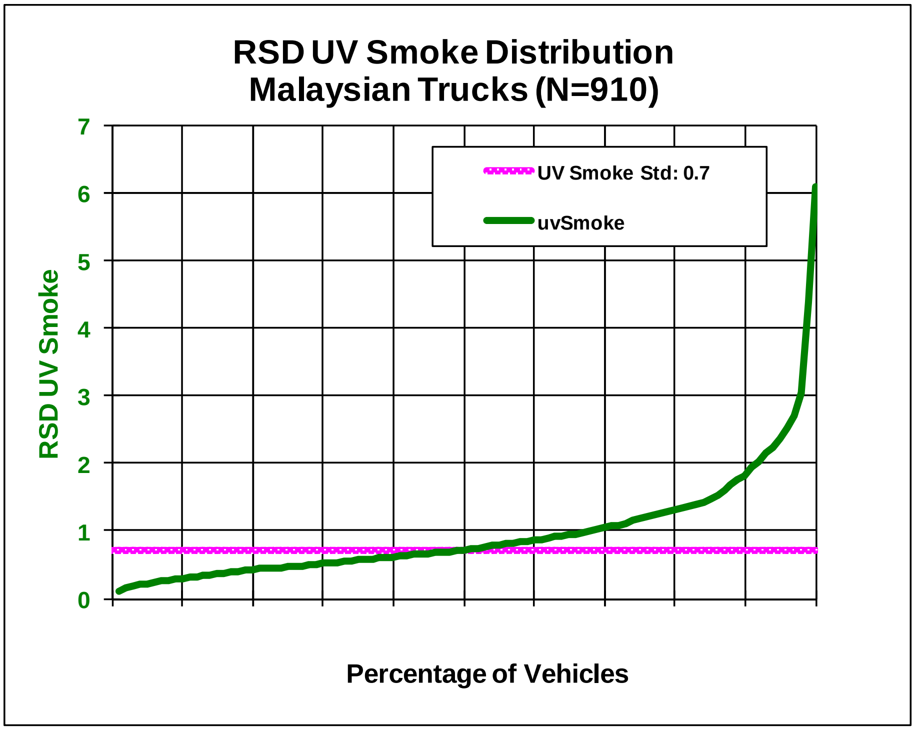


FIGURE 9.7-9: FAS AND RSD DISTRIBUTIONS BY OPACITY

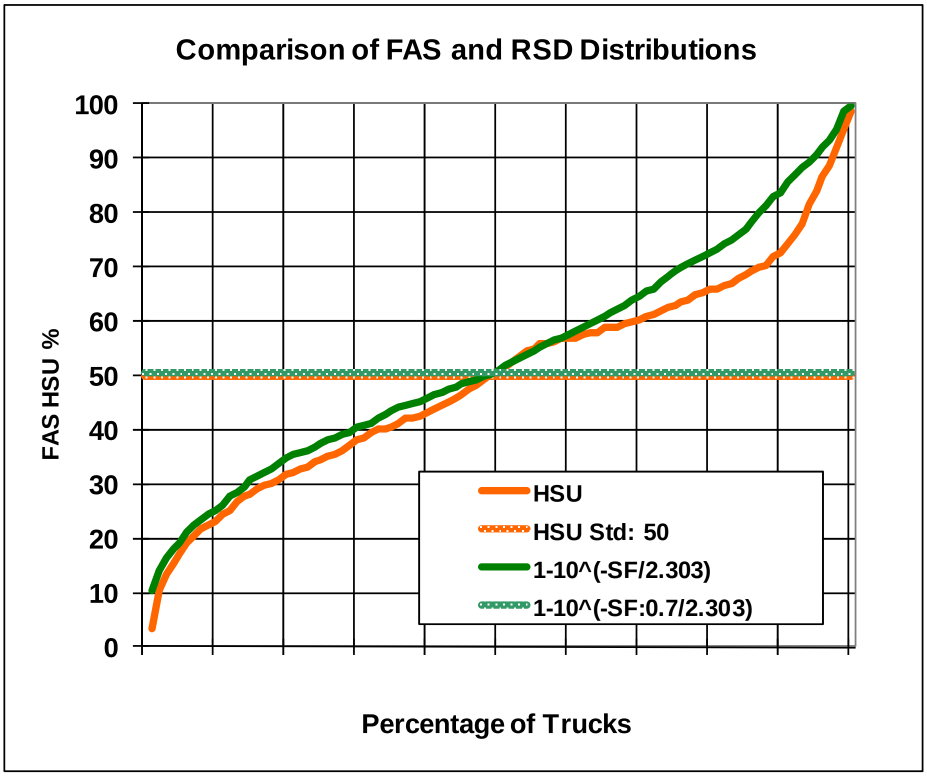
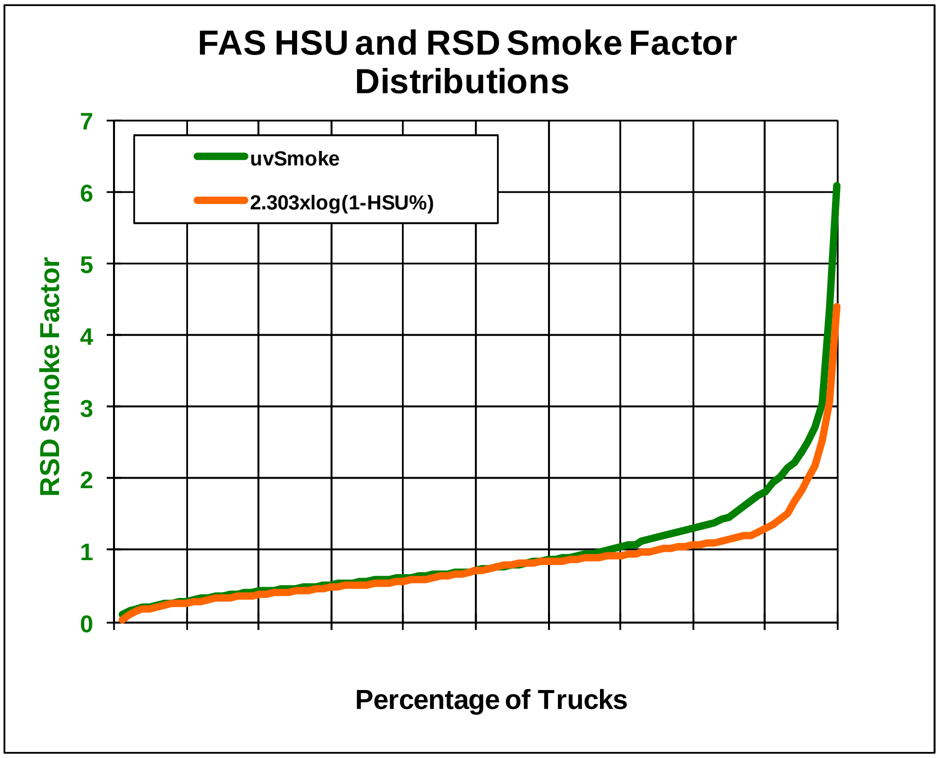


FIGURE 9.7-10: FAS AND RSD DISTRIBUTIONS VS. RSD SMOKE FACTOR



9.6.4 CONCLUSIONS

RSD was able to achieve an 80% capture rate in the on-road set-up.

When converted to similar units, the distributions of smoke emissions from FAS test and RSD truck measurements were similar.

The RSD Smoke Factor cutpoint of 0.7 corresponded to a FAS test HSU standard of 50 and failed the same percentage of vehicles.