A Project Funded by
Coal Services Health and Safety Trust

New South Wales Department of Primary Industries

Mine Safety Technical Services

Methods for Measuring Diesel Particulate Matter from Underground Mining Equipment

November 2004
Report 04/0884

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Acknowledgements

I have pleasure in acknowledging the contributions of the following people to this project:

Mr (now Dr) Brian Davies - Scientific Adviser to the Project

Mr Ernie Lom, of APACE Research - Engineering adviser to the Project.
Ernie played a major role in designing the engineering aspects of the testing, processing the data, performing the calculations, producing the graphs in the Appendices, and writing six appendices detailing the dynamometer tests.

Mr Jon Volkwein, researcher at Centre for Disease Control, NIOSH, Pittsburgh (USA). Jon came to Australia for the dynamometer tests, with the kind permission of NIOSH. His laboratory analysed the filters from this testing, and from the field tests and more.

Mr Peter Anyon of Air Quality Technologies

Members of the Steering Committee:

Mr Leo Roberts, former Senior Mechanical Inspector, NSW DMR
original chair of the Steering Committee

Mr Gordon Jervis, Senior Mechanical Inspector, NSW DPI
chair of the Steering Committee

Mr Stewart Bell, Manager SIMTARS (Qld)

Mr Steve Pratt, BHP-Billiton

Mr Hank Pinkster (replaced Mr Pratt on the Committee)

Mr Ron Stothard, United Mine Workers

Mr Noel Pye, who recorded minutes
for both the Steering Committee and the Working Group

Members of the Working Group:

Mr Wally Koppe, Mechanical Inspector, NSW DPI

Mr Tony Martin, Manager Physical Testing, TestSafe at Londonderry

Mr Ross Stutchbury, Engineer, Boart Longyear
(manufacturers of mining equipment)

Mr Chris Gearing, Mechanical Engineer, West Wallsend Colliery.

Those who assisted in the dynamometer testing and the field testing:

Mr Steve Brown and Mr Darren Patterson of DieselTest Australia

Mr Les Eager of Coal Mines Technical Services

Mr Les Golder of TestSafe Australia. Les dedicated great time and effort in setting up and running the data collection systems at Londonderry.

Mr Geoff Staples, who installed the engines on the dynamometer and operated them during the testing.

Mr Peter Hanson, Mr Zaw Win, Ms Monica Nguyen and Ms Mandy Pham of DPI, who operated the instruments during the testing.

The management and engineering staff of West Wallsend, United, Newstan, Angus Place and Springvale Collieries.

Mr Kelvin Butcher of Air-Met, who assisted with the arrangements for the HazDust instrument, and the import of pumps for the NIOSH equipment.

Mr Grahame Fawcett, Manager, Mine Safety Technical Services

Clive Ellis,
Senior Scientific Officer, Mine Safety Technical Services,
NSW Department of Primary Industries
(Project Manager)

Abbreviations used in the report (other than common engineering units)

ACARP	Australian Coal Association Research Program
AQT	Air Quality Technologies Pty Ltd
BHP	Broken Hill Propriety Co – now BHP-Billiton
CFR	(US) Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSV	Constant Sampling Volume
DMR	(NSW) Department of Mineral Resources – now part of NSW Department of Primary Industries
dP	Refers to the change in pressure drop across the filter in the NIOSH device
DPI	(NSW) Department of Primary Industries– now incorporates the previous DMR
DPM	Diesel Particulate Matter
EC	Elemental Carbon
EPA	Environmental Protection Authority
HC	Hydrocarbon
ISO	International Standards Organisation
IUT	Instrument(s) Under Test
JCB	(NSW) Joint Coal Board, now part of Coal Services Pty Ltd
mm	Millimetres
MSU	Mine Safety Unit (earlier name for Mine Safety Technical Services)
NIOSH	(US) National Institute for Occupational Safety and Health
nm	Nanometres – equal to $1/10^9$ metres, or $1/10^6$ mm
NO	Nitric Oxide
NO_x	Oxides of Nirogen – nitric oxide + nitrogen dioxide
O_2	Oxygen
OC	Organic Carbon
R&P	Rupprecht & Patashnick Co., Inc.
R^2	'coefficient of determination', indicating how well a line fits plotted points
RH	Relative Humidity
TC	Total Carbon
TEOM	Tapered Element Oscillating Microbalance
µm	Micrometres – equal to $1/10^6$ metres, or 1/1000 mm

Executive Summary

The project was funded by the Coal Services Health and Safety Trust, and run by the NSW Department of Mineral Resources (now incorporated into Department of Primary Industries). It aimed to find one or more methods for measuring diesel particulate matter (DPM) in the raw exhaust of diesel-powered mining equipment at underground coal mines. The method(s) were required to correlate reasonably well with the standard method for measuring DPM, and would be practical for use underground at mine sites by mine personnel.

The water scrubber on these machines was recognised from the start as a potential cause of problems.

A number of techniques and instruments were considered, and the project focussed on three laser light-scattering instruments, and a NIOSH pressure-drop method. The light-scattering instruments were found to require diluted and dried sample in order to cope with water in the raw exhaust – either before or after the water scrubber. The NIOSH sampling tubes were modified to handle the water.

The testing included the Bosch smoke meter and the R&P Elemental Carbon Analyser, which have bothe been used extensively in mines in recent years.

The methods were first evaluated against the standard dilution tunnel method (using weighed filter papers) and other recognised methods. Tests were conducted using three engines operating on an engine dynamometer under tight control, using a single fuel. The tests involved steady-state conditions, and also steady state with accelerations.

Correlations between the instruments and the standard method varied. Difficulty was encountered with one light-scattering instrument, which was also much larger than the others. It was not included in the later trials.

The methods were refined in the light of the dynamometer tests. The dilution system for the light-scattering instruments was made much more precise. An improved sample pump for the NIOSH method made this a simpler method to use.

Tests were then conducted at five coal mines. A simple test procedure was devised involving idle in gear, an acceleration, a steady load, deceleration, and more idle in gear. The two light-scattering instruments were found practical to use, although one has advantages in terms of simplicity and ease of use. The NIOSH method also worked well, and was very simple to use.

Neither technique is quite at a commercial stage, but both are clearly suitable as portable devices for use at mines by mine personnel.

- Results from the light-scattering devices vary with engine type, and the method should not be used to set a general standard for all types of engine. The device needs only minor refinements of the mini-dilution/drying unit. In use, the internal battery requires re-charging after about 2 hours' operation.
- Results from the NIOSH pressure-drop device do not match the filter results as well as the light-scattering instruments, but they are far less dependent on engine type. The device is very small, and the pump battery requires only occasional re-charge, but it requires a new tube for each sample. It will be refined by mass production of sample tubes.

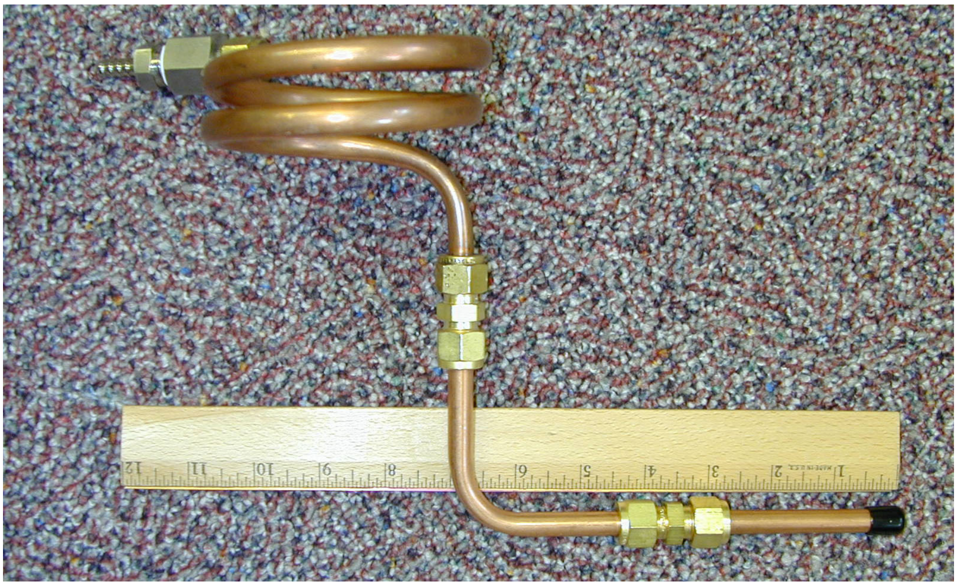
Both devices can be used with or without water scrubbers.

The report reviews the performance of the Bosch smoke meter and the Elemental Carbon Analyser.

The project also leaves the legacy of a full-flow dilution tunnel established in conjunction with the TestSafe facility at Londonderry.

The DustTrak monitor in a case with the dilution and drying unit

The NIOSH probes, with cooling coil. (Note that the ruler measures in inches!)



The probe is connected to a small hand-held pump by clear plastic tubing. The probe is replaced or re-loaded for each test. Production probes are expected to be disposable.

1. Introduction

Health Concerns about Diesel Exhaust and Diesel Particulate Matter (DPM)

Over the past twenty or more years there has been an increasing concern about the health effects of exposure to exhaust emissions from diesel engines. In 1986 the US National Institute of Occupational Safety and Health (NIOSH) was unable to establish a causal link between exposure to diesel exhaust and cancer, but concluded that such a relationship was plausible based on animal studies.

In 1988 NIOSH recommended that diesel exhaust be regarded as a potential occupational carcinogen in conformance with the (US) Occupational Safety and Health Administration (OSHA) Cancer Policy (29 CFR 1990) (NIOSH, 1988). The Bulletin did not recommend methods for monitoring exposure, or control measures for reducing the risks. But it advised that minimising exposure should reduce the risk, and recommended that employers assess the conditions under which workers may be exposed to diesel exhaust and reduce exposures to the lowest feasible concentrations.

The US EPA have more recently stated: *"Using U.S. EPA's revised draft 1999 Guidelines for Carcinogen Risk Assessment (U.S. EPA, 1999), diesel exhaust (DE)* is likely to be carcinogenic to humans *by inhalation from environmental exposures"* (US EPA 1999).

Other environmental and health authorities have expressed similar views.

The focus of the concern is DPM. This material largely consists of carbon produced by the decomposition of fuel, and a very large number of organic components produced by a variety of chemical reactions in the combustion chamber of the engine. Some of these organic components condense readily as they cool, and can be adsorbed on the surface of the carbon particles. The carbon particles can thus become a transport system, conveying these components deep into the respiratory system of an exposed worker.

Others of the products condense less readily. Whether they do condense depends on what happens to the exhaust gases. If they are diluted quickly, the components may remain as vapour; if they are cooled before being diluted they may well condense. It is thus seen that the amount of particulate material measured in the exhaust of a diesel engine depends on how the measurement is made.

Also included in DPM are sulphate compounds, both inorganic and organic, and sulphuric acid. The production of these is directly related to the sulphur content of the fuel. Newer fuels contain far less sulphur than previously, and sulphates will be of much less significance.

The problem of exposure to diesel exhaust is of special concern in enclosed environments where diesel-powered equipment is used — places such as tunnels, underground mines and warehouses. While ventilation can be used to dilute and remove exhaust components emitted into the workplace, the first attention should be given to controlling the source — the products emitted by the engine.

The Problem This Project Seeks to Solve

If employers are to control emissions from engines, they need to be able to measure the emissions in order to determine if their controls are effective.

There is at present no agreed simple method for measuring DPM, known to correlate with recognised standards for emission measurement, that is suitable for field use.

Past research on DPM in Australia (JCB Health & Safety Trust, ACARP & BHP) has highlighted the following factors as affecting emissions of diesel particulates:

- engine type,
- fuel type,
- maintenance,
- activity/duty cycle,
- ventilation, and
- fuel additives.

All of these are under the control of mine operators. It would therefore be beneficial to operators to have an instrument that is easy to use on-site, in order to screen out "dirty" engines before they get into the working environment, and also to reduce on-going maintenance (ACARP report C7014).

The success of raw gaseous exhaust monitoring in NSW coal industry gives reason to believe that similar success could be achieved with DPM. But this depends on identifying a suitable practical technique(s) for use in underground mines. Research previously funded supports the feasibility of the concept. But the instrument used was an elemental carbon analyser, mounted in a trailer with its ancillary gas bottles. This is not suited for general use in an underground environment — it is not portable, and it requires a high degree of technical skill and ongoing maintenance.

Preliminary investigation had identified several different techniques with potential as monitoring methods. However, none of these has been evaluated for use in coal mines, neither have they been correlated with recognised methods of measurement. Such research is necessary to establish if one or more of these techniques would be suitable for use in the general mine environment.

In summary, the aim of the project is to decide upon a method (or methods) for measuring DPM from undiluted diesel engines in coal mines.

Outline of the Course of the Project

The (now) Coal Services Health and Safety Trust[a] awarded a grant to the NSW Department of Mineral Resources[b] to manage the project. The Department has been regulating and testing the exhaust gases from underground diesel-powered equipment as far back as the mid-1960s, and the Mines Safety Technical Services group has considerable experience in this kind of testing.

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[a] Previously the Joint Coal Board Health and Safety Trust

[b] References in this report to “the Department” refer to the NSW Department of Mineral Resources, as it was for most of the duration of the project. From 1 July 2004 it has been incorporated into the the NSW Department of Primary Industries.

A steering committee oversaw the overall direction of the project. It included the project's technical adviser, the project manager, the manager of SIMTARS in Queensland, and representatives from the Department's mechanical inspectors, the mining union and coal operators.

Details of the project were planned by a working group, including the project's technical adviser, the project manager, and mechanical engineers from the Department, TestSafe, a manufacturer and a colliery.

The project was divided into the following major stages:

- select instruments with potential to meet the need;
- conduct carefully controlled testing on several different engines, operating on an engine dynamometer, to give comparisons with the recognised method for measuring DPM;
- evaluate the dynamometer results;
- refine the instruments and method of test (if necessary);
- conduct field trials using the refined instruments and method, to test the practicality of use at mine sites;
- evaluate the field trial results; and
- prepare a report and disseminate the findings.

The working group was first convened on 11 July 2002, and has met on 11 occasions up to the field tests.

The dynamometer tests were conducted on 5 days — 1, 3, 8, 10 and 14 April 2003.

Field tests were carried out at 5 mines on 21-24 June, 30 June and 1 July 2004.

2. Selection of Instruments to Evaluate

The working group established broad criteria, shown in Table 1, as a guide in selecting instruments to evaluate, and attempted to attach priorities to each.

Table 1 – Selection criteria for instruments to evaluate

Selection criteria	Priority	Comments
Available, supported by supplier	2	Problems may exist with a local supplier, but can often 'get around' such problems; need technical specifications for any proposed instruments
Suitable for use by mine personnel	1	The proposal is that mines have the measuring instrument and do the measuring themselves.
Price within budget for project, and reasonably priced for mines	1	As a guide only, the project proposal included 4 instruments at A$15,000 each.
Suitable for sampling before and after water scrubber	2	Not known if this would be possible.
If possible consistent with what others are using	2	Other agencies are asking questions similar to that of this project; eg RTA in NSW, NEPC – National Environmental Protection Council
Suitable for use underground	1	
Suitable for use in hazardous zone	2	
Response time	1	Quick enough to avoid overloading engine during test.
Portable, hand held	1 or 2	
Adequate information available on the instrument	1	Such as accuracy, precision, repeatability
Ability to calibrate	1	
Suitable measurement range	1	
Suitable particle size range	1	
Able to sample transients during acceleration	2	The increasing use of turbo-charged engines makes this desirable.

Several different principles are used in the various methods for measuring DPM. A few of these are outlined below. A more detailed review of methods is given by Burtscher (2001).

- Gravimetry – the exhaust is diluted with air and a portion is drawn through a filter paper, which is then weighed. This is the standard method on which legal limits are based.
- Opacity – a light source is passed through the exhaust stream, and the loss of intensity of the light is used as a measure of the DPM concentration. The instrument is an opacimeter.
- Filter discolouration – a fixed volume of exhaust is drawn through a filter paper, and the discolouration is measured. An example is the Bosch smoke meter.

- Laser light scattering – a portion of the exhaust is drawn continuously through a chamber where a laser light shines through it, and the amount of scattered light is measured. This principle has advantages over the opacimeter for lower concentrations, and gives good zero stability. Instruments of this type are available for measuring airborne dust.
- Continuous mass – the tapered element oscillating microbalance (TEOM). A diluted sample is drawn through a filter paper on a vibrating collector. The change in mass is measured as a change in resonant frequency.
- Pressure drop – a sample is drawn through a filter at constant flow, and the increase in pressure drop from the beginning to the end of the test is a measure of the deposited DPM. This technique was developed recently by the US National Institute of Occupational Safety and Health (NIOSH) for airborne dust, and has been adapted by them for measuring DPM.

After reviewing the available equipment that appeared to fit the criteria, the working group decided to trial three laser-light-scattering instruments and the NIOSH pressure drop method. Details of these methods are given below, and the selected instruments are listed in Table 2.

It should be noted that most of the instruments measure, not mass of DPM, but some other property. It cannot be taken for granted that a nice correlation will be obtained with the mass measurement on the dilution tunnel filters. The measurements have been nicely described as ‘surrogate’ measurements.

Table 2 – Instruments selected for evaluation in dynamometer testing

	DustTrak model 8520 Aerosol Monitor	Personal DataRam pDR-1200	Haz-Dust EPAM 5000[c]	NIOSH dP Measurement
Manufacturer	TSI www.tsi.com	MIE www.thermo.com/com/cda/product/detail/1,1055,22437,00.html#pDR_1200	SKC www.skcinc.com/prod/770-203.asp	Pump: SKC Pocket Pump; Sample tubes: SKC (custom made) http://www.skcinc.com/pumps/210-1000.asp
Australian supplier	Kenelec Scientific and others	Air Quality Technologies (AQT)	Air-Met Scientific Pty Ltd	Pump: Air-Met Scientific Pty Ltd
General description	Provides real-time measurement of liquid and solid particles based on 90° light scattering. Internal pump draws sample. Has analog and digital outputs, adjustable alarms, data logging.	Real-time aerosol monitor, measuring light scattered in a forward angle of 45-90°. Pump and pump-battery are extra units. Has analog and digital outputs, alarms, data logging	Real-time particulate monitor, combines light-scattering and gravimetric techniques. Internal pump and lead-acid battery. Has digital output. Capable of logging data. Analog output was fitted by SKC for this project.	Based on a Personal Dust Monitor (PDM) developed by NIOSH for sampling airborne dust. Deposited DPM increases pressure drop across a filter at constant flow. (Volkwein et al, 2004)
Size (mm) with pump and batteries	221H x 150W x 87D	~320H x 90W x 45D with NO cyclone or filter	152H x 356W x 254D	Pump: 114H x 56W x 36D
Mass with pump and batteries (kg)	1.5	1.58	5.4	0.142
Power supply	Four C-size batteries, or AC.	9V battery for DataRam; re-chargeable battery pack for pump; or mains supply.	Internal re-chargeable lead-acid battery, or AC.	Internal re-chargeable Ni-MH, or AC
Sample flow rate (L/min)	1.4 to 2.4 (user adjustable). Nominal 1.7	1 to 5 (user-adjustable)	1 to 5 (user-adjustable)	0.02 to 0.225 (set to 0.20 for the tests).
Concentration range (mg/m^3)	100	400	200	?

NIOSH Involvement in the Project

The researcher leading the development of the dosimeter at NIOSH in Pittsburgh, Pennsylvania is Mr Jon C Volkwein. The Working Group agreed that we should invite Mr Volkwein to come to Australia during the dynamometer tests. He arrived in time to make final preparations, and participated in all the tests except the

[c] The Working Group chose a different instrument, the much smaller Hazdust Particulate Monitor. SKC supplied the EPAM-5000, believing it better suited for the application.

(unscheduled) final day. He was also able to visit a coal mine and make some measurements in the field with the NIOSH device.

We are grateful to Jon for his work with us during the tests. He made some very helpful suggestions about the conduct of the testing. We are also grateful to NIOSH for permitting him to come, and for supplying the filter tubes for the tests and analysing them afterwards. The only costs of this to the project were the air fares and accommodation.

Not Designed For The Purpose

It must be emphasised that none of these instruments was designed for measuring DPM direct from the exhaust system of a diesel engine. At this stage of the project it was not at all certain that any of the devices would perform the measurements required.

The next sections give a brief description of the operating principle of the instruments, and outline anticipated difficulties in using them for this purpose.

Laser Light-Scattering Instruments

These instruments are all designed to give continuous real-time measurements of airborne dust in the respirable size range (about 1 to 7 μm). A pump, either internal or external, draws sample at a controlled rate through a chamber where a laser light is passed through it. Depending on the number and size of particles in the sample stream, a varying amount of light is scattered, and this is measured as a concentration of dust.

Uncertainty about particle size

Based on the wavelength of the laser light and the angle at which the scattered light is measured, the instruments are claimed to respond to particles down to about 0.1 μm (100 nm).

DPM particles are found in two distinct but overlapping size modes: a mainly volatile nuclei mode and a mainly solid accumulation mode in roughly the 3-30 and 30-500 nm diameter ranges, respectively (Kittelson et al, 2002). Based on the information from the manufacturers, it is to be expected that these instruments will not respond to the smaller size range of particles. However these smaller particles contribute little to the mass of particulate, so a reasonable correlation with a mass-based measurement may be possible.

Uncertainty about concentration range

These instruments are designed to measure airborne dust in a working environment. Their maximum concentration is 100, 200 or 400 mg/m^3. The concentrations of particulate in undiluted diesel exhaust are very different from those in a workplace, and it was not clear that the instruments would be able to cope with the high values likely to be encountered.

Uncertainty about water

The vast majority of the diesel-powered equipment used in underground coal mining in NSW is fitted with a water scrubber as part of the exhaust system. (Despite its name, its purpose is not to scrub the exhaust of contaminants, although it may have this effect. It is intended to cool the exhaust gases and act as a flametrap to prevent an explosion in the exhaust system propagating to an external flammable atmosphere.)

The intention was to measure DPM from the end of the exhaust system, but it was not clear that the instruments could cope with the water entrained in the exhaust gas. As a fall-back position, it was thought that the DPM could be measured *before* the water scrubber, but this would be a less desirable outcome.

Preliminary tests on the laser-light-scattering instruments

The question about the viability of using these instruments needed to be answered well before the dynamometer testing began, and some simple tests were run at a coal mine. Under a few different test conditions, raw diesel exhaust was passed into a DustTrak. The instrument gave sensible readings for a few seconds, then went off scale. It was recognised that a mist was forming as the exhaust gas cooled. The DustTrak saw the mist particles as particulate matter of a very high concentration.

The ‘fall-back’ position was then tested: raw exhaust from the engine was sampled from the exhaust manifold and passed to the DustTrak, bypassing the water scrubber. Unfortunately the same result occurred[d].

An attempt was then made to condense and remove water by passing the exhaust sample through a cooling vessel. This was also unsuccessful.

A dilution device was added to the system. This had the double benefit of reducing the concentration of DPM and reducing the water concentration in the sample. It was found that sensible readings could be obtained under some conditions.

Preliminary conclusions concerning light-scattering instruments

We therefore concluded that:

- water would prevent light-scattering instruments from being used to measure DPM in raw exhaust, either before or after a water scrubber; and
- a dilution unit held promise of making the measurements possible.

As a result of these findings, Air Quality Technologies, who had developed the experimental dilution unit used in this trial, were commissioned to further develop it. The refined unit was further tested prior to the dynamometer tests and found to work effectively.

NIOSH Pressure-Drop Method

The NIOSH method described in the last column of the table deserves special mention here. It is a further development of a dosimeter device developed by NIOSH for measuring airborne dust. In its original version, a small pump draws air at

[d] On reflection, this result should have been expected. The combustion water content of exhaust gas from a diesel engine is roughly the same as the CO_2 content. This ranges from around 2% by volume at idle to around 10% by volume under load. The corresponding dew points range from around 18°C to 46°C – and this ignores water vapour in the intake air. The water in the exhaust must condense as it cools.

a constant flow through a filter mounted in a holder worn by a worker. As material is deposited on the filter the resistance increases, and the pressure drop can be used as a measure of airborne dust. After the measurement the filter can be removed and the amount and composition of the dust determined. This permits a correlation to be established between the measured pressure drop and the amount of deposited material.

It should be noted that the device can be used to record real-time measurements of deposited material. The pressure drop is monitored and logged, and the data can later be examined. A high rate of increase signifies a high concentration of dust.

DPM, being finer than mechanically generated dust, is more effective in blocking a filter than airborne dust, so a short exposure to the high concentration of DPM in raw exhaust is quite sufficient to provide useful readings. After the measurement the filter can be removed and the amount of elemental carbon and organic carbon determined. This allows correlations to be established between the measured pressure drop and the amount of deposited DPM.

Uncertainty about water

In our discussions with NIOSH about the use of the device for measuring DPM, we outlined the potential problem with water from the engine and the scrubber. NIOSH responded with a modified design which they then tested in a hot condensing sample stream. They were confident it would cope with sample from an exhaust for the intended duration of a test.

3. Dynamometer Testing

The Working Group considered the merits of measuring DPM using full-flow and partial-flow dilution tunnels, and chose to use a full-flow tunnel. No suitable facility was available, so we negotiated with DieselTest to set up a tunnel they already owned at the TestSafe dynamometer facility at Londonderry.

The dynamometer testing is outlined here. The reasons for selecting a full-flow tunnel, and technical aspects of the operation of the tunnel are described in detail in Appendices 1 and 2.

Engines Used in the Testing

Three engines were involved in the testing. Specifications are given in Table 3.

- A Caterpillar 3306 engine with water scrubber, representing the engines most commonly in use in underground coal mines at the present time.
- A KIA engine with water scrubber, representing smaller engines in common use in underground coal mines. PJ Berriman & Co Pty Ltd configured this engine for use on the dynamometer.
- A Caterpillar 3126 engine with water scrubber, representing the newest design of engine being introduced into underground coal mines. VA Eimco set up both Caterpillar engines on frames to suit the dynamometer.

Table 3: Engine Specifications (as configured for underground coal mining)

Engine	Caterpillar 3306	KIA 4100	Caterpillar 3126
Cylinders	6	6	6
Capacity (L)	10.5	4.052	7.2
Bore x Stroke (mm)	121 x 152	92.0 x 101.6	110 x 127
Injection	Indirect	Indirect (pre-chamber)	Direct
Air induction	Naturally aspirated	Naturally aspirated	Turbo-charged (boost measured up to 122 kPa @ 2400 RPM)
Rated power (kW), @ speed (RPM)	101 @ 2200	52 @ 2600	153 @ 2300
Rated torque (Nm), @ speed (RPM)	556 @ 1100	204 @ 2300	766 @ 1700
Max. power measured (kW), @ speed (RPM)	90.2 2100	43.5 2500	131.5 2100
Max. torque measured (Nm), @ speed (RPM)	526 1100	174 2200	622 2000
Max. power during tests (kW), @ speed (RPM)	71.9 1500	37.4 2150	129.3 2100
Max. torque during tests (Nm), @ speed (RPM)	458 1500	166 2150	588 2100

Tests Conducted

The dynamometer tests were conducted on five days in April 2003 as shown below.

Date	Engine	Scrubber?	Comments
1 April	Caterpillar 3306	Yes	
3 April	Caterpillar 3306	No	Weld in exhaust system split at some stage
8 April	KIA	Yes	
10 April	Caterpillar 3126	Yes	
14 April	Caterpillar 3306	No	Repeat of 3 April test

At first only four days were scheduled. However prior to the start of testing on 8 April it was discovered that a weld on the exhaust water trap system, concealed under covers, had split open. The split must have happened on 3 April, but it was not known at what stage it had occurred or whether this had affected the results on 3 April. A further day was scheduled to repeat the testing of 3 April.

The split in the exhaust is believed to have been caused by excessive vibration from the engine operating without the water scrubber and with no muffler. On the repeat test a truck muffler was fitted to the exhaust, and the water trap system was supported more rigidly. No further problem of this nature was encountered.

Because of the location of the split, it could only affect the measurements taken at the dilution tunnel – the filters and TEOM. Thus, for the tests on 3 April, valid comparisons could be drawn between the various instruments, or between the filters and TEOM, but not between instruments and filters or instruments and TEOM. (The test results show that there is a difference between the two dry tests; this will be demonstrated in the discussion of the test results.)

The tests without a water scrubber were intended to allow some assessment of the measurement techniques on an engine without a scrubber. The data could also provide information about the effectiveness of a scrubber in removing DPM. Engines used in the non-coal sector of the mining industry are not usually fitted with water scrubbers.

With each engine, several test modes were run for about 30 minutes each – depending on the time needed for the measurements. Appendix 3 (Test Procedures) details the considerations which led to the particular modes used. The intention was to have a number of test conditions in which the output of DPM ranged from high to low. This would allow a correlation to be established between the various measurement methods over a range of DPM concentrations.

There were seven or eight steady-state modes for each engine. Then there was a test that included two accelerations and a power phase. Again, details of this are given in Appendix 3. The transient test ran over a 2-minute cycle, and was repeated many times until all the measurements were complete. In one test the cycle was repeated 30 times, taking an hour to complete.

Fuel Used in Dynamometer Tests

The Working Group considered what fuel should be used for the dynamometer tests. The same fuel should be used for all tests, so that comparisons would be valid. It would be necessary to analyse the fuel, because the ratio of carbon to hydrogen is an important quantity used in calculations related to the operation of the dilution tunnel.

The sulphur content of the fuel was an important consideration. Sulphur in diesel fuel produces sulphates in the exhaust, largely in the form of particulates. It was desirable to choose a fuel with a reasonably low sulphur content, as the allowable sulphur contents of diesel fuels in Australia are being progressively reduced (as shown in table 4).

Table 4: Allowable Sulphur Content of Diesel Fuels in Australia

Date	currently	From 1/01/2006	From 1/01/2009
Sulphur content (parts per million by mass)	500	50	10

A fuel commonly used in underground mining comes from the Eromanga field in Queensland, and is marketed by BP. This is chosen by several mines because it gives less objectionable emissions. Its specification shows a maximum sulphur content of 0.02% (200 ppm) by mass.

It was decided to use Eromanga fuel for the tests, as it is readily available, is in common use underground, and has a moderate sulphur content.

A batch of the fuel was delivered by tanker into a new tank at Londonderry and used for all the dynamometer tests.

Limitations in the Dynamometer Testing

Measurement on a Volume Basis

There is a special problem in relation to turbo-charged engines. Standard methods for measuring DPM produce results in terms of particulate generated for a given amount of mechanical energy output from the engine. Common units are mg/kWh.

It is not readily possible to measure power as part of a simple field test of the type envisaged. The proposed measurement is therefore in concentration terms – mg/m^3 of exhaust volume.

This gives an advantage to a turbo-charged engine, because the volume of exhaust is greater for a given power output, due to the effect of the turbo-charger. Without measuring exhaust volume – and again adding to the complexity of the field measurement – it is not possible to compensate for this effect.

Turbo-charged engines commonly differ from naturally aspirated engines in their emission characteristics. Naturally aspirated engines are likely to produce their worst emissions under full load.

Turbo-charged engines are likely to be worst during acceleration, especially if the fuel-air ratio is not well controlled. At constant full load the turbo charger would usually be delivering ample combustion air to give clean emissions.

It is therefore rather important that any test method include an acceleration, so that a turbo-charged engine will be tested at its worst condition.

Possible Large Measurement Uncertainty in Filter Weighings

A review shows that the possible measurement uncertainty in the mass of DPM on the filters is surprisingly large. It would be expected that mass is a quantity that can be determined with great precision. But the determination requires the filter papers to be conditioned in a humidity cabinet both before and after use. Control filter papers are weighed each time with the sample filters. Corrections are made for the apparent change in weight of the control filters, and the initial weight of each filter is subtracted from its final weight.

The question of the magnitude of this uncertainty can be addressed by examining the correlations with the TEOM, and is further discussed later in the report.

Possible Large Measurement Uncertainty in Dilution for Instruments

The configuration of the mini-dilution system used with the light-scattering instruments led to large uncertainty in the dilution ratio. This is discussed quantitatively in the section entitled “Refinement of the Laser Light-Scattering Instruments”.

Some conclusions about the extent of the imprecision can be drawn from an examination of the dynamometer test results, and comparing with some of the field test results. This is also further discussed later in the report.

Other Measurements Taken

In addition to the three laser light-scattering instruments and the NIOSH pressure-drop device, several other measurements were made.

- Filter papers were collected after 2-stage dilution with filtered air. They were conditioned and weighed before and after use, giving a measure of mass of DPM. This is the standard method for measuring DPM. Details of the dilution tunnel are given in Appendix ??.
- Mass measurements were taken on a TEOM – a tapered-element oscillating microbalance. These samples were also drawn from the dilution tunnel, and provide a direct comparison with the filter paper measurements.
- Readings of Bosch smoke number were taken during the steady-state modes (only). The Bosch smoke meter has been used extensively for measuring particulates from diesel engines in NSW coal mines. The particular model in use can only be used during steady-state testing.
- Exhaust gases were analysed for carbon dioxide, carbon monoxide, oxides of nitrogen, oxygen, and hydrocarbons (as propane).
- Total carbon, organic carbon and (by difference) elemental carbon were measured using a R&P 5100 elemental carbon analyser. This is a large analyser, mounted in a trailer with its ancillary gas cylinders. It has been used extensively in monitoring the particulate emissions from diesel engines at BHP-Billiton coal mines in the Illawarra region of NSW.

Data Collection

With data coming from so many sources, there were two possible approaches to data collection:

1. The data could be collected in separate data loggers, and combined later; or
2. The data could be fed to a single computer.

The first approach would be quicker to implement, as many of the data sources already had data logging facilities built in. But it would require a much more complicated procedure for combining the data sets for processing.

The second approach would have the opposite properties – easier manipulation of data after the testing, but a much more complicated setup.

It was decided to follow the first approach. This decision was taken because the time needed to establish a centralised data system could not be estimated with any precision, and such a system could not be tested until all other measurement systems were in place. This would have jeopardised the scheduling of the project, which required firm dates to coordinate with other participants such as Jon Volkwein at NIOSH in the US, the TestSafe facility at Londonderry, and DieselTest Australia.

This arrangement also permitted the data to be viewed as it was collected. A centralised system would have made this more difficult.

The detail of the data to be collected, and the work involved in collecting and combining the data, is given in Appendix ??.

Outline of a Day's Testing

The tests on an engine occupied a day.

The various instruments were prepared and calibrated as needed, and the engine was run under load to bring it to operating temperature.

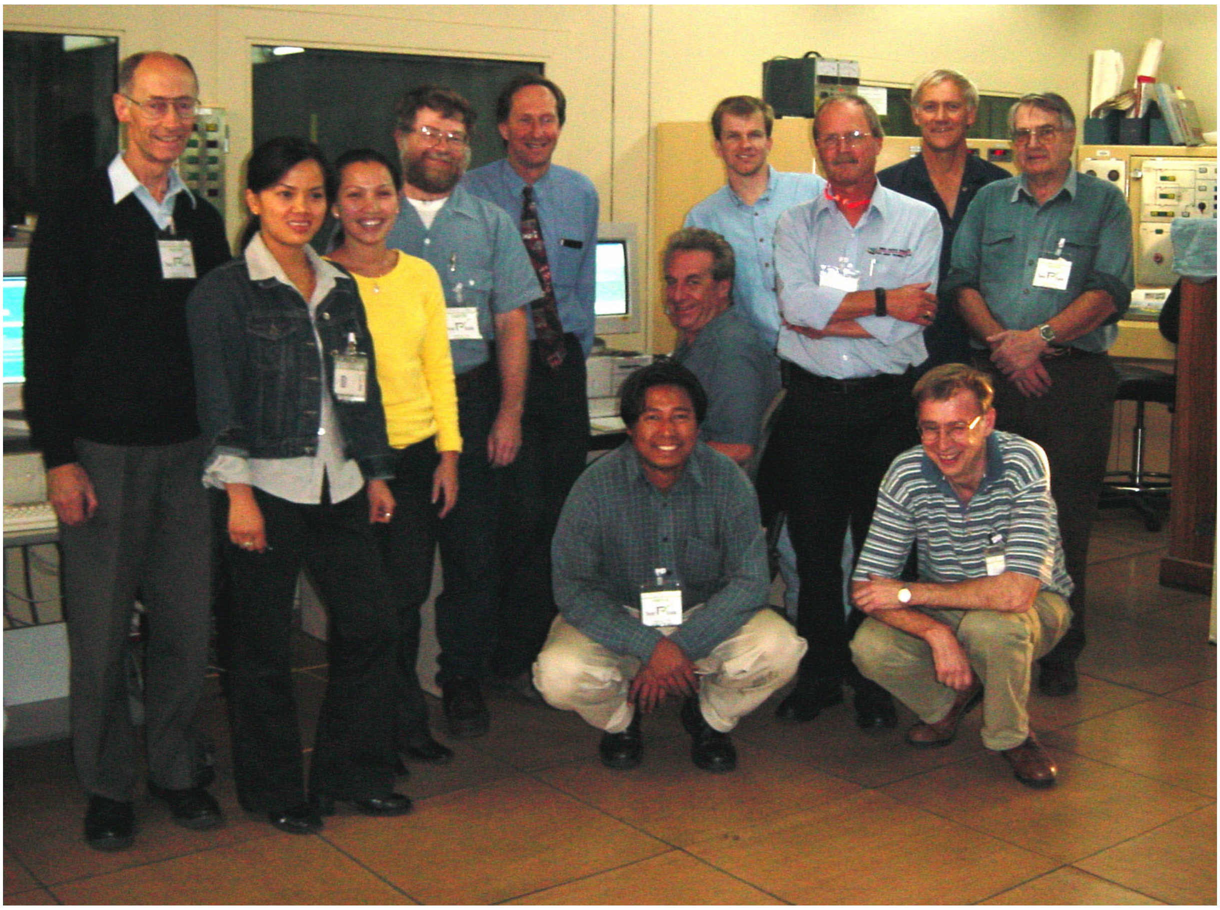
Power curves for the engine were determined, but particular attention was paid to the characteristics at a chosen engine speed. This was usually around the speed of 'torque stall' when the engine was built into a machine with a torque converter. Machines at mines are usually tested under 'torque-stall' conditions. The chosen speeds were: Caterpillar 3306 – 1500 RPM; KIA – 2150 RPM; and Caterpillar 3126 – 2100 RPM.

The first test mode was commenced, with the engine operating at maximum torque at the chosen speed. The dynamometer instruments and the exhaust gas compositions were observed for a few minutes, until it was determined that the engine operation was quite stable. Readings were commenced on the elemental carbon analyser, the dilution tunnel, TEOM, and the DustTrak, DataRam and HazDust (these last three in sequence); then Bosch smoke measurements were taken. When all these were complete a port in the sample pipe was opened to allow NIOSH measurements to be taken. Gas analysis was continued throughout the mode to monitor any changes. This sequence typically took 30 minutes.

The engine was then set to a reduced load and allowed to stabilise, and the whole series was repeated. There were seven or eight of these load settings for each engine, the last being 'no-load' at the same engine speed. See Appendix ?? (Test Procedures).

After all the steady-state tests were completed the transient-and-load tests were run, taking up to an hour to complete. The various instruments took measurements beginning with one of the repeated 2-minute cycles until all were finished.

The testing crew in the TestSafe control room at Londonderry



Observations During the Dynamometer Testing

Water problems

Water was a problem during the tests with water scrubbers. Despite the care taken to condense water vapour and to separate and remove condensate, water accumulated in the dilution tunnel, sufficient to eventually interfere with the operation of the fan. It was necessary to stop the testing, shut down the tunnel, drill into a low point in the tunnel, drain the accumulated water, and swab out parts of the tunnel.

After the first occurrence the sound of water could be recognised as it built up, and the draining of the tunnel was included in the test program as needed. Typically this was necessary once during each day and at the end of the day.

An in-line opacimeter was found to work very well during the dry tests, but the readings were meaningless during wet tests, and we have reported no results. It was originally proposed to use the opacimeter to monitor DPM concentrations in the tunnel, but this was abandoned.

Limited Range of DPM Concentrations

Serious attempts were made to generate high concentrations of DPM from each of the engines: they were operated at maximum throttle at the chosen speed, and the air intakes were restricted to increase the fuel/air ratio. This produced results typical of highly-fuelled – but not over-fuelled – engines. (This was judged from the carbon dioxide content in the exhaust gases.) The range may be similar to those from reasonably clean fleets at coal mines as shown by the Bosch results – the highest Bosch reading obtained during dynamometer tests was 3.1, while in the subsequent field tests values up to 2.7 were measured.

Behaviour of the Instruments During Dynamometer Tests

Readings were able to be collected from all the instruments, with a few difficulties.

Dilution tunnel

Filters were collected, re-conditioned in a humidity cabinet, and re-weighed. At higher load, where the rate of deposition was higher, two pairs of filters were collected for each test. For others a single pair was used.

TEOM

The TEOM operated well in conjunction with the dilution tunnel filters.

Opacimeter

As has been mentioned, readings from the opacimeter were useless in tests with a water scrubber. In later tests it was not included in the system. No results are reported.

R&P Elemental Carbon Analyser

Samples were collected routinely through a heated sample line. In most cases two samples were run on each steady-state mode.

Gas Analysis

The mobile gas laboratory drew its samples through a heated sample line. No particular difficulties were encountered in these measurements. These samples were taken before the water scrubber. The mobile laboratory dries the sample and reports results on a dry basis.

Bosch Smoke Meter

The Bosch meter was used in each steady state mode. Three filters were taken. As is commonly found, the 1st result sometimes differed from the 2nd and 3rd, so the 2nd and 3rd results were averaged. (This effect is due to more complete purging of the sampling unit on later samples.)

DustTrak and DataRam

These instruments were used in conjunction with the mini-dilution unit, as described earlier. Results were recorded both by data logger and from the display of each instrument.

HazDust

This instrument was also used in conjunction with the mini-dilution unit.

The analog output on the first HazDust unit had been fitted specially before it was despatched. It was found to provide a signal that could not be read on a data logger. The output had a waveform, rather than a DC signal. Some effort went into troubleshooting this, including urgent email correspondence with the US suppliers. A work-around was devised, where the output was passed to a digital multimeter capable of reading it.

It was then found that the readings did not vary on exposure to particulates. It was discovered that a sample tube inside the instrument was not connected when it was received. These unfortunate events prevented meaningful data being obtained during much of the testing.

A second unit arrived after the completion of the scheduled tests, just in time for the repeat test.

NIOSH Pressure-drop device

The NIOSH device required a 1-minute sampling time, preceded by a 20-second temperature equilibration. With the pump drawing a constant flow through the filter probe, the pressure drop across the filter was recorded at the start and end of the 1-minute period.

The filters were later returned to NIOSH in Pittsburgh where they were analysed.

Different filter probes were used for the dry tests, where the exhaust was much hotter. These probes were made of stainless steel, and did not include the drying medium.

4. Results of the Dynamometer Testing

The dynamometer testing produced a large amount of data under well-controlled conditions. In this report, analysis of the data has been confined to the subject of the project – developing a method for measuring DPM. But the data could be analysed to show other information such as:

- relationships between gaseous and particulate emissions under a limited range of load conditions for a type of engine;
- comparisons of particulate emissions for the different type of engines;
- the effect of the water scrubber on particulate emissions.

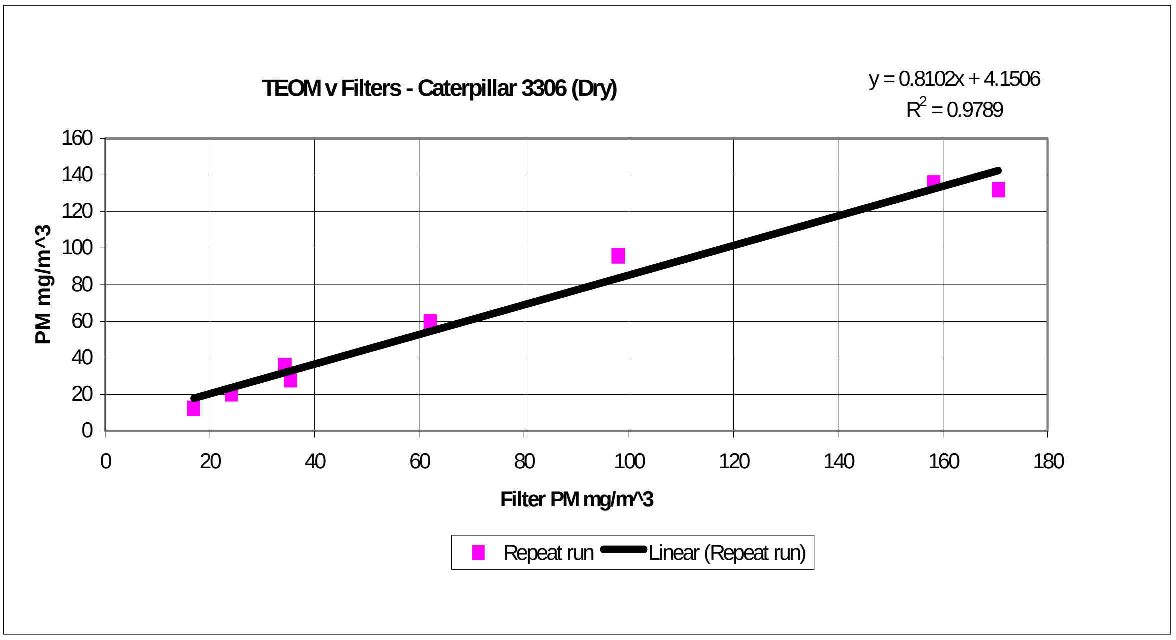
Before the correlations between the various measurement methods are discussed, some preliminary questions can be answered.

How precise are the dilution tunnel filter results?

The TEOM and the dilution tunnel filters both sampled the same diluted exhaust stream, and both measured mass. A comparison between these results could therefore be used as an indicator of the precision of these measurements. If the correlation between these two shows a spread, it suggests there is a significant uncertainty in one or other (or both) of these measurements. If the correlation is tight, both must be quite precise.

The filters were conditioned to a constant humidity before weighing, while the TEOM weighed particulate as it was received. The presence of water may therefore have caused a discrepancy, so the comparison is best made on a dry test. This comparison for the repeat dry test on the Caterpillar 3306 is shown in graph 1.

Graph 1: Relationship between TEOM and tunnel filters

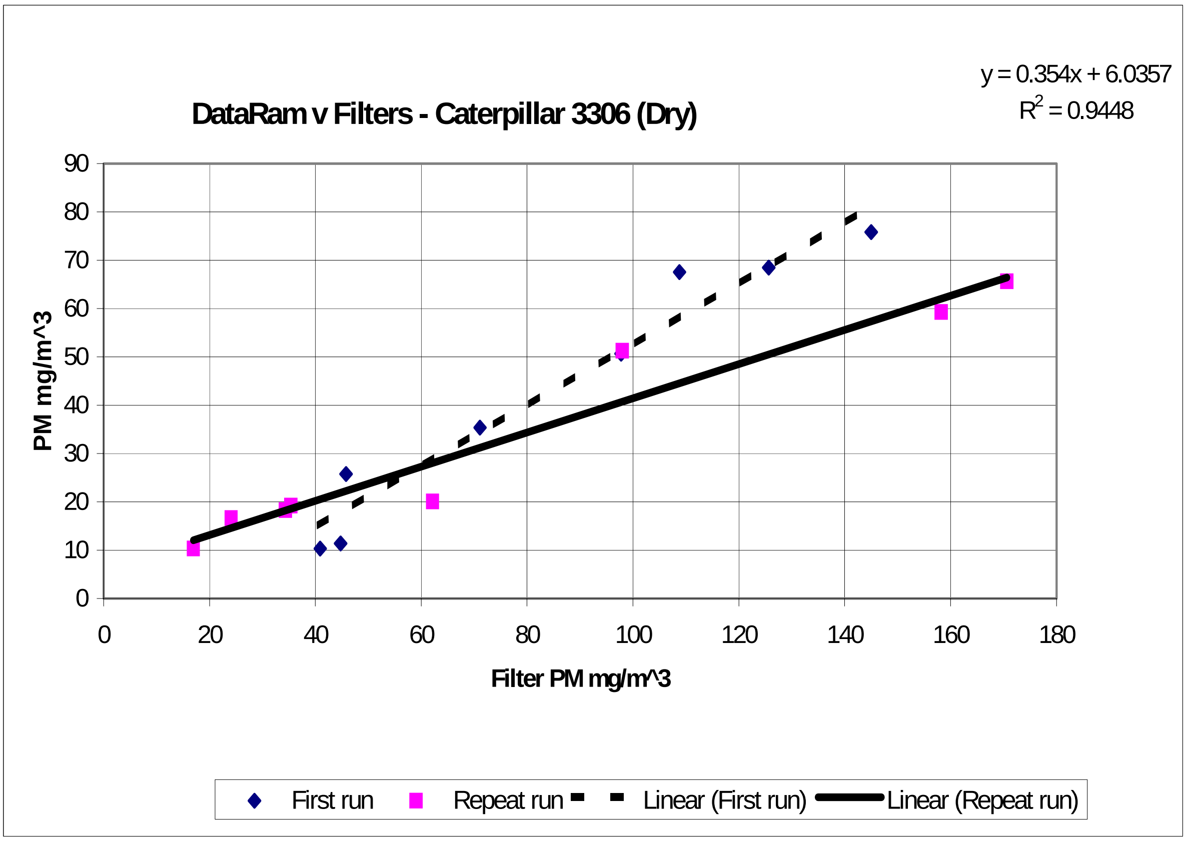


The graph shows a good relationship, with some scatter, and a value for R^2 of 0.979. (R^2 is the 'coefficient of determination', and is an indicator of how well the equation resulting from the regression analysis explains the relationship among the variables. A value of 0 would indicate that there is no meaningful relationship between the quantities; a value of 1 would indicate a perfect fit.) This shows quite good agreement between the methods. The point near 100 mg/m^3 is the worst fit, and is about 10% away from the line. Probably most of the uncertainty is in the filter method, and 10% would represent the maximum error in the filter determinations.

Did the failure of the exhaust system affect the results on 3 April?

A plot of results for DataRam and filters, for both tests on the Caterpillar 3306 engine without water scrubber (see Graph **2**), clearly shows a difference. For a given reading on the DataRam, the filter result for the first test gives reduced values. We must conclude that the failure did affect the results, and the repeat test was justified. (This could not be known at the time.)

Graph 2: DataRam and Filters for both dry tests.



Correlations Shown in the Appendices

Appendices 7, 8 and 9 show sets of graphs depicting various correlations. In Appendix 7 various instruments are plotted against the tunnel filters; in Appendix 8 against the DustTrak; and in Appendix 9 against the total carbon values from the R&P 5100 Elemental Carbon analyser.

In the following discussion, the focus is on the correlations with the tunnel filters. This is the standard method from measuring DPM, and is what the project set out to test. The other sets of graphs are presented, but are left to the reader to examine.

Correlations with Filter Tests

Graphs of the various measurements against filter papers from the dilution tunnel and given in Appendix 7. For each instrument there are five graphs, showing:

- the Caterpillar 3306 engine tests without water scrubber (the 'dry' tests) - both on one graph);
- the Caterpillar 3306 engine 'wet' test;
- the Caterpillar 3126 engine;
- the KIA engine; and
- the Caterpillar 3126 engine (one trace) and all other engines (the other trace).

Thus there are sets of five graphs for each of: Bosch smoke meter, DustTrak, DataRam, HazDust, NIOSH, R&P (elemental carbon), R&P (total carbon), and TEOM. Each graph also has a straight line of best fit.

For the 3306 dry tests, the equation is shown for only the second test, as the first has been shown to be affected by the problem with the exhaust system. However there **is** a valid comparison with the TEOM, and this graph includes both equations and both R^2 values.

Table **5** shows the "R^2" values for the correlations with the filters from the dilution tunnel.

The sections after the table comment briefly on these results.

It should be noted that the range of DPM concentrations for the 3126 engine is quite small, and this makes it difficult to obtain reliable correlations.

Table 5: R^2 values for correlations with dilution tunnel filters

	Cat 3306 dry (1)	**Cat 3306 dry (2)**	**Cat 3306 wet**	**Cat 3126**	**KIA**	**All except 3126**	**All engines**
Bosch	-	0.91	0.81	0.22	0.80	0.74	0.76
DustTrak	-	0.93	0.88	0.72	0.79	0.87	0.04
DataRam	-	0.94	0.81	0.72	0.77	0.62	0.01
HazDust	-	0.27	0.42	0.49	0.92	0.11	0.03
NIOSH	-	0.55	0.91	0.58	0.88	0.48	0.49
R&P (EC)	-	0.89	0.78	0.63	0.95	0.79	0.56
R&P (TC)	-	0.90	0.82	0.77	0.91	0.77	0.38
TEOM	0.93	0.98	0.91	0.94	0.94	0.96	0.96

Bosch smoke meter

The Bosch results do not include the transient tests, as it is not possible to sample transients with this model of smoke meter.

With the exception of the 3126 engine, the correlations are quite good, and the result including all engines is also quite good. While there is a spread of results, the graph shows that a Bosch number of 2.0 would be equivalent to a DPM concentration of 100 mg/m^3 for all engines.

DustTrak

Each engine – except the 3126 - gives a quite good correlation, and the relationship is quite good for all engines excluding the 3126.

The 3126 gives a totally different plot from the others, and this suggests a significant difference in the type of DPM emitted by this engine. It is possible that the DPM is finer, and produces greater light scattering for a given mass of DPM.

This characteristic dictates that the DustTrak can be used for the measurement of DPM only if the type of engine is taken into account.

DataRam

The DataRam results are very similar to those for the DustTrak. The correlation for all engines excluding the 3126 is not quite as tight as for the DustTrak.

The comments about the 3126 engine and particle size apply here as for DustTrak.

HazDust

Much less data was obtained from the HazDust, and the correlations are in most cases much poorer than with the other light-scattering instruments.

The correlation for all engines excluding the 3126 is very poor, and nothing like the results from the DustTrak or DataRam.

The comments about the 3126 engine and particle size apply here as for DustTrak.

NIOSH

The spread of results is greater for this device than for the DustTrak, for most engines, and for all engines excluding the 3126 (R^2 of 0.48 for NIOSH and 0.87 for DustTrak). But in sharp contrast to the DustTrak, the all-engines result is made no worse by including the 3126.

R&P Elemental carbon analyser (elemental carbon)

This show quite good correlation for each engine (but not so good for the 3126), and for all engines excluding the 3126. The 3126 seems to exhibit a different relationship, and the R^2 value including all engines is 0.56.

R&P Elemental carbon analyser (total carbon)

Correlations for total carbon are similar to those for elemental carbon from the same analyser, except for all engines, where the correlation is poorer (R^2 of 0.38 compared with 0.56 for elemental carbon.)

TEOM

Both the TEOM and the tunnel filters measure the mass of deposited DPM, and both sample the same diluted sample stream simultaneously. It would be expected that the methods would agree well.

This expectation is borne out by excellent correlation between these two for all measurements.

Conclusions from the Dynamometer Tests

1 Of the three laser light-scattering instruments, results from the Hazdust are not nearly as good as the DustTrak and DataRam. The HazDust is also a much larger and heavier instrument than either of the others, and its size is further increased by the addition of the drying/dilution unit.

It was further found that the flow system for the HazDust made it unsuitable for the improved dilution arrangement suggested by Air Quality Technologies, designers of the dilution system.

The Working Group therefore decided to omit the HazDust from further testing.

This decision in no way reflects on the suitability of the HazDust for its intended use as a high sensitivity particulate monitor for ambient environmental and indoor air quality applications. As mentioned earlier in the report, none of the instruments was designed for the purpose of measuring DPM in undiluted diesel exhaust.

2 The DustTrak and DataRam gave quite good results, especially given the poor precision in the dilution of the sample. But the results for the Caterpillar 3126 are quite different from those for other engines. It seems clear that engine type must be taken into account when assessing the results from these instruments.

The results for the 3126 engine are much higher than would be expected for the measured mass of DPM. This is thought to be related to a different range of particle sizes from the 3126 engine, but this has not been further explored.

3 The NIOSH pressure-drop device produced moderately good results. It has the advantage that the results do not vary dramatically with engine type.

The correlations between the measured pressure changes and the DPM determined from the analysis of the filters have not been reported here in any detail. Jon Volkwein is publishing a report on the development of the NIOSH device for diesel exhaust measurement, and is reporting in detail on these correlations.

The correlation of pressure change with measured DPM is the means by which the device will be given a calibration, so that its readout can be in terms of DPM rather than units of pressure. The final calibration can only be decided after the filter units are standardised; this will occur as the unit is developed into a commercial device.

5. Refinement of the Instruments

With the positive outcomes from the dynamometer tests, some improvements were seen as desirable and possible for the light-scattering instruments, and for the NIOSH device.

Refinement of the Laser Light-Scattering Instruments

The dilution and drying unit used in conjunction with these instruments was an experimental unit. The developer, Air Quality Technologies, had offered a better arrangement of the dilution system. During the dynamometer testing the setting and measurement of the dilution ratios was found to be a cause of significant measurement error. This was because the sample flow was calculated by measuring the total flow and the dilution flow and subtracting these values to give the sample flow. With dilution ratios around 5:1, a small error in either of the measured values has a major impact on the dilution ratio.

The better arrangement could have been used during the dynamometer testing, but it depended on certain characteristics of the instruments to be used with it, and these were not known prior to the testing. Accordingly the dynamometer testing proceeded with the less precise arrangement.

The improved arrangement involved subtracting the total and dilution flows, and measuring the difference (corresponding to the sample flow) on a flowmeter with a smaller range.

The difference in precision of the two systems is illustrated in Table 6.

Table 6: comparative precision of dilution arrangements

	Method 1 - measure flows & subtract		Method 2 - subtract flows & measure	
Quantity	**Value**	**Comment**	**Value**	**Comment**
Target sample + dilution flow (L/min)	5.00		5.00	
Target dilution flow (L/min)	4.00		4.00	
Target sample flow (L/min)	1.00		1.00	
Error in setting & reading rotameters	5%		5%	
Target dilution ratio	5.00		5.00	
Possible maximum total flow (L/min)	5.25	+5%	5.25	+5%
Possible minimum total flow (L/min)	4.75	-5%	4.75	-5%
Possible maximum dilution flow (L/min)	4.20	+5%		
Possible minimum dilution flow (L/min)	3.80	-5%		
Possible maximum sample flow (L/min)	1.45	difference	1.05	+5%
Possible minimum sample flow (L/min)	0.55	difference	0.95	-5%
Possible maximum dilution ratio	9.55	5.25/0.55	5.53	5.25/0.95
Possible minimum dilution ratio	3.28	4.75/1.45	4.52	4.75/1.05
Worst case % error (+ve)	+91%		+11%	
Worst case % error (-ve)	-34%		-10%	

With the retirement of the Hazdust from the project, the other light-scattering instruments were tested and found to be suitable for the revised dilution arrangement. The system was revised to incorporate the improved arrangement. Other changes were also made, the main one being the replacement of desiccant in the original version with a Peltier cooler. This necessitated the addition of a sealed lead-acid storage battery, since the cooler draws substantial current.

The re-designed unit was built into a briefcase-size waterproof, heavy-duty and impact-resistant polypropylene instrument case. With the DustTrak unit included, it has a mass of 14kg, and dimensions of 52 x 41 x 22 cm. The battery is reported to allow it to operate for 2 hours on a charge. Alternatively the unit could be run continuously with support from the mains or external battery supply.

While the earlier unit required the desiccant to be replaced or regenerated periodically, the new version required only the occasional operation of a pair of valves to purge accumulated water.

The DataRam with a pump and battery pack could be substituted for the DustTrak.

Refinement of the NIOSH Pressure-Drop Method

The sample pumps used in the dynamometer tests were SKC Pocket Pumps. They are quite small and light. For those tests a small pressure and temperature recorder (logger) was attached to them, and this was used to monitor the pressure drop across the filter. The sampling was timed manually.

After these tests SKC produced a custom version of the Dust Detective pump. This has the pressure transducer built in, and a ‘diesel’ mode, activated by a single key, displays a count-down during the sampling, and starts and stops the pump. At the end of the sample the LCD shows the change in pressure drop over the 1-minute measurement period, in “in/min” – referring to units of inches water gauge per minute.

The sample tubes remained unchanged.

6. Field Testing

Following the rather artificial, well-controlled dynamometer testing on only three engines, the field testing was intended to refine and demonstrate the practicality of the measurement methods for use on machines at coal mines.

Five mines were chosen after consideration of the range and accessibility of the machines at each site and some geographic factors. For simplicity it was preferred to carry out the tests on the surface, although the proposed test methods could easily be used underground in safe areas.

The mines were: West Wallsend, United and Newstan in the Hunter region, and Angus Place and Springvale in the Lithgow area. We are grateful to the management of these mines for their cooperation, and to their mechanical staff who assisted us so capably during the preparation and testing.

Instruments Under Test

The instruments continuing from the dynamometer tests were two laser light-scattering instruments – DustTrak and DataRam - and the NIOSH pressure-drop method.

The light-scattering instruments were to be used with the revised dilution/drying system, and this would give more precise dilutions, as discussed above.

Only one dilution/drying unit was available, and this would normally necessitate the repeat of tests so that readings could be taken with each instrument. To avoid this it was decided to run the sample through the dilution/drying unit, then to the DataRam, and then to the DustTrak. The pump in the DustTrak would draw the sample through both instruments. It was considered that no significant loss of DPM would occur between the two instruments. Readings on the two instruments would therefore be on the same sample, with only a slight delay between them.

The NIOSH device now consisted of the new SKC Dust Detective pump with the same type of sample tubes previously used. The tubes were supplied by NIOSH. As all the machines to be tested would have water scrubbers, the only tubes to be used were the copper ones with desiccant included. (As mentioned previously, stainless steel tubes without desiccant are used for exhaust gases above 100°C.)

As previously, the NIOSH device required a 20-second period to stabilise the probe temperature. The internal timer in the Dust Detective pump is programmed to operate the pump for a total of 80 seconds. It records a pressure measurement at the end of 20 seconds and a second measurement at 80 seconds, and then displays the difference between these two readings. It is necessary to have the exhaust at the same velocity and temperature at the start and end of the 1-minute sample period.

Test Cycles Used

As discussed in reference to the dynamometer testing, it was desired to devise a test procedure which would be a realistic check on both naturally aspirated and turbo-charged engines – although the latter are not yet common in the underground coal mining industry. After some experimentation on the first day of the field testing, it was decided to adopt three different test procedures for different purposes.

Transient-and-load test

- the engine was operated (preferably by driving) to bring it fully to operating temperature;
- the machine was positioned near the test equipment, and suitable precautions were taken to prevent it from moving during the test;
- the transmission was placed in neutral, and the engine accelerated a couple of times to flight speed, and brought back to idle;
- the test probes were inserted in the exhaust;
- the transmission was placed in a high gear and the brakes were applied;
- the SKC pump was started, and the test was commenced with 20 seconds at idle in gear;
- when the display on the SKC pump showed “sa” (for ‘sampling’), the machine operator was signalled, and the throttle was opened suddenly (raising the engine speed to a torque stall condition);
- 20 seconds after the first signal, the operator was signalled again, and the throttle was closed suddenly (allowing the engine to return to idle in gear);
- sampling continued with the machine in gear until the SKC pump showed it had completed its sampling.

This procedure is reasonably quick, and includes a period at idle, a sudden acceleration, 20 seconds at torque stall, and a sudden deceleration, and a further period at idle. It requires only a heavy foot on the throttle, and the timing which could be from the SKC pump or a watch. The 20 seconds at torque stall is well within the safe period for the torque converter on these machines.

The initial 20-second equilibration is only needed for the NIOSH device. Sampling for the light-scattering and other instruments was commenced immediately after this, at the start of the 1-minute period. If the NIOSH device were not in use, sampling would be over the 1-minute period, and could be timed with a watch.

Transient-only test

The engine was accelerated at full throttle in neutral from low idle to flight speed. Immediately flight speed was reached, the throttle was released suddenly, and the engine allowed to return to idle, when it was immediately accelerated again. The test consisted of a succession of five of these acceleration-deceleration cycles.

During the acceleration phase the engine is subject to maximum fuel input until flight speed is approached. During this time it works at maximum torque, the load being its own inertia.

This test was included because it was within the measurement capability of the light scattering instruments, and might provide useful information about engine behaviour under transient conditions – especially for turbo-charged engines.

The test requires only a heavy foot on the throttle. Engine speed – idle and flight – is judged by ear.

Load-only test

This is the test currently used for exhaust gas checks. The engine is operated under torque stall conditions – or other load conditions if this is not appropriate. Measurements are made during this steady load.

The test was included to permit exhaust gases to be analysed, and Bosch smoke measurements to be taken.

Idle test

This test was to permit exhaust gases to be analysed at idle, because exhaust gases are usually tested at load and idle.

Other Measurements Taken

Other measurements were included in the test program to give a more complete picture of the behaviour of the engines:

- organic carbon, total carbon and (by difference) elemental carbon were measured with the R&P 5100 Elemental Carbon Analyser;
- Bosch smoke readings were taken at a steady torque stall condition;
- exhaust gases (CO_2, CO, NO_x, and O_2) were analysed at a steady torque stall condition and at idle;

The range of tests conducted is summarised in Table 7.

Table 7 – measurements taken during the field tests

Measurements	Transient-and-load test	Transient-only test	Load-only test	Idle test
DustTrak	✓ max, min & average readings recorded	✓ max, min & average readings recorded	✓ max, min & average readings recorded	
DataRam	✓ average readings recorded	✓ average readings recorded	✓ average readings recorded	
Elemental carbon etc	✓ TC, OC & EC recorded			
NIOSH	✓ pressure drop recorded. Filters analysed for EC			
Bosch smoke meter			✓	
Gases			✓ CO_2, CO, NO_x & O_2	✓ CO_2, CO, NO_x & O_2

Findings During Testing

- All of the test procedures described above were easily carried out at mine sites on most machines. The various engine operating modes required only minimal pre-arrangement between tester and driver, and simple communication during the tests.
- On most machines, the exhaust stream could be sampled without much difficulty. On some machines a short, curved extension was fitted to the end of the pipe. On others, probes could be inserted directly. One machine required more difficult access to a downward-facing exhaust, and another was found to be too difficult to sample without re-designing the probe.
- Increases in engine speed and exhaust flow were at first found to cause increases in sample flow in the dilution/drying system used with the light scattering instruments. This would change the dilution ratio and invalidate the measurements of DPM. The sample pipe at this stage had an open end, and the effect was recognised as being caused by dynamic pressure of the exhaust gas stream.
  A transmission breather plug was fitted to the end of the pipe. The plug has a hexagon head measuring about 17 mm across the flats, with holes in three of the flats. The pipe was tried again, and the opposite effect was observed – *increased* exhaust flow caused a *reduction* in sample flow.
  A further series of modifications were made, in which the head of the plug was rounded, and channels were cut past the holes. It was then found that changes in exhaust gas flow had little effect on sample flow.
- In early testing, readings on the DustTrak exceeded the measuring range on one engine. This effect had been seen before, and was recognised as being caused by mist passing into the instrument. The dilution ratio was increased from 5.0 to 6.0. The DPM readings then stayed well within the measuring range of the light scattering instruments for the remainder of the tests.
- Difficulty was experience with one of the small pumps in the dilution/drying unit. After maintenance it worked successfully for the remainder of the testing, but the nature of the problem was reported to Air Quality Technologies.
- The pump in the DustTrak had to be operated at near its maximum flow in order to achieve the desired dilution ratios. As the internal filter became restricted the flow could not be maintained. We suggested to AQT that the flows in the unit be reviewed.
- There was a difference in the ease of use of the DustTrak and DataRam, summarised in Table 8.

Table 8: Comparison Between Ease of Use of DustTrak and DataRam

Property	DustTrak	DataRam
Size of instrument	Larger, but complete	Smaller, but needs pump and battery pack, making it larger and heavier.
Suitability for precise dilution arrangement	Suitable as supplied	Found not be well sealed, so that intake and outlet flows were not the same. The unit tested was re-assembled using sealant to eliminate leakage.
Size of characters on display	Very large numbers, with smaller units	Small 2-line display with words to prompt which keys to press.
Operation of keys	'Sample' key starts and stops measurement	Different keys used to start and stop measurement.
Response to keys	Measurements commence immediately the 'sample' key is pressed	Instrument performs a 'setup' routine when key is pressed; measurement commences a few seconds later.
Display of max, min & average results	Repeated pressing of 'statistics' key shows max, min and average readings.	Display of these results is more complicated.
Ability to correlate with filters	No provision	Can be fitted with a filter unit; filter can be weighed to compare with measured values.

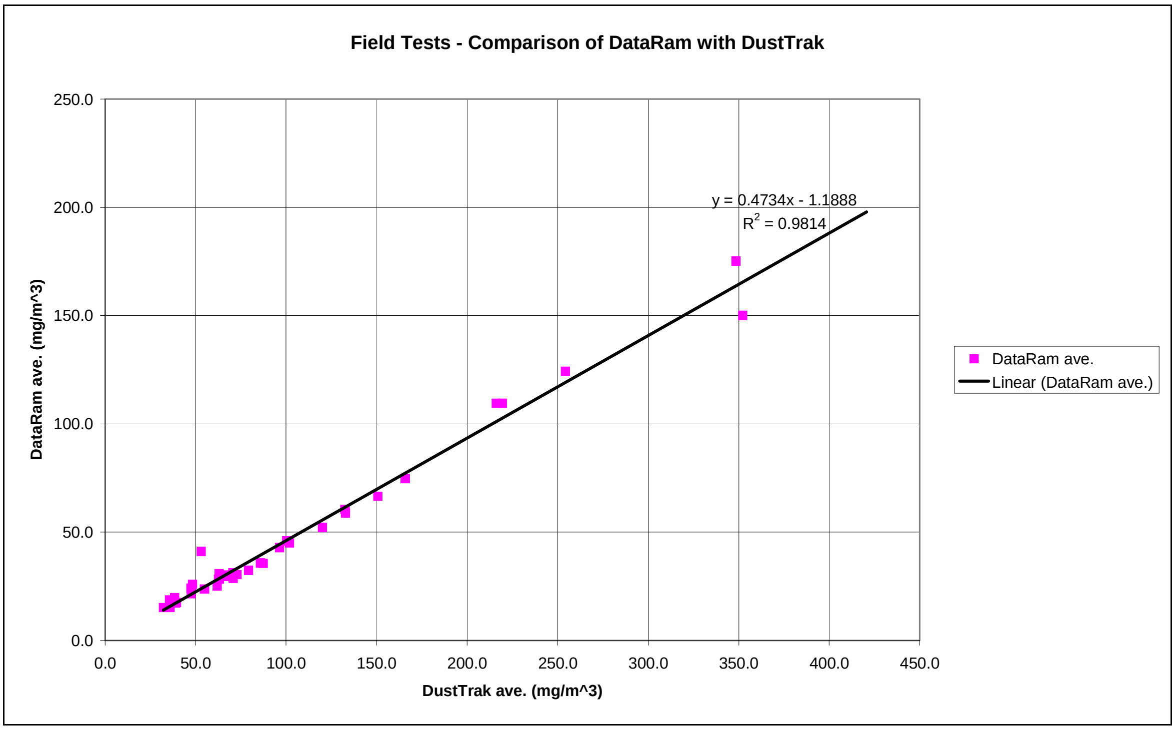
Simultaneous testing with several instruments at West Wallsend Colliery

Results of the Field Tests

Comparisons of Results Between Instruments

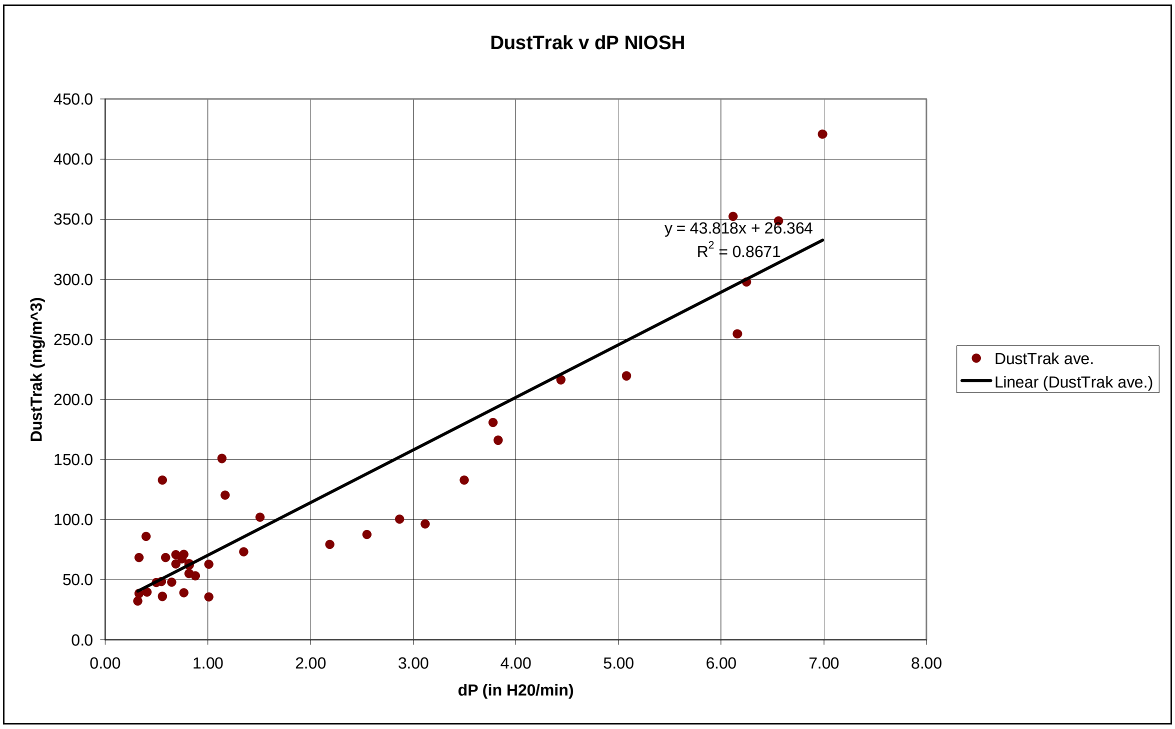
Because the tests were run simultaneously on all instruments, it became possible to compare results. This was not an original intention of the field tests, but does provide useful extra information.

Graph 3: Comparison of DataRam with DustTrak in Field Tests.



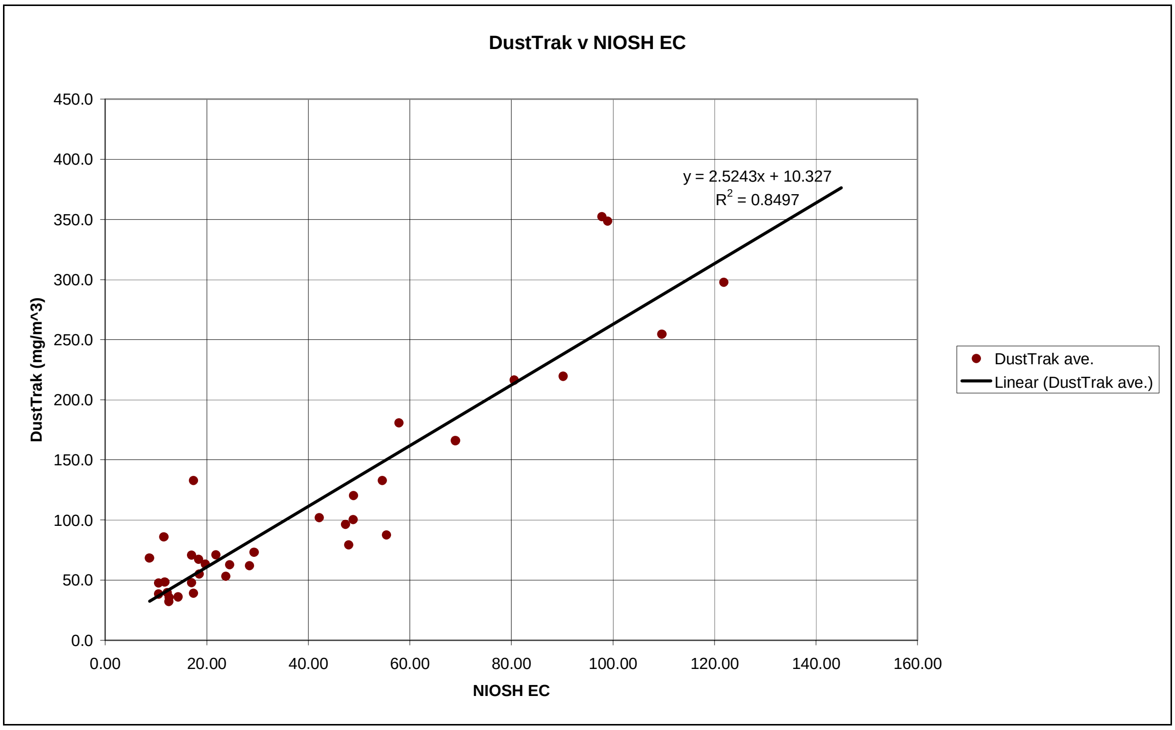
The same diluted sample was passed to the DataRam and DustTrak in series, and the agreement between the two instruments is excellent. Clearly there is a calibration difference, but the graph shows that the two instruments are equivalent in terms of their results.

Graph 4: Comparison of DustTrak with dP NIOSH in Field Tests.



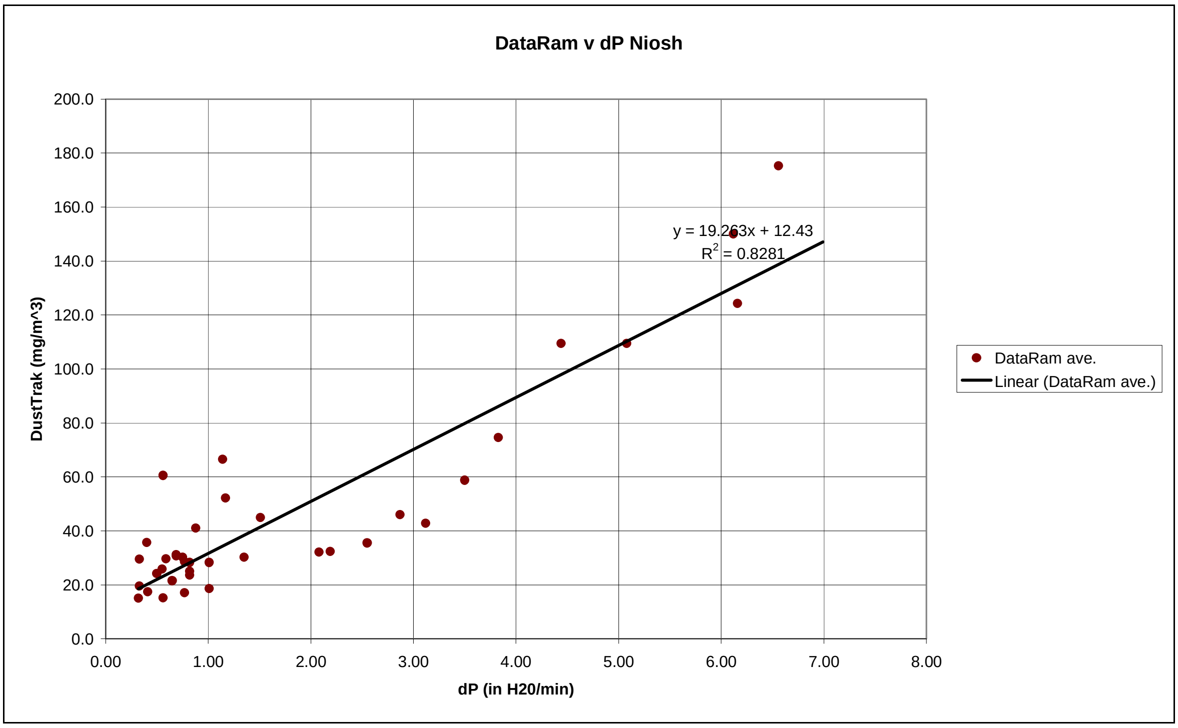
Quite good agreement is seen between these two methods. Note that no engines similar to the Caterpillar 3126 were tested in the field trials. The spread of results is more obvious at lower readings than at higher ones. This is a region where the results are less important, since the devices would be used to target engines with high readings.

Graph 5: Comparison of DustTrak with NIOSH Elemental Carbon in Field Tests.



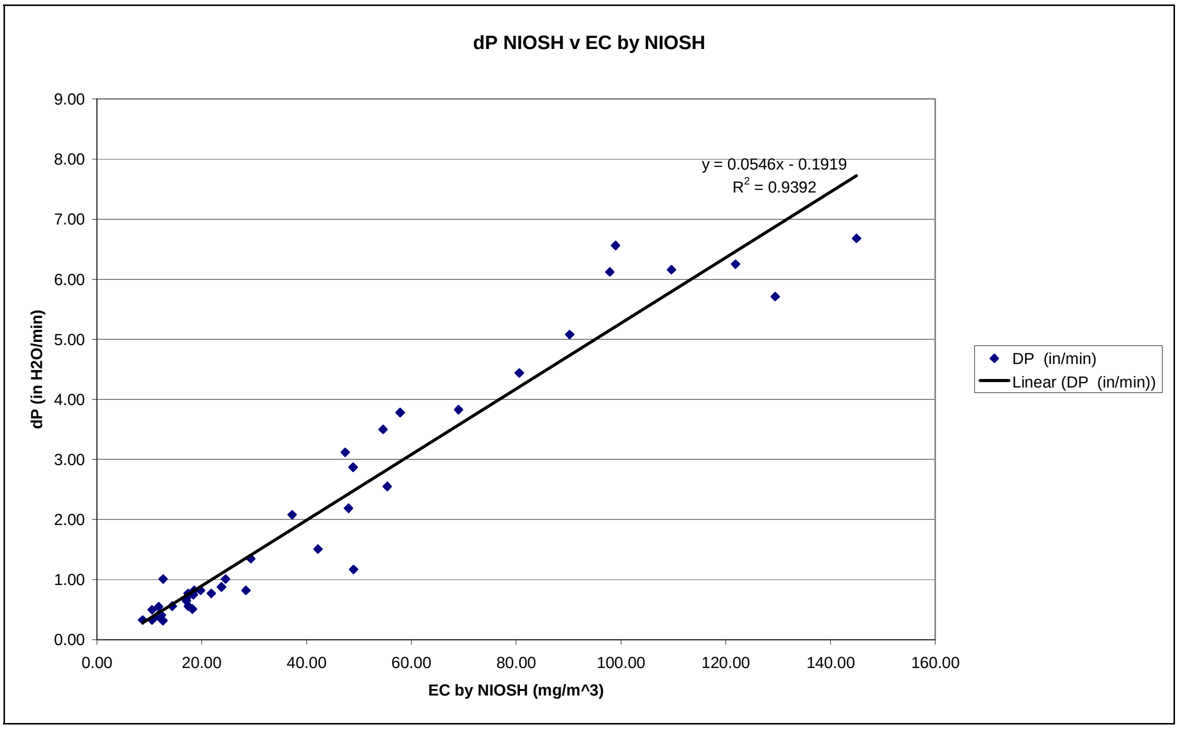
There is reasonably good agreement between these two methods.

Graph 6: Comparison of DataRam with dP NIOSH in Field Tests.



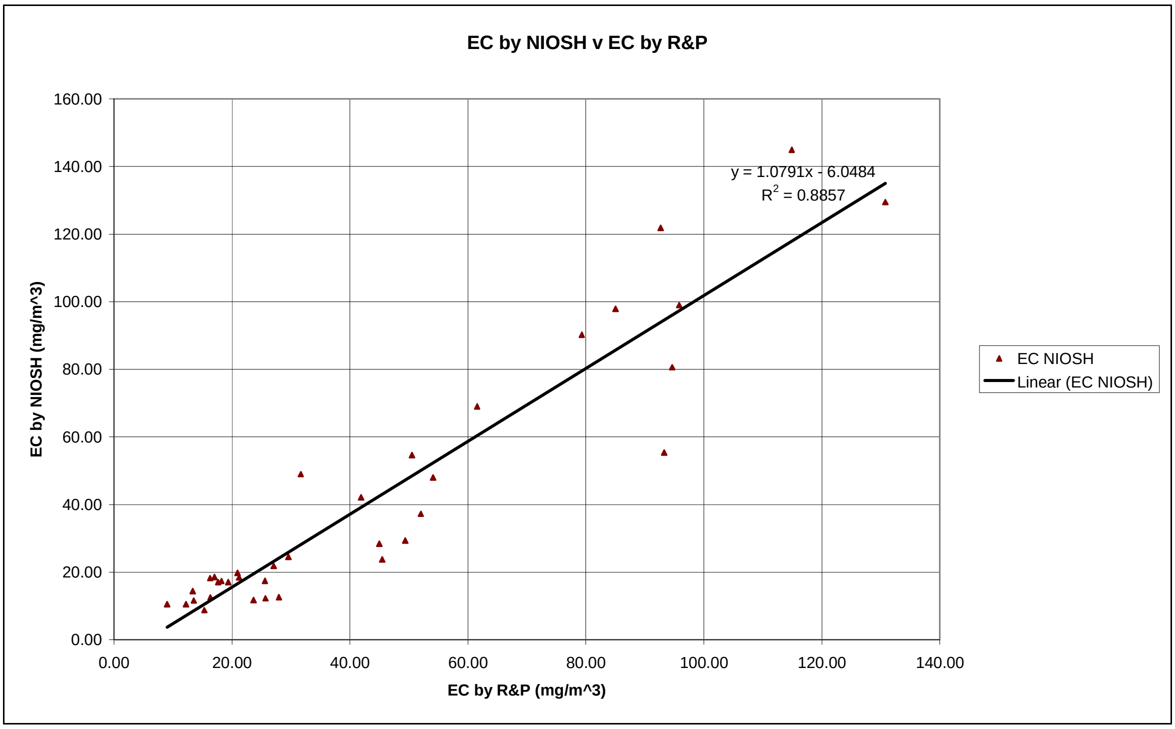
There is a reasonably good agreement between the two methods.

Graph 7: Comparison of dP NIOSH with NIOSH Elemental Carbon in Field Tests.



This shows quite a good fit, demonstrating that it is possible to establish a calibration in terms of DPM.

Graph 8: Comparison of EC NIOSH with EC R&P in Field Tests.

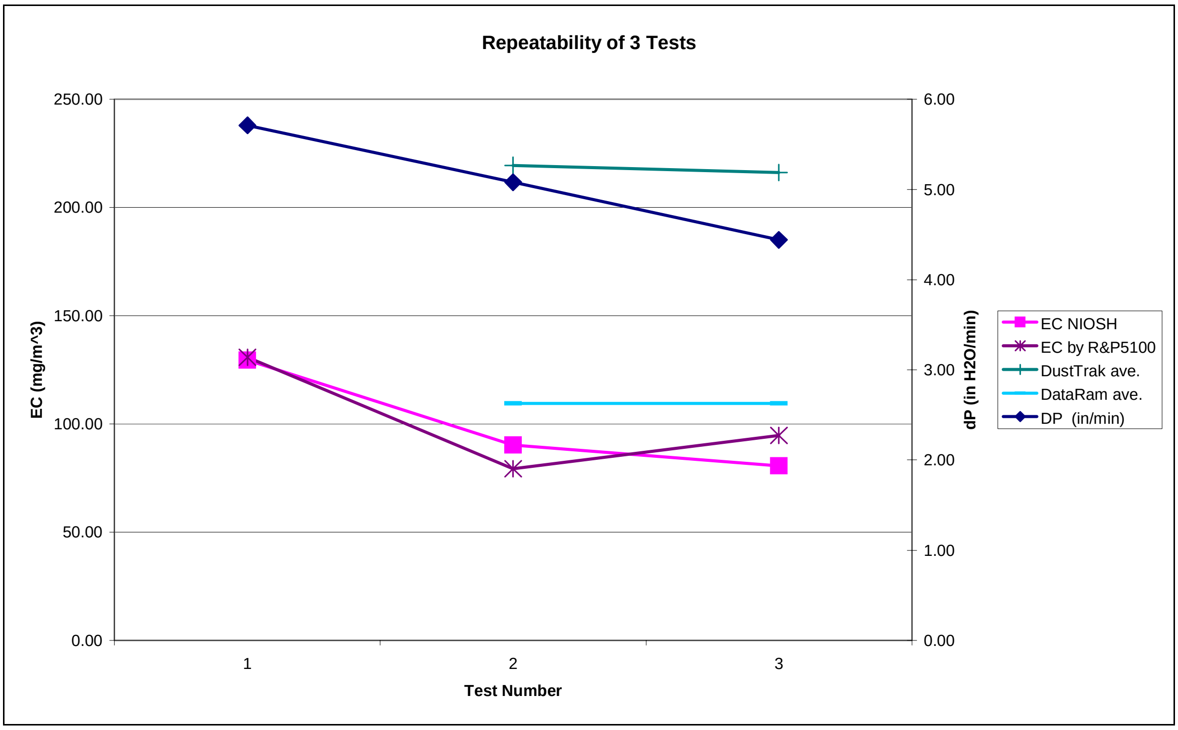


The two methods show reasonably good agreement.

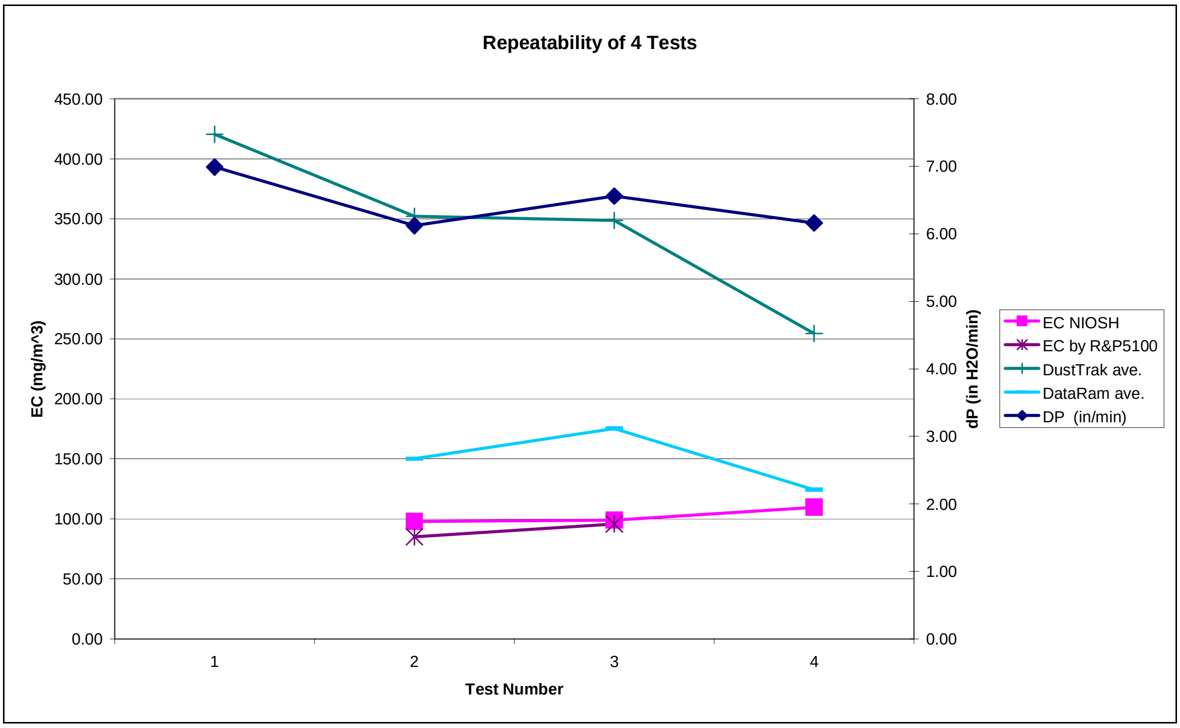
Repeatability of Tests

On some engines repeat tests were run to show how much variation could be expected in the results. The following graphs show the results of 3, 4 and 5 tests on different engines. The engines selected for these repeats were ones giving higher results, so the variation could be more easily seen.

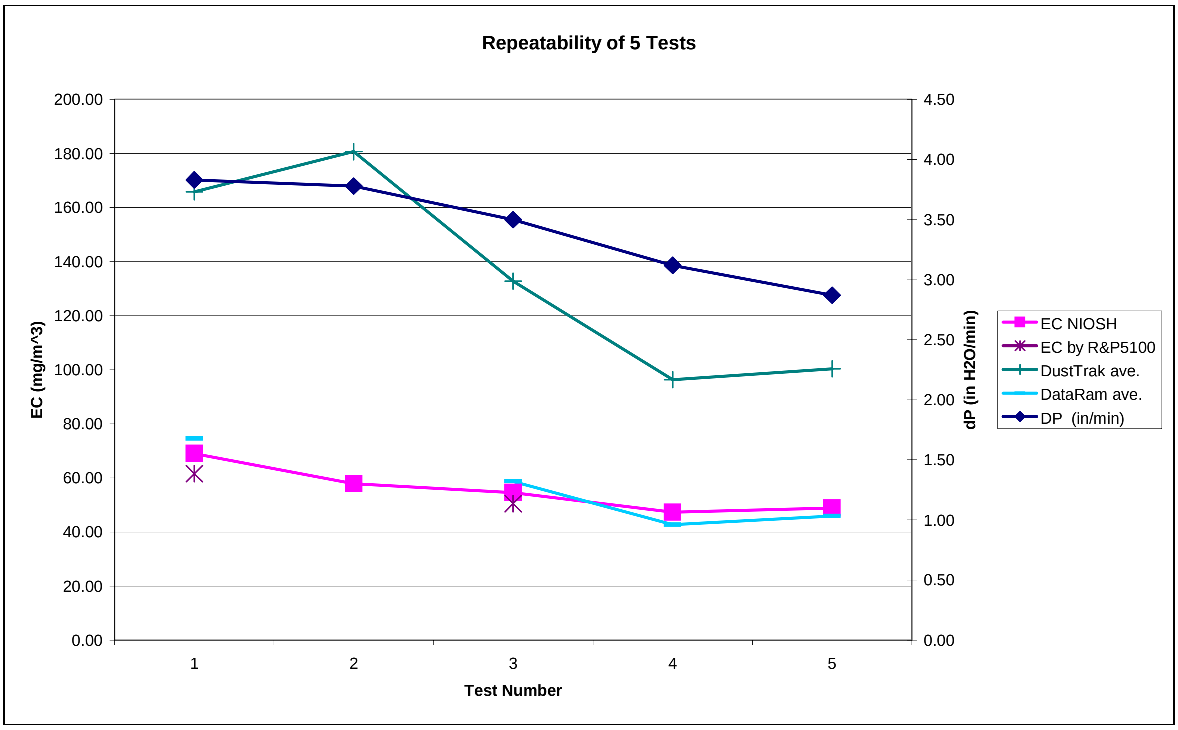
Graph 9: Repeatability of 3 Tests



Graph 10: Repeatability of 4 Tests



Graph 11: Repeatability of 5 Tests



It is clear that there is a major variation in the results from one test to another. The instruments vary against each other to some extent, but together they depict a variation in the results.

The test procedure used is believed to be not difficult to reproduce with some accuracy. In these cases the tests were performed by the same machine operator and the same instrument operators.

This serves as a reminder that field testing of engines is a screening operation, rather than one for precise measurement.

Conclusions from the Field Tests

1 The test method devised is simple to use in the field, and can be applied to almost every machine type encountered without too much difficulty. In some cases short extensions to the exhaust system were used. If the testing were to become routine, it would not be difficult to establish access to the raw exhaust for testing.

2 Because the measurements were carried out simultaneously with all the instruments it was possible to make comparisons. These showed reasonable agreement between the various measurement techniques.

3 Repeat tests using the same operators for the engine and the instruments showed a significant variation in results. The tests should be regarded as a screening test to reveal engines with abnormally high emissions.

4 Only one turbocharged engine was encountered, and no engine similar to the Caterpillar 3126.

5 We have not reported the results of the steady state tests or of the transient-only tests. If mines wanted to devise separate tests using steady state (such as torque stall) and transient (successive accelerations) they could do this and establish their own benchmarks for each type of engine. This could be especially useful if the fleet contained turbocharged engines, as it could show whether high readings were from load conditions or under acceleration.

6 Although the two light-scattering instruments gave readings which tracked each other very closely, the DustTrak was found to be easier to use than the DataRam. There are some sophisticated features of the DataRam which permit monitoring and logging of results from different sites. In this application the DustTrak's simplicity is an advantage.

7 The design of the probe for the light-scattering instruments may need further attention. Our pragmatic modifications may not be adequate in all situations.

7. Conclusions and Recommendation

The project has shown that it is possible to measure DPM in the undiluted exhaust of diesel-powered mining equipment by means of simple hand-held devices.

Test Procedures

The procedure used in the field tests was simple and quick. We would recommend, after a thorough warm-up of the engine:

5 seconds at idle in gear
a sudden full-throttle acceleration
20 seconds at full load
a sudden deceleration, and
a further 35 seconds at idle in gear.

This test takes only one minute, and should be a good test for both naturally aspirated and turbocharged engines. The NIOSH device requires a 20-second equilibration time before the measurement commences, and the engine should be at idle speed at the start and end of the 1-minute period. This removes the effect of changed dynamic pressure from the exhaust flow on the pressure measurements being made.

It is important to follow a consistent test procedure, or comparisons will be meaningless.

Mines could choose to supplement (or even replace) this test procedure with separate test at steady state and during several sudden full-throttle accelerations.

Light-scattering Instruments

Light-scattering instruments can be used - even on engines without a water scrubber – only if the water content is reduced. In the method used in the project this was achieved by diluting the sample. This has the added benefit of reducing the range of concentrations to be measured. The light-scattering instruments are capable of measuring accurately at low concentrations, so the lower concentrations are quite desirable and do not affect the accuracy of the measurement.

The precision and accuracy of the dilution can have a major impact on the reliability of the result. Good precision could be achieved using mass flow controllers, but this would add to the cost and the difficulty of maintenance. Very good precision is achieved by the improved method used in the field tests.

For a given engine, the results of the DustTrak and DataRam correlate well with the filters from the dilution tunnel. The HazDust was less effective for this purpose. But the results for different engine types do not match, and especially the Caterpillar 3126 – a relatively new design of turbo-charged engine – is very different from the other engines used in the dynamometer testing.

For this reason, it is not possible to use the light-scattering instruments to set a standard for DPM emissions from all diesel engines. However it is possible to measure emissions from each type of engine, and identify those that are higher than others of their type. The reason for the higher emissions can then be sought.

This is the approach taken by BHP-Billiton over several years using the elemental carbon analyser, and has been the means of progressively improving the DPM emissions from their diesel fleet.

Of the two instruments tested in the field trials, the DustTrak has distinct advantages over the DataRam in terms of ease of use, although the results from the two match very closely.

The revised dilution and drying unit designed by Air Quality Technologies performed well in the field trials. Some suggestions for refinements were passed to AQT. The unit could be further developed to make it even simpler to use, and AQT may already be planning this.

Neither the DustTrak or the drying unit is intrinsically safe, so this would be suitable for underground use only in restricted areas.

With an instrument, such as the DustTrak, built into the case together with the dilution and drying unit, the device is self-contained and portable. Its sealed lead-acid battery requires charging after a couple of hours' operation. Other maintenance is minimal.

The size and cost of the assembled device suggest it would be more appropriate for use in a workshop.

The sampling probe probably needs further refinement. Others have reported that the flow continues to be affected by exhaust velocity when the probe is used on large machines with high-velocity exhaust. The Bosch smoke meter has a probe that draws sample from openings behind the tip in a way that avoids this problem, and other designs for probes may be suitable.

The NIOSH Pressure-Drop Device

The NIOSH device is remarkable for its small size, portability and ease of use. If the pump is suitable designed it could be used in hazardous areas underground. This, and the lower cost, make it suitable for carrying in a toolbox by fitters.

The results do not match the dilution tunnel filters as well as the DustTrak and DataRam, but they are more consistent across engine type. It seems to be a very useful screening device.

Bosch Smoke Meter

It is appropriate to discuss the Bosch meter here, as it has been used in the NSW mining industry for many years, and is prescribed in the Australian Standard AS 3584 as the method for measuring smoke from underground diesels.

Taken across all engines, the Bosch meter gives a better correlation with the dilution filters than any other device except the TEOM (which is not a portable instrument). The graphs and Table 5 (page 28) show that there is some spread at low values (which are of little importance) but the spread at higher values is not as great as for the NIOSH device.

The limitation with the Bosch meter is that this model can be used only at steady state. There is another model that samples over a few seconds, and is designed to be used with acceleration tests, but we have not tested it. With the coming of increasing numbers of turbocharged engines into the underground coal industry we consider it is appropriate to move to a measurement method other than the present Bosch meter.

Elemental Carbon Analyser

This analyser has been used extensively in recent years to monitor and improve the DPM emissions from diesels in the BHP-Billiton Illawarra coal mines.

The graphs and Table 5 (page 28) show that the correlation with the dilution tunnel filters is quite similar to the Bosch meter, if the Caterpillar 3126 engine is excluded. The 3126 engine shows quite a different correlation, but not as pronounced as the behaviour of the DustTrak and DataRam. It is clear that it is a very good tool for monitoring DPM emissions. The correlation of Total Carbon from this analyser with the dilution tunnel filters is quite similar to the Elemental Carbon results.

The Elemental Carbon analyser can be used with a transient test, making it quite suitable for testing turbocharged engines.

Its cost and size – trailer mounted, with mains power and gas bottles – and the need for a trained operator, make it suitable for routine use only on the surface.

Calibration

The question of calibration for the instruments has not been addressed in the report. The various instruments, even when they correlate well with each other, do not give the same readings. A factor must be applied in order to obtain comparable results.

- The light-scattering instruments can be calibrated by their suppliers. We have not investigated this, and have no information on the consistency of these calibrations.
- The NIOSH device will depend on the consistency of the filters and the assembly of the probe unit. It will be important that reasonable quality control is maintained in this process. The constant flow settings and the pressure transducer in the pump can be checked with readily available equipment.
- The Bosch smoke meter draws a fixed volume during sampling, controlled by the stroke of a spring-loaded plunger. It works reliably and requires little maintenance. The read-out unit is calibrated on use to read 9.9 in a black chamber in the case, and 0.0 on a new filter paper on top of several other new filter papers.
- In the Elemental Carbon analyser the deposited carbon is converted to carbon dioxide and measured. The analyser is calibrated, and the system is checked for flow.

Recommendation

The DustTrak with the AQT dilution and drying unit, and the NIOSH device, although both have limitations, are suitable instruments for measuring DPM from raw exhaust.

They should be further refined to provide mines with simple and helpful equipment to monitor the DPM emissions from their diesel-powered equipment.

Appendix 1: Equipment

The engine test laboratory used in the project is located at the TestSafe facility, Londonderry NSW. The general layout of the laboratory is shown in Figure 1 and comprises the following equipment:

- Dynamometer - Eddy Current, Borghi & Saveri FE 600 S (450kW over the1500-5000RPM range) with torque, load and throttle control. The dynamometer control system is limited to simple torque/speed ramp application and is unable to perform any kind of more complex drive cycle. No inertia or motoring functions are available.
- Particulate Emission Dilution Tunnel - the dilution tunnel (owned and operated by DieselTest Australia , formerly Parsons Australia) was installed at the TestSafe Londonderry engine test cell to provide reference particulate emissions measurement.

  The tunnel is of a full flow Constant Volume Sample/Critical Flow Venturi (CVS/CFV) design. It can be used in a single dilution mode (primary dilution tunnel only) for testing engines up to approximately 40kW or in double dilution mode (primary plus secondary dilution tunnels) for engines in excess of 250kW. For the purposes of the project's tests it was operated in the double dilution mode.

The tunnel is suited to both steady state and transient test procedures and generally complies with the requirements of US Code of Federal Regulation 40, Parts 86.109-94, 86.110-94, 86.1309-90 and 86.1310-90.

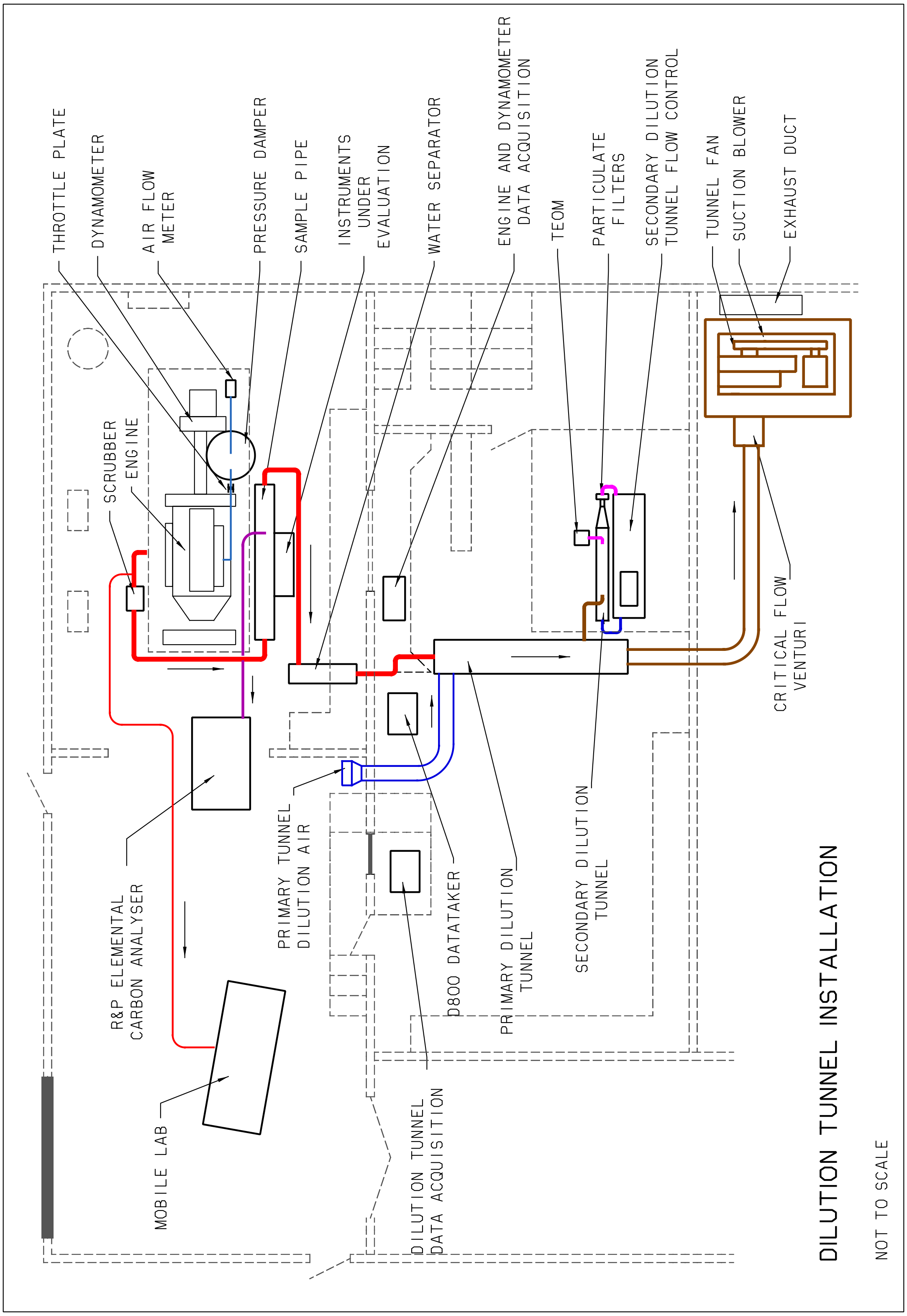
The operation of the tunnel is simple and the general schematic layout of the double dilution option is shown in Figure 2.

- Primary Dilution Tunnel - The primary section of the dilution tunnel consists of a 3.5m length of 304.8 mm dia stainless steel pipe connected at one end to a dilution air filter and engine exhaust and at the other end to a selection of critical flow venturis (CFV) and a suction blower. The total gas flow through the primary dilution is set by the proper selection of the size and number (up to 3) of the critical flow venturis. All of the engine exhaust gas flow is directed in to the tunnel where it is thoroughly diluted by the ambient dilution air. The volume of dilution air is determined by the difference between the flow through the CFVs, flow to the secondary tunnel and the exhaust gas flow.

  There are two sampling probe ports in the primary tunnel at approximately the same point; one of these is for total hydrocarbons (which was not used within this project), while the other is a transfer tube to the secondary dilution tunnel.

  When the primary tunnel is used with a blower (blowers) of capacity of 2000 cfm, engines can be tested at continuous power outputs of up to approximately 45 kW without exceeding CFR temperature limits.

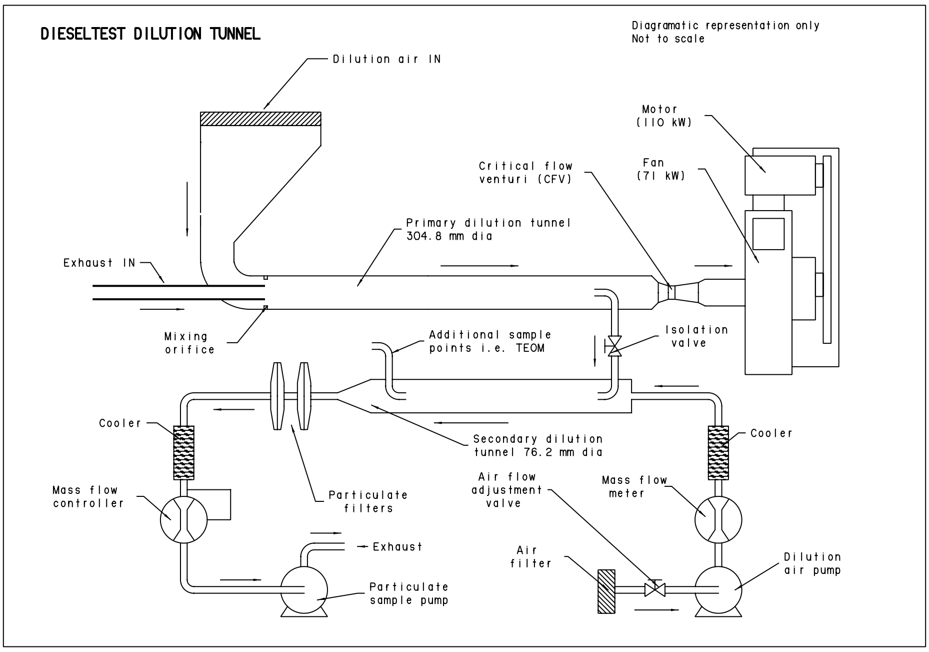
Figure 1 - TestSafe Engine Test Facility - Londonderry



- Secondary Dilution Tunnel - The secondary tunnel is used for the particulate measurement on medium and heavy duty engines. Diluted sample is drawn from the primary tunnel and diluted a second time in order to restrict the particulate sample temperature to less than 52°C. Again, the tunnel is built to the requirements of the CFR, part 86.1310-90. When used with a primary tunnel flowrate of 2000 cfm, engines may be tested at continuous power outputs of up to approximately 250 kW without exceeding temperature limits within the CFR (191"C for the primary tunnel).

  The tunnel is 76.2 mm in diameter and 1 m long. Two filter holders for particulate filters (one 70mm dia, the other 42mm dia) are attached to the downstream end of the tunnel. Filters used are Pall T60A20 filters which are approved by the US EPA. A temperature probe is located just upstream of the filters.

Figure 2 - Dilution Tunnel Schematic



Two Gast rotary vane pumps are used, one to deliver secondary dilution air, and the second to draw the total flow through the filters. A Bronkhorst mass flow meter (MFM) measures the volume of the dilution air, and a Sierra mass flow controller (MFC) meters and controls the total flow through the filters.

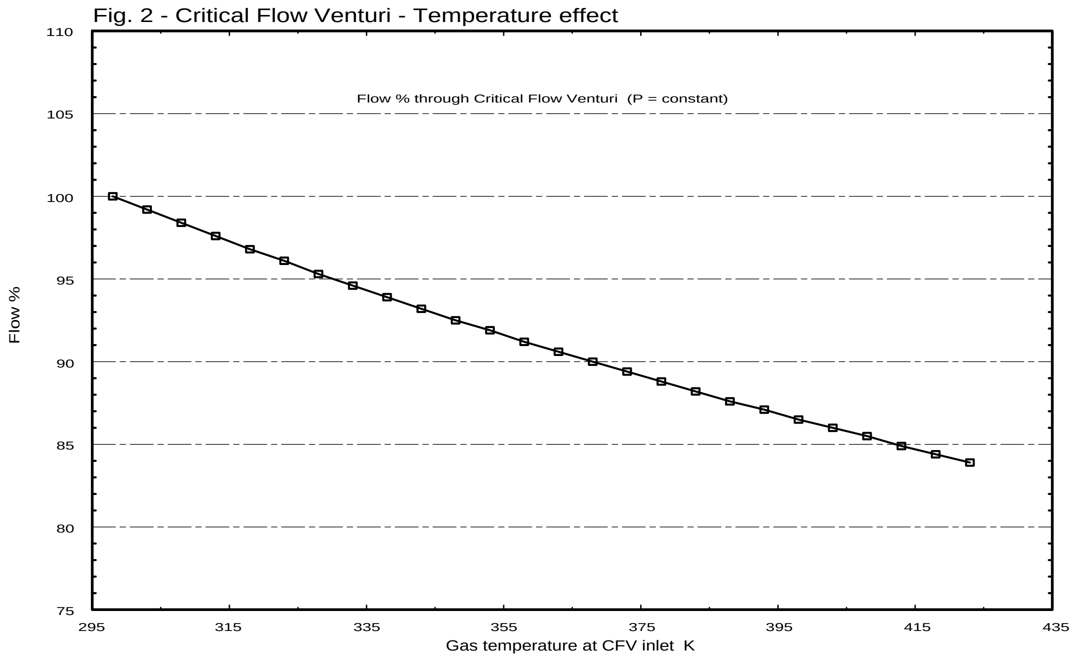
A Campbell Scientific datalogger monitors all the temperatures and records and totalises the flowrates. In addition, the datalogger can monitor the total primary tunnel flow (whether a CFV or PBP CVS is used) and drive the Sierra MFC to ensure the mass proportionality of the sampling. This flow control methodology (termed "electronic flow compensation") is utiltised by the emissions laboratory at West Virginia University.

Additional sampling take-offs e.g. for TEOM (Tapered Element Oscillating Microbalance) are provided.

The tunnel as installed does not fully meet the requirements of the Federal Register in the following area:

1. "No heat exchanger is used" (Clause 86.1310-90). The effect on the flow rate is shown in Figure 3.
2. Lack of temperature measurement and monitoring at the inlet of the particulate sample pump and gas meter.

Figure 3 - Critical Flow Venturi Temperature Sensitivity



The deviations from the CFR regulations of the proposed dilution tunnel equipment are considered minor, mainly affecting clauses concerning absolute mass proportionality of the particulate sample. The combined effect of these CFR deviations are expected to be negligible in absolute terms, and certainly negligible within the context of emissions inventory construction.

Calculation of Emission Species Mass

The total flowrate of dilute exhaust gas in the primary tunnel is known at any time through the measurement of temperature and pressure at the inlet to a calibrated critical flow venturi of known flow characteristics. The instantaneous mass flowrate is given by:

$$m = K_v \frac{p_i}{\sqrt{T_i}} \rho_{STP}$$

where K_v is the Venturi coefficient, and p_i and T_i are the instantaneous absolute pressure and temperatures at the inlet to the venturi and ρ_{STP} is the density of the dilute gas mixture at standard temperature and pressure (20°C, 101.3 kPa).

The particulate sample flowrate is controlled by a mass flow controller driven by an input signal proportional to the total flow through the primary dilution tunnel as measured by the venturi. Thus the particulate sample flowrate is approximately proportional to the total flowrate at all times, whether it is sampled directly in the primary tunnel or using two stage dilution through the secondary tunnel. This configuration of sampling system is known as flow compensation and is allowed for in the CFR 40 part 86.1310-90. It is the sampling methodology used by such US EPA approved laboratories as West Virginia University.

At the end of a test the total mass of dilute exhaust mixture that has flowed through the primary dilution tunnel, and the amount that has flowed through the particulate filters is known. The particulate filters are conditioned back to standard conditions, and the mass of particulate material collected on them determined by weighing on precision balances.

The total amount of particulate emitted by the engine through the test is then given by:

$$M_p = \frac{(V_{mix} + V_{ep}) \times P_e}{V_{ep}}$$

where V_{mix} is the total volume of dilute gas per test (at STP), V_{ep} is the total amount of sample passed through the particulate filters, and P_e is the mass of particulate collected on the filter (see CFR 40 part 86.145-82, 86.1343-88). This assumes that the dilution air is filtered and does not contribute any significant particulate material.

As the sampling is proportional at all times through the test, this methodology gives the total mass of particulate emitted by the vehicle throughout the transient test procedure. To consider the process that occurs though a test, as the dilute exhaust gets hotter though high load phases of the transient procedure, the total mass flow through the primary tunnel decreases due to the decrease in density of gas flowing through the choked venturi. This increases the mass concentration of the particulate in the tunnel, which would lead to over-sampling onto the filter. Hence the mass flowrate of the sample is decreased in proportion to the total flow.

It is easy to see with the particulate sampling how a mass is arrived at, as the quantity that is measured is a mass.

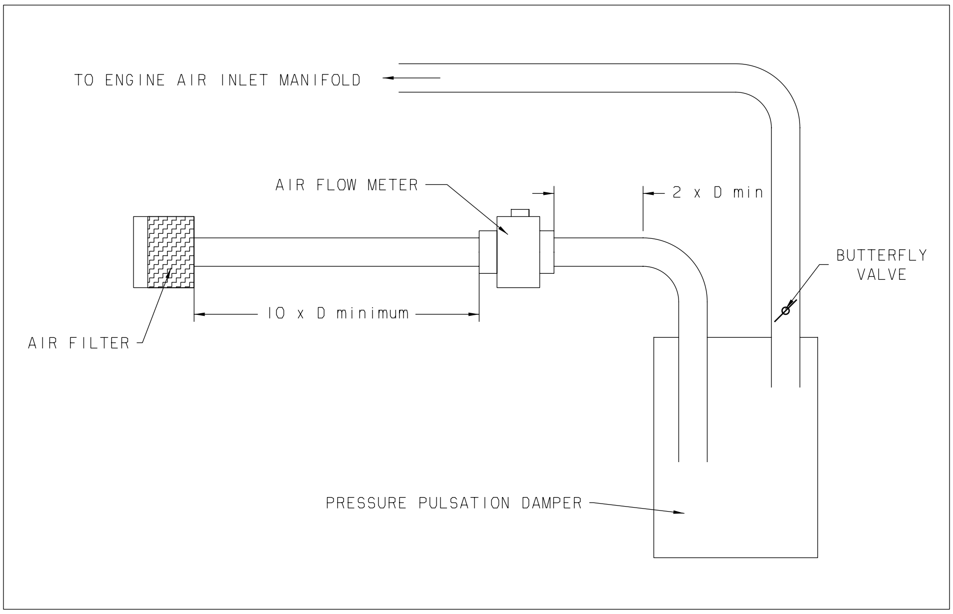
The gaseous pollutant mass is determined using continuous measurement of the volumetric concentration of the species in the total flow. The mass of the species over the course of a transient cycle is given by, using HC as an example:

$$HC_{mass} = \sum_{i=1}^{n} \frac{(HC_e)_i}{10^6} \times (V_{mix}) \times (Density_{HC}) \times \Delta t$$

Where $(HC_e)_i$ is the instantaneous concentration of HC measured by the HFID analyser in ppm C_t, (V_{mix}) is the instantaneous total dilute exhaust gas flow at STP conditions, density is the density of the average HC in C_t equivalent, and Δt is the time interval, usually one second. The hydrocarbon concentration needs to be corrected for the time lag of transport time of the sample to the analyser and the actual analyser response time (usually <2s), so as to correlate the concentration with the instantaneous flowrate. This procedure (as per CFR 40 part 86.1342-90) not only gives a total mass of each pollutant species analysed for the whole transient cycle, but also the second by second mass flowrate of each pollutant species, enabling the high emission episodes to be identified.

- Engine air flow measuring system - AC Rochester, Hot wire anemometer and associated data collection system. The air flow meter(s) were sourced from Holden Commodore VS engine and have the capability to measure accurately up to 240 g/s per meter. The overview of the physical parts of the system is shown in Figure 4.

Figure 4 - Air Flow Measurement



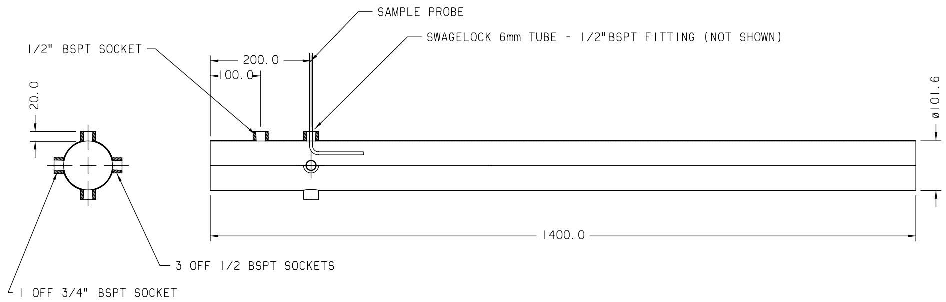
Particulate emission measurement requires either air flow or fuel flow to be measured together with exhaust gas composition determination.

The fuel mass flow measurement system as installed in the engine test laboratory is unable to respond accurately under transient test cycle conditions.

However the AC Rochester, hot wire anemometer is well suited for this purpose, exhibiting a response time to final value within 150msec.

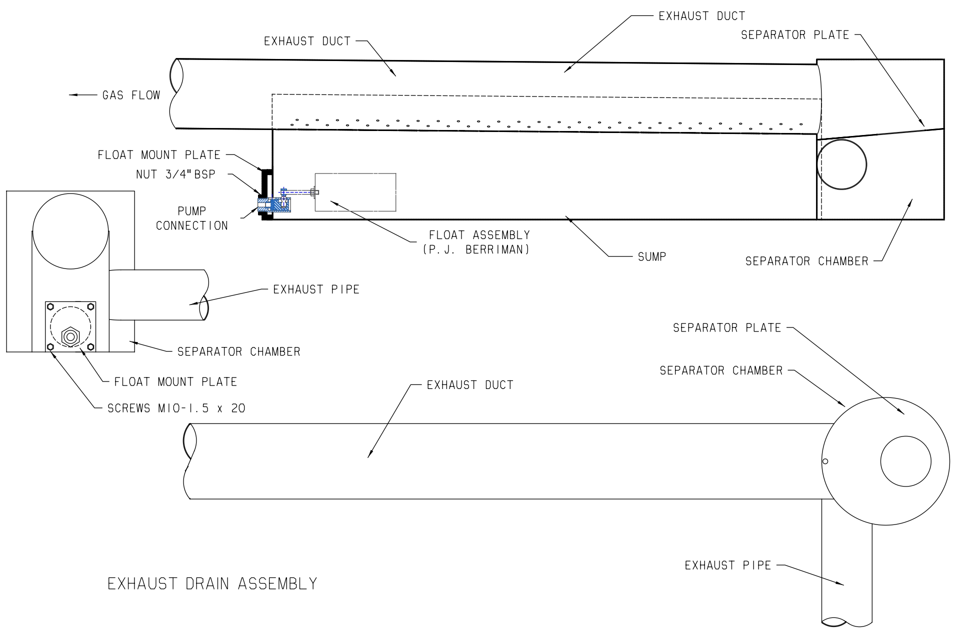
- Exhaust sample pipe for instruments under test (IUT) - A 100mm dia section of the exhaust system was replaced by a sample pipe shown in Figure 5. The four 1/2" BSPT sockets accept the probes from the various IUT's and the elemental carbon analyser and the single 3/4"BSPT socket is for the NIOSH probe.

Figure 5 - Sample Pipe



- Water separator - the dilution tunnel copes well with the water quantity normally found in exhaust gases. However, use of the scrubber generates excessive quantity of water and it was considered prudent to remove as much of this excess water as possible. A simple cyclone/separator was designed, manufactured and installed at the lowest point of the exhaust system. 6 shows the internal arrangement of the float valve which is connected to an external diaphragm pump.

Figure 6 - Water Separator



In addition to the above, the following items of equipment were utilised to measure exhaust condition and/or record collected data:

- Mobile laboratory - for the measurement of CO, CO_2, HC, NO_x and O_2 supplied and operated by the Mine Safety Unit, Dept of Primary Industries.
- R&P Elemental carbon analyser - supplied by BHP Billiton Illawarra Coal and operated by Coal Mines Technical Services.

- Data collection - It was not possible to consolidate the data collection and analysis systems into one coherent unit and therefore individual data acquisition units and their respective computers were utilised. This had some repercussions on post processing of the data. The system consisted primarily of:
  - Datataker D500 logger for the collection of low data rate engine data. Labview was used to control the logger.
  - Datataker D800 for the collection of high data rate engine and TEOM data. Labview was used to control the logger.
  - Datataker D500 for the collection of IUT data.
  - Datataker D500 for the collection Mobile lab data.
  - Campbell logger for collection of the dilution tunnel data. This logger forms part of the computer based controller and the data was extracted from the controller computer to a PC via RS232 interface. Labview was used to control the transfer of data.

Appendix 2: Operation

Particulate measurement using a full flow CSV tunnel is relatively simple and is described in Appendix 1. However the project's need to evaluate various instruments (IUTs) located near the engine exhaust outlet resulted in a deparure from the usual method of particulate emission determination due to:

- Exhaust composition measured upstream of the scrubber;
- Presence of exhaust scrubber as part of engine exhaust;
- Undiluted exhaust drawn from sample pipe to IUT dilution system;
- IUTs data output as mg/m3; and,
- Duration of sampling period.

Figure 7 - DPM project gas flows - shows the exhaust flow through the test equipment. All the gas flows throughout the system were calculated on both wet and dry mass basis. Where measurements were conducted on a volumetric basis at STP, i.e. the dilution tunnel flows, they were converted to mass basis. Conversely where a result was required to be on a volume basis this was converted using the molecular weight of the sample and STP.

The operation of the various sections is briefly described below:

Engine

For the purposes of this project the engine was used as a diesel particulate matter (DPM) generator. The applied engine load and air inlet throttling were adjusted to obtain the required level of DPM emissions as set out in the Test Procedure section.

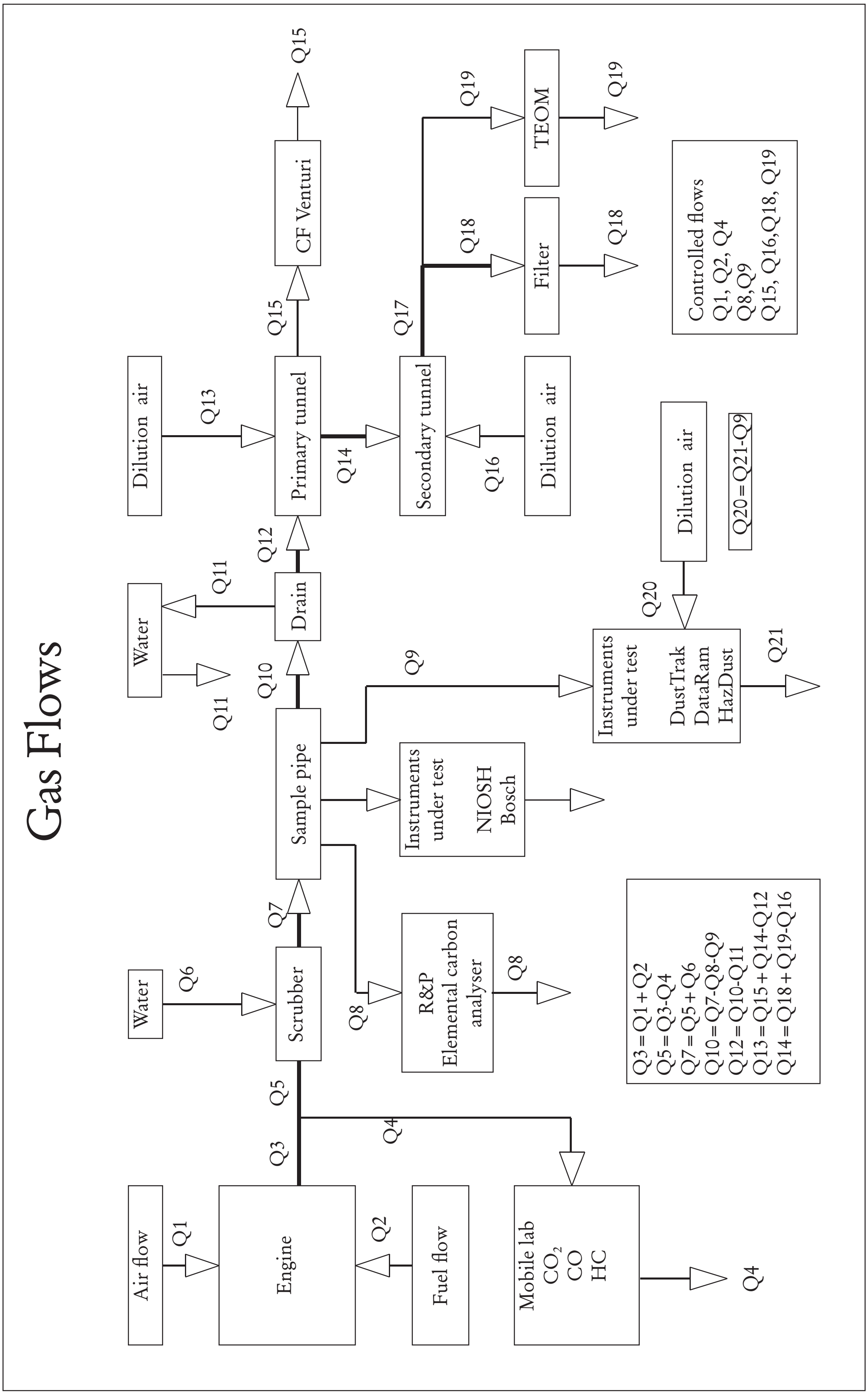
The raw exhaust gas (prior to entering the scrubber) was sampled by the Mobile Lab analyser (Q4) to determine THC, CO, CO_2 and NO_x which in turn were used to calculate the fuel flow. The fuel (Q2) and air (Q1) flows were then used to calculate both the mass and composition, wet and dry, of the exhaust (Q3).

Scrubber

It was assumed that, in the instances where a scrubber was installed and operational, the exhaust out of the scrubber (Q7) was saturated i.e. 100% humidity at the scrubber temperature.

Sample pipe

The quantity of water contained in the exhaust gas within the sample pipe and "condensed water", if any, was determined according to the sample pipe temperature and the quantity of water present in the exhaust upon leaving the scrubber.


Gas Flows
Air flow
Q1
Engine
Q2
Fuel flow
Mobile lab
CO_2
CO
HC
Q4
Q3
Q4
Q5
Water
Q6
Scrubber
Q7
Q8
R&P
Elemental carbon
analyser
Q8
Sample pipe
Instruments
under test
NIOSH
Bosch
Q9
Instruments
under test
DustTrak
DataRam
HazDust
Q21
Q20
Dilution air
Q20=Q21-Q9
Q10
Drain
Water
Q11
Q11
Q12
Dilution air
Q13
Primary tunnel
Q14
Secondary tunnel
Q16
Dilution air
Q15
CF Venturi
Q15
Q17
Q18
Filter
Q18
Q19
TEOM
Q19
Controlled flows
Q1, Q2, Q4
Q8,Q9
Q15, Q16,Q18, Q19
Q3=Q1+Q2
Q5=Q3-Q4
Q7=Q5+Q6
Q10=Q7-Q8-Q9
Q12=Q10-Q11
Q13=Q15+Q14-Q12
Q14=Q18+Q19-Q16

- R&P Elemental Carbon Analyser was supplied directly from the sample pipe (Q8) via a heated line at 180°C which is significantly higher than the sample pipe temperature of approximately 65°C. (Only applies to engine operation with scrubber).
- The NIOSH and Bosch instruments sampled directly from the sample pipe with no sample preconditioning such as drying or dilution by ambient air.
- The three light scattering instruments (DustTrak, DataRAM and HazDust) required sample (Q9) drying and dilution with ambient air (Q20).

Drain

The drain was placed at the lowest position of the exhaust system to remove any free (condensed) water (Q11) from the system prior to dilution with ambient air in the primary dilution tunnel.

Primary dilution tunnel

The flowrate of dilute exhaust gas out of the primary tunnel (Q15) is known at any time through the measurement of temperature and pressure at the inlet to a calibrated critical flow venturi of known flow characteristics. The instantaneous mass flowrate is given by:

$$m_{Q15} = K_V \frac{p_i}{\sqrt{T_i}} \cdot \rho_{STP}$$

Where K_v is the Venturi coefficient, and p_i and T_i are the instantaneous absolute pressure and temperature at the inlet to the venturi and ρ_{STP} is the density of the dilute gas mixture at standard temperature and temperature (20°C, 101.3 kPa).

The flow through the venturi is significantly higher than that from the exhaust, with the difference being made up by the dilution air (Q13=Q15+Q14-Q12)

Secondary dilution tunnel

The particulate sample (Q14) drawn from the primary tunnel is mixed with ambient air (Q16) and is set by a combination of three mass flow controllers (Q16, Q18 and Q19). The mass flow controllers for the dilution air (Q16) and filter (Q18) flows are driven by an input signal proportional to the flow through the primary dilution tunnel as measured by the venturi. The TEOM controller only sets the sample flow (Q19) through the instruments and remained constant throughout the testing period. Thus the particulate sample flowrate is approximately proportional to the flowrate through the primary tunnel at all times.

At the end of a sampling period the masses of dilute exhaust mixture that has flowed through the primary dilution tunnel, and the amounts that have flowed through the secondary tunnel, particulate filters, TEOM and the sampling period are known. The particulate filters are conditioned back to standard conditions, and the mass of particulate material collected on them determined by weighing on precision balances.
The total amount of particulate per second emitted by the engine at the outlet of the scrubber through the test is then given by:

$$M_{p(Q7)} = \frac{P_e}{t} \times \frac{m_{Q17} \times m_{Q7}}{m_{Q18} \times m_{Q14}}$$

Where:

m_{Q17} = the dry mass of dilute gas per second in the secondary tunnel
m_{Q18} = the dry mass of sample passed through the particulate filters
m_{Q14} = the dry mass of the sample drawn from the primary tunnel per second
m_{Q7} = the dry mass of exhaust per second at the outlet of the scrubber
P_e = the mass of particulate collected on the filter
t = the sampling period in seconds.

This assumes that the dilution air is filtered and does not contribute any significant particulate material.

Particulate filter use and handling

The particulate mass was collected by a pair of filters, a 70mm dia main and 47mm dia backup (A and B respectively).

The procedure adopted for handling, conditioning and use was:

- Each pair of filters was conditioned in a temperature and humidity controlled cabinet at 25°C and 50% RH for an extended period in a covered, but not sealed Petri dish.
- Following conditioning each filter was weighed and its mass recorded. The filters were then placed in the Petri dish in pairs and the dish sealed.
- The filters were carefully handled to and from the Petri dish when required for testing. The dish was sealed immediately after use and returned to the weighing station.
- At least one pair of filters was used during each test mode. A sample of the double diluted exhaust was drawn through the pair of filters arranged in series with the B filter collecting the particulates. Filter A served as a backup and ideally should not have collected any of the sample particulates.
- The duration of the test filter's PM loading was, in the main, determined by pressure drop across the filter (25-35kPa). When this duration was such that a second filter pair could be installed and loaded to the same extent within the allocated time then a second test was performed and the two results averaged.
- Following the test the filters were placed back in the Petri dish and sealed.
- At the weighing station the Petri dish was unsealed and the filters placed in the temperature and humidity cabinet for a minimum of 4 hrs.
- Each test filter was weighed three times at differing times and the mass recorded.

In addition to the test filters a reference pair of filters was kept in the controlled environment cabinet under identical conditions as the test filters. These reference filters were weighed concurrently with the test filters and were therefore weighed four times in total.

Appendix 3: Test Procedures

Test protocols

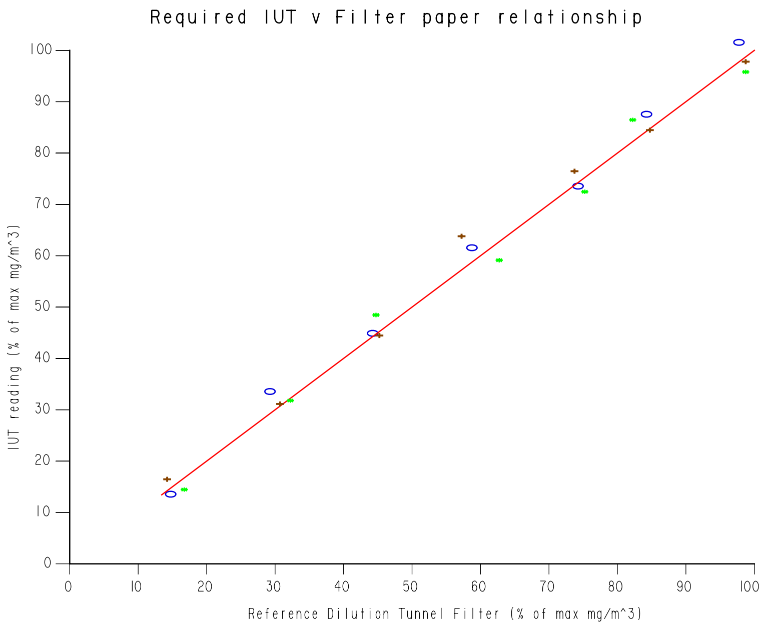
The project need was to evaluate the IUTs using an acceptable test procedure and then to apply that procedure to field testing without use of additional equipment.

The program thus required two separate approaches to determine the test protocols to be applied:

- Assess the performance of each IUT against an appropriate reference particulate measurement under steady state conditions; and,
- Develop suitable steady and transient state test procedures to be applied in both engine dynamometer assessment and field testing.

IUT performance assessment - steady state

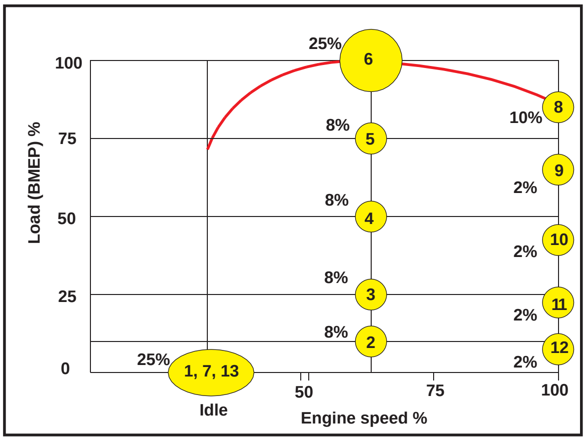
To establish the relationship between the IUT and the reference it is only necessary to consider the engine as a particulate generator. The reference particulate measurement is that collected on a filter paper using a dilution tunnel complying with one or more ISO, US or ECE standards/regulations/ directives and the desired ideal relationship is shown in Figure 8.



Several established steady state drive cycles were assessed for suitability to provide the required relationship however none of these met the criteria. These comprised:

- ECE R49 - Steady state cycle for heavy duty truck engines. Consists of a sequence of 13 engine dynamometer test modes. Used for heavy-duty engine emission certification before the year 2000. It is also applicable to Australian Design Rule (ADR 70/00). Shown in Figure 9 - ECE R49.

Figure 9 - ECE R49

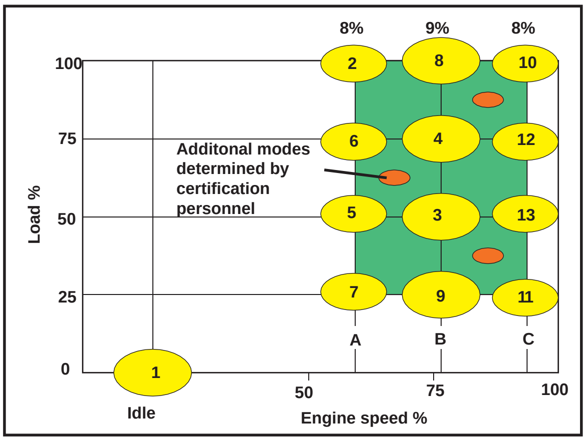


- US EPA (13 mode)- This steady state cycle is no longer used, it was superseded by the FTP Transient Cycle. Also known as SAE Recommended Practice J1003, "Diesel Engine Emission Measurement Procedure. Very similar to ECE R49 but uses different weighting factors.

- ISO 8178 - A steady state engine dynamometer test comprising several test modes applicable to selected non-road engine applications. Similar to ECE R49.

Figure 10 - ESC

- ESC (OICA) - New steady - state cycle for truck and bus engines. Effective year 2000 the ESC test is used for emission certification of heavy-duty diesel engines. Similar to ECE R49 but includes additional speed setting. Shown in Figure 10 .

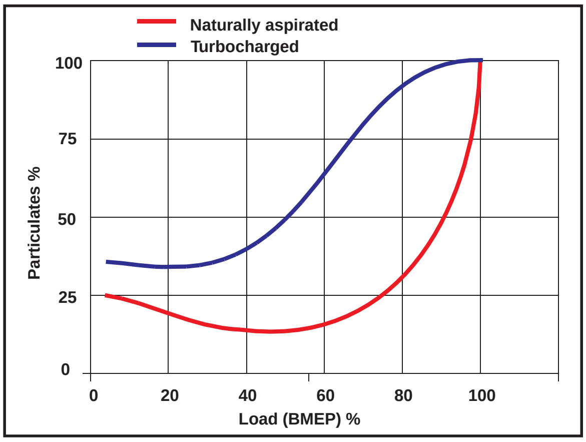


In general, the majority of particulate emissions for a naturally aspirated engine occur within the top 20% of the torque range and a typical PM emission versus Load (BMEP) is shown in Figure 11. It should be noted that max BMEP occurs at max torque.

In the case of a turbocharged engine the drop off in PM emission is more gradual with reduction in BMEP but it must be recognised that the maximum PM emission is significantly lower than that from a naturally aspirated engine.

Analysis of the relationship of PM v BMEP indicated that the PM emissions were sensitive to the combustion excess air leading to the development of steady state test procedure that met the requirements of IUT evaluation.

Figure 11 - PM Emission v BMEP



Mine Safety Unit (MSU) Test Procedure (engine dynamometer)

The test procedure's main purpose was to generate equally spaced PM emissions as shown in in order to evaluate the IUT's response to a wide range of PM emissions.

The underlying test protocol was the same as that used for several of the steady state test procedures e.g. ECE R49, EPA 13 mode, ISO 8178 and ESC. Thus test equipment, PM measurement, engine conditioning, etc. were identical, with the main differences being limited to:

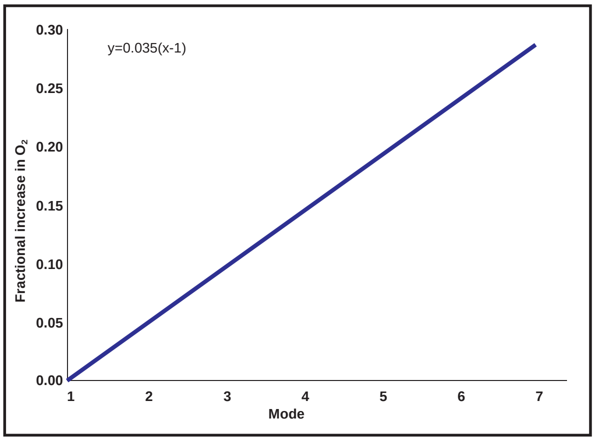
- Air inlet throttling - the engine was considered purely as a PM generator and throttling of the air intake is a way of representing in-service maintenance problems such as blocked air filters and/or overfuelling.

  Throttling was achieved by means of a throttle plate installed at the outlet of the pressure damper and the degree of throttling determined by the percentage of CO_2 in the exhaust. The method adopted for setting the throttle was to measure CO_2 without throttling and then gradually close the throttle plate to increase the CO_2 by approximately 5%. Care was taken not to allow excessive air inlet depression and at the same time maintaining max power output.

- Selection of test modes - The use of test modes, such as those specified in ECE R49, would result in an undesirable proportion of test results falling within the low emission range and therefore the use of these modes was considered inappropriate.

However, it was noted that a relationship existed between excess oxygen and emissions of PM

Figure 12 - Mode factors



emission and this relationship at maximum torque speed is shown in Figure 12.

The excess oxygen setting for each mode, with the exception of the mid speed idle, was calculated according to the following:

$$O_M = O_{(M-1)} * (1+0.0354*(M-1))$$

where O = Excess oxygen %

M = Mode number

Figure 13 depicts the resultant mode selection, note the congestion of the modes at the high loads (BMEPs) and the isolated medium speed idle mode.

A typical result (corrected Cat 3306D) is shown in Figure 14 .

Figure 13 - MSU Test Modes

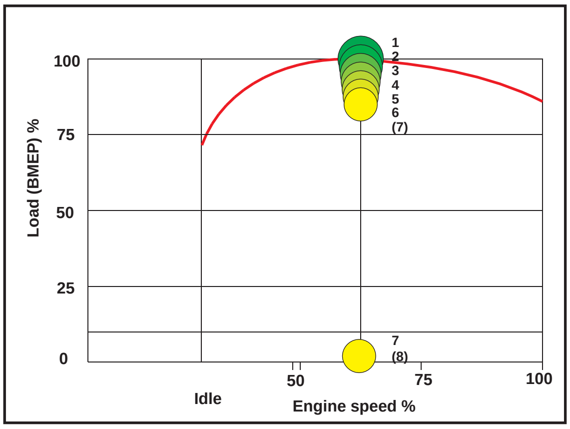
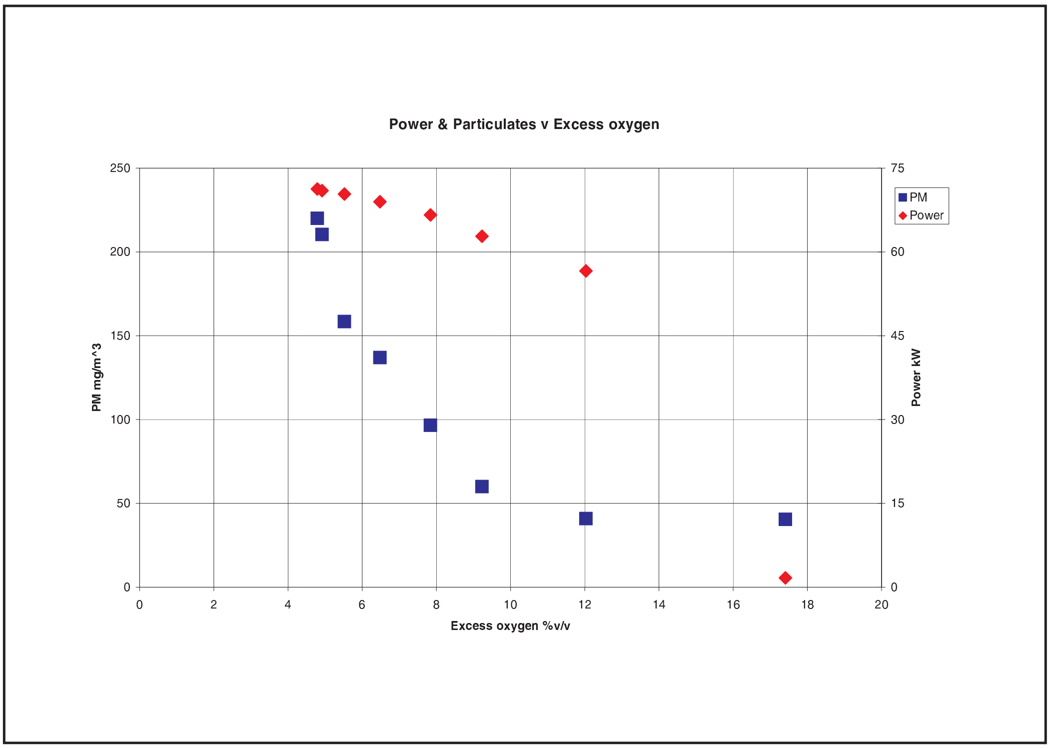


Figure 14 - Caterpillar 3306 (corrected dry data)



- Use of individual filter pairs - at least one pair of filters (main and backup) was used for each test mode compared to the single pair of filters used for all modes when performing testing to ECE R49, EPA 13 mode, ISO 8178 or ESC procedures.

  The duration of the test filter's PM loading was, in the main, determined by pressure drop across the filter (25-35kPa). When this duration was such that a second filter pair could be installed and loaded to the same extent within the allocated time then a second test was performed and the two results averaged.

IUT performance assessment - transient cycle

It was considered advantageous to apply existing test protocols wherever possible however this did not prove to be the case.

The majority of existing diesel engine test protocols to determine particulate emissions were developed for on-road (and limited off-road) applications and not for use with underground mining equipment. These protocols require the use of either an engine or a chassis dynamometer and many are application specific. They range from the fairly complex cycles to relatively simple ones as shown below

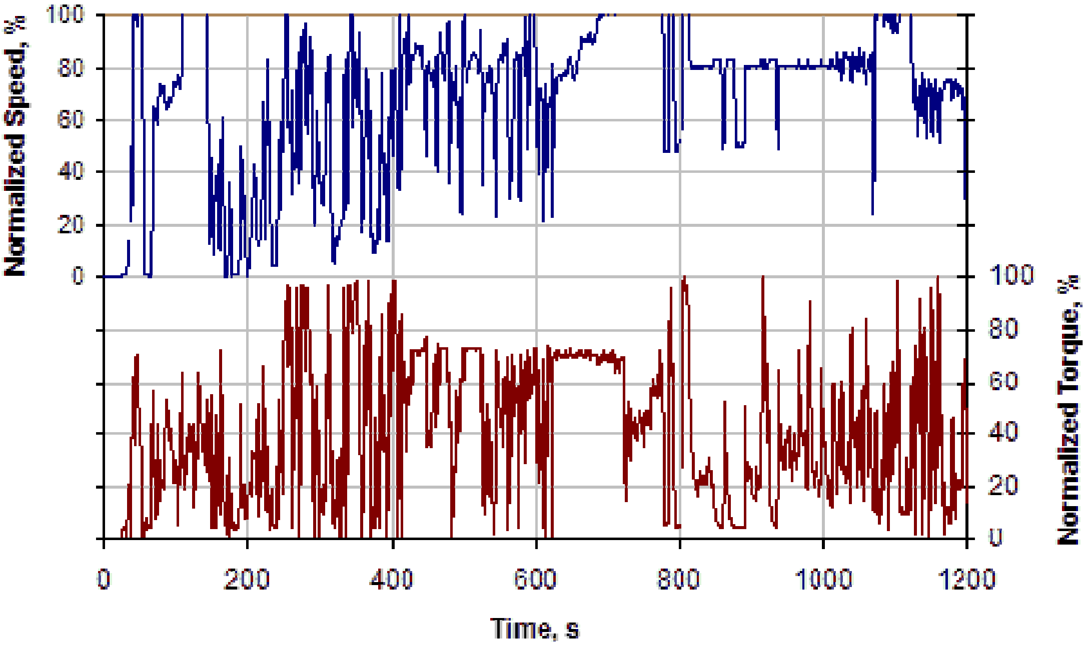
It should be noted that in many cases a test cycle specified for an engine dynamometer can also be carried out on a chassis dynamometer. The converse also applies. In the assessment of the various test cycles engine and chassis dynamometer was used interchangeably.

The following approved engine certification test protocols were considered for the evaluation of the IUTs under transient conditions:

Complex transient test cycles

- Nonroad Transient Cycle (NRTC), Figure 15 - A transient engine dynamometer cycle for mobile nonroad engines, to be used for engine emission certification/type approval in the USA and in European Union.
- FTP Transient - A transient engine dynamometer cycle for heavy-duty truck and bus engines. Used for emission certification testing of heavy-duty diesel engines in the USA.
- ETC (FIGE Transient) - New transient cycle for truck and bus engines. It is used, together with the ESC, for heavy duty engine emission certification. Also applicable to ADR 80/00 (01).
- UDDS - (Urban Dynamometer Driving Schedule)- EPA transient test cycle for heavy duty vehicles.

Figure 15 - Example of Complex Transient Test Cycle (NRTC)



The above transient cycles are incorporated in emission regulations. The following cycles were developed to meet various local conditions:

- CSVL - Constant speed, variable load transient test cycle developed by the US EPA. Not used in emission regulations;
- CTA - Chicago Transit Authority - Chassis dynamometer cycle;
- CSC (City Suburban Cycle) - Chassis dynamometer test cycle;
- NYB - New York Bus Chassis dynamometer test cycle;
- Manhattan Bus Cycle- Chassis dynamometer test cycle;
- Orange County Bus Cycle - Chassis dynamometer test cycle
- Braunschweig Cycle - Chassis dynamometer test cycle.

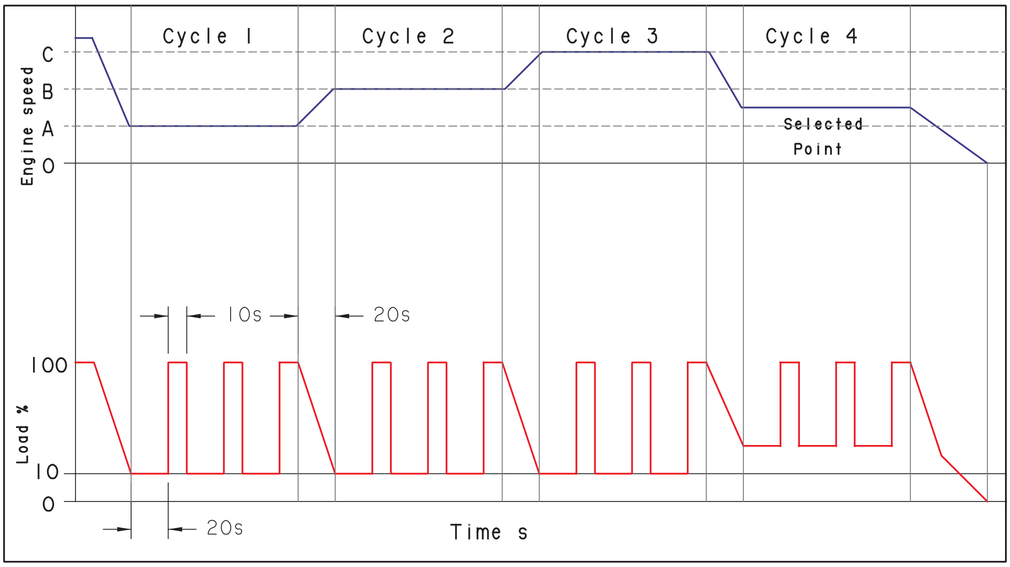
The limitations imposed by the available test equipment (engine dynamometer) and field test conditions excluded the adoption of above test cycles.

Simplified transient test cycles

The following transient emission test cycles were considered to be suitable for use with existing engine dynamometer:

- ELR - Effective year 2000, the ELR test is used for smoke opacity determination during emission certification of heavy-duty diesel engines. Also applicable to ADR 80/00 (01).

Figure 16 - ELR Transient Cycle



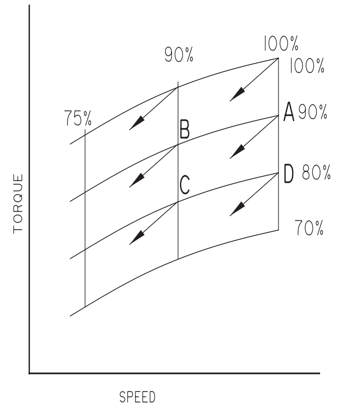
- ECE+EUDC (NEDC) - A chassis dynamometer test used for emission testing and certification in Europe. It includes four ECE 15 Urban Driving Cycles, simulating city driving, and an Extra Urban Driving Cycle (EUDC), simulating highway driving conditions. Also applicable to ADR 80/00 (01);
- WVU- (West Virginia University) -Chassis dynamometer test cycle;
- AVL 8- Mode Heavy-Duty Cycle - A steady-state test designed by AVL to correlate emissions with those measured over the US FTP Transient test;
- BAC (Business Arterial Commuter - Chassis dynamometer test fuel economy cycle; and,
- CBD (Central Business District) - Chassis dynamometer transient test cycle.

All the cycles considered so far exhibit a need to have variable speed and load control. Although this is relatively easy to achieve on engine and chassis dynamometers it is virtually impossible to do so in field testing.

Further assessment was made of a number of "old" - i.e. the first ones that were thought of - acceleration and torque stall cycles. Field emission testing to date consists only of some form of steady state "torque stall" measurement and this will continue into the future. However it was deemed necessary to incorporate some form of transient test in order to deal with turbocharged engines and to establish IUT performance under these conditions.

One shot transient test cycles

Figure 17 - Free Acceleration



- ADR 30/01 Free acceleration -This is probably one of the oldest methods used for assessing exhaust PM emissions without the use of dynamometers or other means of applying a load. The free acceleration visible pollutants shall be measured with the engine at the maximum rated speed and maximum power condition. shows the measuring points when derating an engine, each measuring point governs the power and speed area to the left and below that point.

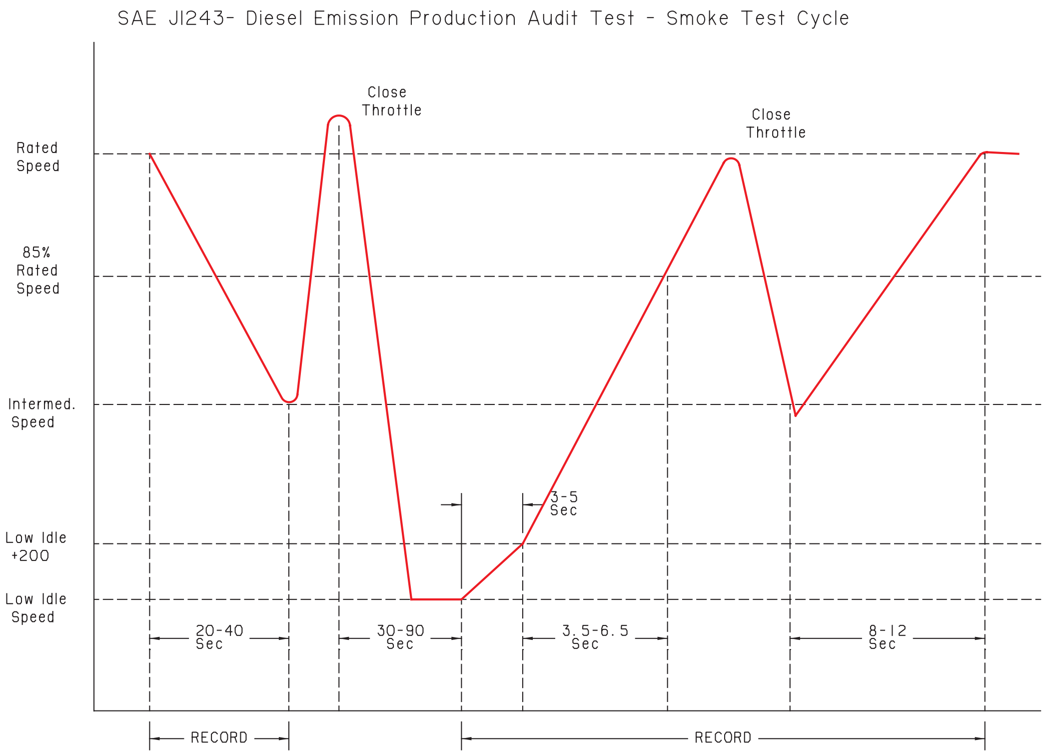
  An opacimeter is generally used to measure PM.

  With the engine idling, the accelerator control is operated quickly so as to obtain maximum delivery from the injection pump. This position is maintained until maximum engine speed is reached and the governor comes into action. As soon as this speed is reached the accelerator is released until the engine resumes its idling speed and the opacimeter reverts to the corresponding conditions.

- SAE J1243 Diesel Emission Production Audit Test Procedure - Smoke Test Cycle. Although designed primarily as part of a short production dynamometer test procedure the smoke test cycle can be adapted for full "free" acceleration or "torque stall" maximum power.

- SAE J35 Smoke Measurement Procedure - This procedure was designed for the assessment of transient smoke emissions utilising an engine dynamometer. Similar in characteristics to SAE J1243 it is an easier procedure to adapt to field testing using "torque stall" speed as the "rated" speed.

Figure 18 - SAE J1243



- Mine Safety Unit (MSU) Transient Test Procedure - The procedure consists of four individual cycles shown in Figure 20. Each cycle consists of the following basic steps:

  1. Set dynamometer to maximum torque at intermediate speed equivalent to torque stall speed of intended application. This is generally close to peak torque speed of the engine.
  2. Idle for 30 seconds with throttle closed.
  3. Open throttle fully for 10 seconds or until intermediate speed is reached.
  4. Return throttle to idle position for 5 seconds.
  5. Open throttle fully for 30 seconds while maintaining maximum torque attainable at the intermediate speed. This time limitation is imposed to minimise torque converter temperature rise during field testing.
  6. Return throttle to idle position for 45 seconds.
  7. Repeat the above steps further three times. Record maximum, minimum and average instrument reading for each cycle.

Figure 19 - SAE J35

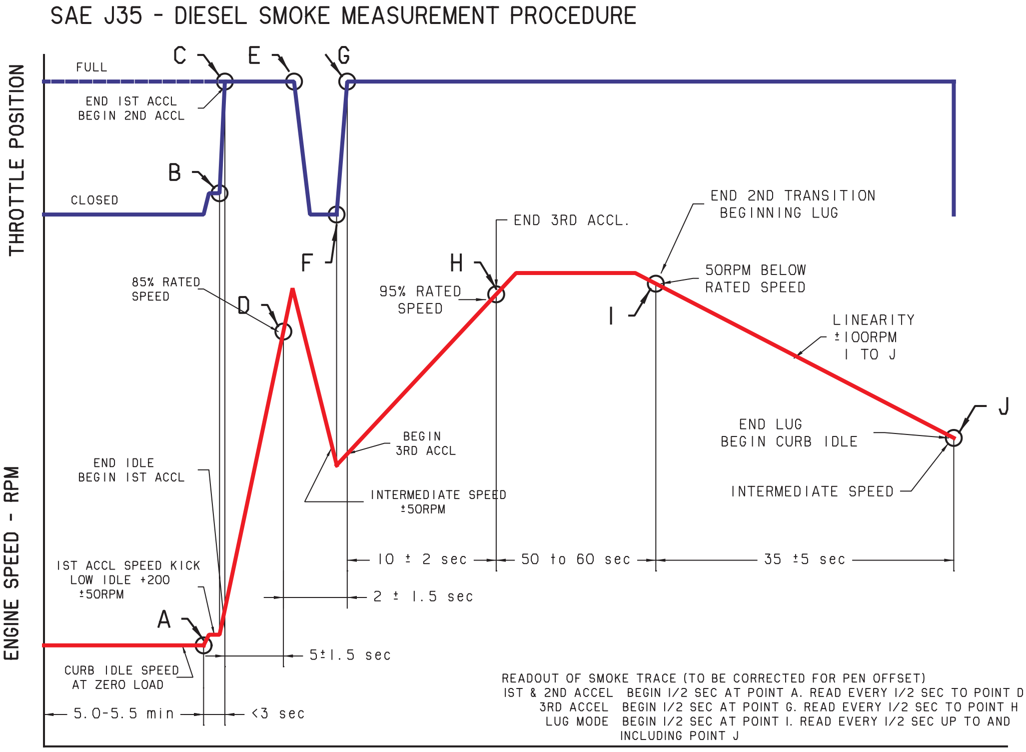


Figure 20 - MSU Transient individual test cycle

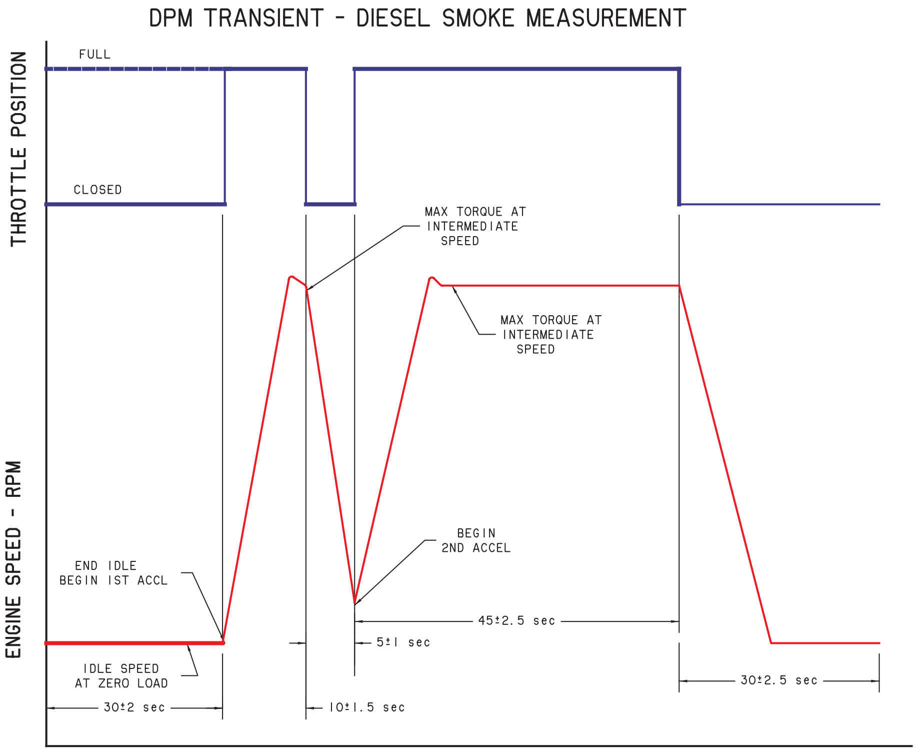
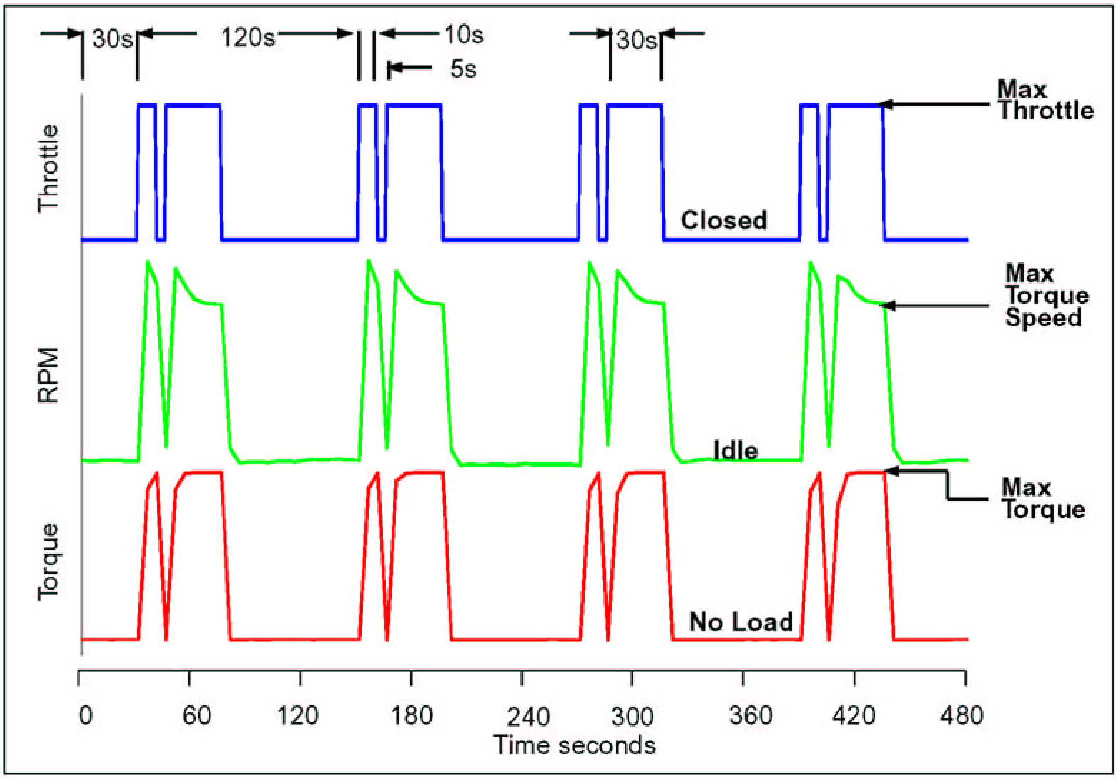


Figure 21 shows the typical transient test with the load and speed achieved on an engine dynamometer. Please note the overshoot of engine speed towards the end of the acceleration phase. This overshoot is not likely to occur during field testing due to the differing dynamometer and torque converter characteristics.

Figure 21 - Recorded dynamometer transient (MSU)



Appendix 4: Instrumentation and data acquisition

The instrumentation and data acquisition system used for the project can be conveniently divided into the following areas:

- Engine performance;
- Raw exhaust emissions (prior to scrubber);
- Dilution tunnel gas flows; and,
- "External" particulate measuring instruments

Engine performance

Parameters critical to the evaluation of the IUTs are limited to:

- Air flow;
- Barometric pressure;
- Ambient temperature;
- Ambient RH; and,
- Fuel flow.

These, together with the C/H ratio of the fuel, determine the mass of exhaust entering the particulate measuring system and were measured and collected at the specified data acquisition rate.

All other parameters being used for either setting up, engine control, safety and housekeeping issues were also collected:

- RPM;
- Torque;
- Boost pressure;
- Intake air temperature;
- Inlet restriction;
- Oil pressure;
- Exhaust pressure;
- Exhaust out temperature; and,
- Coolant temperature.

The data was collected by means of two Datataker data loggers, a D800 and a D500 model.

D800 - This model is capable of higher data acquisition rates than the D500 and was used to achieve the required 10Hz rate for a number of data during transient testing. However it was found that significant data dropouts occurred at the 10Hz rate and this was reduced to 5Hz in later tests.

Engine data collected at the 10Hz (5Hz) rate was:

~ Engine speed (RPM);

~ Torque (Nm);

~ Air flow 1 (g/s);

~ Air flow 2 (g/s); and,

~ Sample pipe temperature (ºC).

Engine data collected every 20 seconds was:

~ Sample pipe temperature (°C);

~ Engine air IN barometric pressure (bar);

~ Engine air IN ambient air temperature (°C); and,

~ Engine air IN relative humidity (RH %).

Housekeeping data consisted of:

~ Date/Time (dd/mm/yyyy) hr:min:sec);

~ Offset (in tenths of a second);

~ Schedule (A for 10Hz (5Hz), B for 20second period); and,

~ Synchronising signal (V)

The D800 datalogger was also used to collect some data from the dilution tunnel and TEOM. These are listed in the Tunnel Gas Flows section. The synchronising signal is a 1.5V step signal manually generated for all steady state test (or 120 seconds on/120 seconds off for the transient tests) when the operator decides that test conditions have been met and are considered valid. It is connected to a spare channel on each datalogger with the exception of the Campbell datalogger.

D500 - This datalogger forms part of the standard engine dynamometer setup and in this instance serves mainly in a "housekeeping" role as well as providing some duplicate information. The following data was collected at 5 second intervals:

Information used in further analysis:

~ Date/time;

~ Primary tunnel dilution air barometric pressure (bar);

~ Primary tunnel dilution air temperature (°C);

~ Primary tunnel dilution air relative humidity (RH%); and,

~ Synchronising signal (V)

"Housekeeping" information

~ Engine speed (RPM);
~ Engine torque (Nm);
~ Oil pressure (kPa);
~ Boost pressure (kPa);
~ Air inlet restriction (kPa);
~ Exhaust pressure (kPa);
~ Fuel flow (g/s);
~ Inlet air temperature (°C);
~ Exhaust temperature (°C); and,
~ Coolant temperature (°C).

Raw exhaust emissions

The Mobile Lab was used for the analysis of the raw exhaust stream upstream of the scrubber and collect the data required in calculations of fuel flow, gas flow and molecular mass. The data was collected at 2 second intervals using a Datataker D505 datalogger and consisted of:

~ Date and time
~ Barometric pressure (bar)
~ CO_2 (%)
~ CO (%)
~ CO (ppm)
~ NO_x (ppm)
~ O_2 (%)
~ HC (ppm)
~ Synchronising signal (V)

Dilution tunnel

A Campbell Scientific Datalogger monitors all the temperatures and records and totalises the flowrates through the tunnel at 1 second intervals. In addition, the datalogger monitors the total primary tunnel flow and sets the mass flow controllers to achieve the required sample flow rate and dilution within the secondary tunnel. The dedicated computer used to control the tunnel operation, in conjunction with the datalogger, proved unsuitable to record the collected data and the following data was therefore transferred to another computer via a RS232 interface:

~ Internal synchronising signal for filter flow (value);
~ Primary tunnel flow (m^3);
~ Secondary tunnel sample flow (L/min);
~ Secondary tunnel dilution air flow (L/min);

- ~ Filter flow (L/min);
- ~ Primary tunnel temperature (°C);
- ~ Secondary tunnel temperature (°C);
- ~ Critical Flow Venturi temperature (°C);
- ~ Critical Flow Venturi pressure (kPa);
- ~ Cumulative volume through primary tunnel (m3);
- ~ Cumulative sample volume (L);
- ~ Elapsed time for cumulative volumes (s)
- ~ Julian day;
- ~ Time (hr);
- ~ Time (min); and,
- ~ time (s)

No synchronising signal was used due to lack of available channels, however the computer clock was reset to correspond to that serving the D800 datalogger.

The TEOM is installed as part of the dilution tunnel however it is not included within the tunnel control or data collection system. Attempts were also made to utilise an AVL opacity meter but proved unsuccessful due to the extent of water vapour within the exhaust stream. Unused channels in the engine D800 datalogger were therefore utilised to collect the following data:

- ~ TEOM mass rate (mg/sec);
- ~ TEOM concentration (mg/m^3);
- ~ TEOM total mass collected during test (mg);
- ~ Opacity meter %; and,
- ~ Exhaust temperature at dilution tunnel entry.

"External" particulate measuring instruments (IUT)

The test instruments under evaluation were connected to a separate D500 Datataker with the following data recorded:

- ~ Date and time;
- ~ DustTrak (mg/m^3);
- ~ DataRam (mg/m^3);
- ~ HazDust (mg/m^3); and,
- ~ Synchronising signal (V)

The HazDust's analogue output was incompatible with the Datatakers input resulting in no valid data being available for further processing. However the manually recorded data was later inserted into the final data analysis sheet. The Hazdust output could, however, be captured using a single channel digital voltmeter with an RS232 interface and this was recorded as output voltage in a separate file. Where available this was used in the presentation data.

Manual data collection

In addition to the above "automated" data acquisition process much data was generated in other areas as part of the evaluation program and was recorded manually. This was later entered into the data analysis stage and consisted of:

- Dilution tunnel
  - ~ Filter ID
  - ~ Filter weights (g)

- DustTrak, DataRam, HazDust
  - ~ Dilution air flow for each instrument(L/min);
  - ~ Total flow (sample + dilution air) flow for each instrument (L/min);
  - ~ Measurement duration (sec);
  - ~ Time between measurements (sec);
  - ~ Test start time (hr:min:sec) for each instrument; and,
  - ~ Instrument panel display (max, min, average mg/m3)

- Other instruments
  - ~ Bosch Smoke Numbers (BSN);
  - ~ R&P Elemental Carbon analyser - (OC, TC, EC mg/m3 and flow L/min);
  - ~ NIOSH PM meter (Pressure P "WG and dP "WG/min); and,
  - ~ Start and stop times for Bosch, R&P and NIOSH tests (hr:min:sec).

Appendix 5: Data Preparation

The data as collected from the various dataloggers was found to be unsuitable for analysis of engine and test instrument performance and required massaging in one or more of the following areas:

- The data formats used in each datalogger differed from each other and were "standardised" to a common format (csv);
- The time recorded by each datalogger differed and the data required to be synchronised using the external "sync" signal (no "sync" signal was recorded by the dilution tunnel datalogger);
- Several test stages were recorded within one file and a number of duplicate records were created. The file type may have been in csv, dat or "screendump" format.
- The data required to be "topped and tailed" according to the timing of tunnel operation, manual time entry and the "sync" signal;
- Different dataloggers used different sampling frequencies (datalogger limitations) and it was preferable to generate the "missing" data by simple interpolation rather than use the average value;
- A data integrity check for missing data and "noise spikes" was made; and,
- Data columns needed to be identified and units specified.

Brief process description

The process to perform the above manipulation varied significantly from datalogger to datalogger. Initially much of the preliminary data manipulation was performed using a word processor however subsequently only the dilution tunnel data was done in this manner. All other data was reformatted in various Excel templates. Generally the data for further processing needed to be in the following format:

- Single data file for each mode in Excel format;
- All data to be available at 1 second intervals;
- Invalid or non existent data needed to be identified, corrected and regenerated;
- File length "topped and tailed" according to timing table; and,
- Recorded time to be adjusted to reference time (according to the differences in synchronising signal to that of the D800 datalogger).

Following the above data manipulation each template was saved as "values only" comma separated file (XX.csv).

A more detailed description is given below:

Mobile Laboratory

The Mobile Lab data log was one of the more simple to adapt for further analysis. It was recorded at 2 second intervals as one continuous file spanning several test modes and was processed in several steps within the one template:

- ML file imported into Excel as a XX.dat (comma seperated) format;
- Column "D" (^v) contained unwanted data and was deleted;
- The varius modes were separated based on start and end times for each mode;
- The selected data range for a given mode was pasted into the ML-Template where:
- Times were adjusted to correspond with the D800 synchronising time;
- Consecutive data was averaged to generate additional data at 1 second interval; and,
- The resulting data block was then copied to the data analysis Excel spreadsheet.

Datataker D800

The Datataker D800 proved to be the most difficult to handle, however the initial processing was similar to that of the Mobile Lab:

- D800 log file imported into Excel as a XX.csv (comma seperated) format;
- The varius modes were separated based on start and end times for each mode; and,
- Schedule A and B separated into two log files for further processing within individual A and B templates.

Schedule A

Problems encountered and remedies

- ***Date, time and offset***
  - ~ The date and time was separated by space whereas all other data was comma separated (csv); and,
  - ~ Time was output as fraction of a 24hr day with a separate column, Offset, output as fraction of a second.

  A new column was created where a "new time" was generated as seconds since midnight.
- ***Data integrity***

  The D800 was found to be susceptible to noise spikes generated by the engine dynamometer controller mainly during the transient testing.

The procedure adopted was to import the file into an Excel spreadsheet (Table 1, either D800A_Template for steady state or D800A5_Template for transients). In this template the following took place:

~ Max values of each data column were found;

~ If the max values were outside the expected range then a second table (Table 2) was created which located the out of range value and replaced them by values created by simple interpolation of preceding and following values; and,

~ The new table was tested for max values.

- ***Missing data and consolidation***

The D800 tended to miss recording data at the specified interval resulting in incomplete data log. This was more prominent during the early tests prior to reducing the Datataker's averaging sample period.

The missing data was "recovered" in another table (Table 3) based on the VLOOKUP function. The procedure was as follows:

~ Another "Time" column was created having the required time increment, 1 second for steady state, 0.1 (0.2) seconds for transients;

~ The VLOOKUP function was used to create a new table (Table 3) resulting in duplicate values for the missing time interval equal to the nearest lowest time in the "Data integrity" Table 2; and,

~ A new table (Table 4) was created by checking the "Missing" data Table 3 for duplicate data and the duplicate data was replaced by the average of the previous and following data.

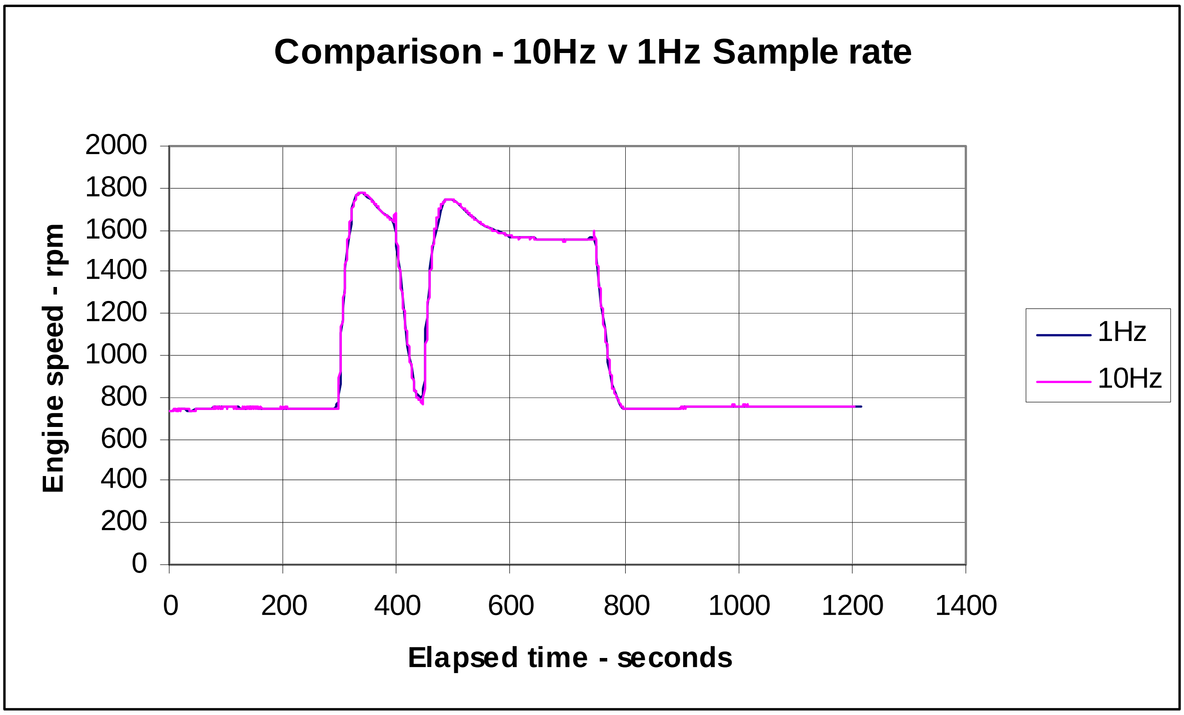
- **Size of data tables**

The spreadsheets became very large, unwieldy and slow. As an example a transient test generated in excess of 20,000 rows. Excel 97/2000 was unable to handle subsequent spreadsheets due to a "bug" and therefore the 10Hz and 5Hz data had to be reduced to 1Hz. Although various regulations specify the 10Hz data acquisition rate the effect of "downsampling" from 10Hz to 1Hz was considered to have negligible effect on the end results. Figure 22 shows the difference in sampling rates as applied to the engine speed (RPM).

~ The "downsampling" was achieved by averaging the previous 10 (5) readings including the elapsed time and forming Table 5 (Average); and,

~ Table 5 contained the averaged data every 10th (5th) row, the in-between rows contained a value of 23:59:59 in the time column and null data in the remainder. The whole of this table was copied as values only to Table 6 where it was sorted in ascending elapsed time order.

Figure 22 - Comparison - 10Hz v 1Hz Sample rate



Schedule B

This schedule was recorded at 20 second intervals in the same log file as Schedule A. The procedure for the preparation for inclusion in the data analysis stage was:

- Schedule B for each mode was identified and copied to an Excel template as Table 1 where:
  - A new "Time" column was created having the required time increment of 1 second;
  - The VLOOKUP function was used to create a new table (Table 2) resulting in duplicate values for the missing time interval equal to the nearest lowest time in Table 1. The new table now contained 20 duplicate entries for each recorded entry; and,
  - Table 3 was now created where the duplicate entries were replaced by interpolated data generated from the recorded entries.

Dilution tunnel

The dilution tunnel data was collected using a Campbell logger and a separate log file was created for each test mode. The data is space delimited and was in the following format:

```
10s17s14ss01+0157.ss02+0.979ss03+0.065ss04+0.534ss05+0.088ss06+20.06ss07+22.29ss08-28.09ss09+20.31ss
10+101.6ss11+0.979ss12+0.012ss13+0.600ss14+0091ss15+1014.ss16+014.7 CRLF
```

where s = space

This was modified in a text editor by simple search and replace functions in three steps:

- Search string 1 = ss** Replace string = comma
- Search string 2 = Space Replace string = colon
- Search string 3 = CRLF Replace string = LF

* = wild card

to produce the data stream in the following format (csv):

```
10:17:14,0157,0.979,0.065,0.534,0.088,20.06,22.29,-28.09,20.31,101.6,0.979,0.012,0.600,0091,1014,014.7LF
```

The data was imported into a template, columns were identified, data was topped and tailed according to its internal sync data and sample volume corrected (the internal datalogger calculations are out by a factor of 10). New time column was created and corrected by manual entry of time difference between the internal and D800 clocks.

D500

- The data in the D500 log was recorded at 5 second intervals and the procedure for the preparation for inclusion in the data analysis stage was handled in similar fashion to the D800 Schedule B data and consisted of:
- Each mode was identified and copied to an Excel template as Table 1 where:
- A new "Time" column was created having the required time increment of 1 second;
- The VLOOKUP function was used to create a new table (Table 2) resulting in duplicate values for the missing time interval equal to the nearest lowest time in Table 1. The new table now contained 5 duplicate entries for each recorded entry;
- Table 3 was now created where:
  - ~ The duplicate entries were replaced by interpolated data generated from the recorded entries; and,
  - ~ New time column containing the D800 reference time was created.

Instruments

This log file data was recorded at 1 second intervals and the procedure for the preparation for inclusion in the data analysis stage was handled in similar fashion to the D800 Schedule A data and consisted of:

- Each mode was identified and copied to an Excel template as Table 1;
- Table 2 with a new "Time" column was created having the required time increment of 1 second and corrected to D800 time;
- The VLOOKUP function was used to create a new table (Table 3) resulting in duplicate values for any missing time interval equal to the nearest lowest time in Table 1; and,
- Table 4 was now created where the duplicate (i.e. missing) entries were replaced by interpolated data generated from the recorded entries.

Timing table (Data synchronisation)

The synchronising signal (approximately 1.6V DC) was recorded on all the dataloggers with the exception of the Campbell logger used for dilution tunnel control. For the initial testing the Campbell computer time was corrected by noting the difference between the logged file time and the D800. Although in subsequent testing the Campbell computer time was adjusted to conform with the D800 time some discrepancies still existed.

A timing table was created listing the manually entered start and stop times for all the test equipment and these were adjusted according to the synchronising signal.

This practice ensured synchronisation of the data on time basis only, no correction was made for delays occuring between the engine, mobile lab analysis, sample pipe or the dilution tunnel. The delays could be quite large, however in the case of steady state tests the changes in exhaust conditions were minor and the effect on the end results considered negligible. The most noticeable effect of any delay should have been detected during transient testing but even here the repeatability of each of the cycles was such that the net effect was also negligible.

Appendix 6: Data Analysis

The data available for analysis was voluminous ranging from 3655 to 1102 Excel spreadsheet rows (1653 average) depending on engine and mode. This size was achieved after the reduction from 10Hz (5Hz) to 1Hz of the transient test sampling rate.

It proved impossible to perform analysis of the data within a single Excel workbook for each mode mainly due to Excel 97/2000 being unable to handle a file size greater than approximately 47MB. Following several unsuccessful attempts it was decided to split the analysis procedure into several linked workbooks. Figure 23 depicts the overview of the data flow to and from the various separate, but linked, workbooks.

The approach taken was to create the following Excel workbooks from templates (Forms) into which the previously prepared data could be pasted as values only. The templates initially contained dummy data string "ND" in all the cells which could, eventually contain real data.

Form A Workbook (49MB)

One workbook was required for each test mode and contained seven worksheets as follows:

- D800 - The prepared D800A data was simply pasted commencing in cell A15 displacing the dummy data. The D800B data was pasted in commencing at cell R15 ensuring that its time aligned with that of the D800A.

  Only minimal calculations were performed within this worksheet and were limited to:

  ~ Conversion of synchronising signal to integers with a value of 0 or 100;

  ~ Establishing time when synchronising signal first goes "high"; and,

  ~ Establishing time when synchronising time returns to "low".

- D500 - Column A of this worksheet was updated to contain the same time as that in Column A of D800 worksheet.

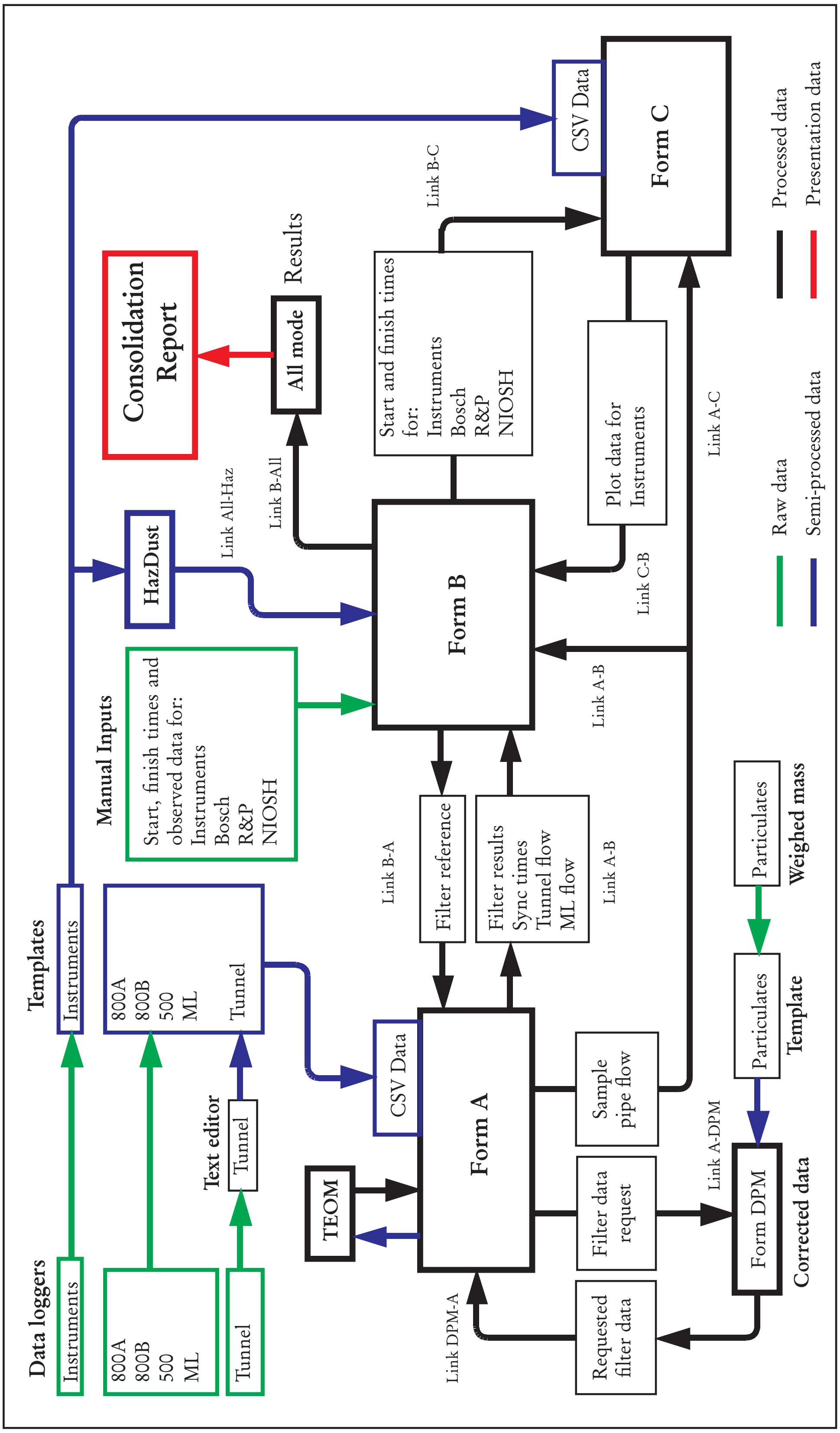
  The prepared D500 data was pasted commencing at cell B15 ensuring that the corrected time in Column B corresponded with that of Column A.

  No data manipulation was performed.

- Mobile Lab (ML) - Column A of this worksheet was also updated to contain the same time as that in Column A of D800 worksheet.

  The prepared Mobile lab data was pasted commencing at cell B15 ensuring that the corrected time in Column B corresponded with that of Column A.

Figure 23: Flow of Data in Workbooks



In contrast to the previous two worksheets significant calculations were performed:

- ~ Exhaust composition converted from % v/v and ppm to a mass basis, both dry and wet;
- ~ Establish density of raw exhaust (wet) during dilution tunnel operating periods;
- ~ Compensate for water content due to scrubber;
- ~ Establish density of exhaust in the sample pipe during dilution tunnel operating periods; and,
- ~ Establish exhaust composition (wet) at entry to primary tunnel.

- Tunnel - Again Column A of this worksheet was updated to contain the same time as that in Column A of D800 worksheet.

  The prepared dilution data was pasted commencing at cell B15 ensuring that the corrected time in Column B corresponded with that of Column A. It should be noted that there exists a significant interaction with the "Gas flows" worksheet. The emphasis within the “Tunnel” worksheet is on exhaust composition, whereas the “Gas flows” worksheet deals mainly with exhaust and moisture mass flows. The following calculations were carried out:

  - ~ Internal synchronising signal converted from level change form to progressive mode in order to cater for more than one sample during a single mode;
  - ~ Primary tunnel dilution air mass flow;
  - ~ Tunnel inlet mass flow and composition added to dilution air flow;
  - ~ Secondary tunnel sample mass flow;
  - ~ Secondary dilution air flow mass flow;
  - ~ Secondary tunnel mass flow and composition;
  - ~ Filter sampling start time, finish time and duration.
  - ~ Flow through filters and TEOM according to the start time and duration; and,
  - ~ Flows at the following locations during filter sampling:
    - o Raw exhaust;
    - o Primary tunnel; and,
    - o Primary tunnel sample.

- Gas flows - This worksheet is handled in a similar fashion to the previous worksheets in terms of synchronisation. It combines the data calculated in Worksheet "Tunnel" with the engine air and fuel flows from Worksheet "D800" as well as making allowances for the various sample flows.

- Particulates - The only interactive worksheet within this workbook has links to three other workbooks, "Form B", "Filters" and "TEOM", and is used to calculate the mass of particulate collected by the filter and the TEOM on required mg/m^3 basis.

  Workbook "Form B" contains the manual entry for the filter ID, workbook "Filters" covers a single engine test and contains a table which lists all the manually generated filter data as well as calculations determining the mass of particulate deposited. Workbook "TEOM" retrieves the raw data from worksheet "D800", manipulates the data and returns the appropriate values to this worksheet.

- Constants - As the title suggests this worksheet contains all the constants required to manipulate the collected raw data. It includes:
  - Mobile lab correction factors;
  - Assumed pressure within the exhaust/dilution tunnel system;
  - Molecular weights;
  - Dry or wet exhaust;
  - Vapour pressure constants; and,
  - Fuel analysis data.

Form B Workbook (1. 5MB)

One workbook was required for each test mode and the "Form B" workbook was designed to link "Form A" and "Form C" workbooks in such a way as to ensure that:

- All workbooks fell within Excel 97/2000 file size limit; and,
- It contained all of the manual data entries applicable to each mode with the exception of filter weights. These were:
  - Time increment for instrument testing and duration, usually 30 seconds;
  - Start time of test for each instrument;
  - Observed and manually recorded readings for each instrument;
  - Volume flows of dilution air and total flow for each instrument;
  - Tunnel filter ID;
  - Times and duration for Bosch, R&P, and NIOSH sample;
  - Sample flow for R&P elemental carbon analyser; and,
  - Processed results for the R&P elemental carbon analyser and NIOSH sampler.

The link to other workbooks provided the manually entered data to that workbook which performed the necessary data processing and returned the processed data to "Form B". The return data is presented in "Form B" in two formats:

- Calculated values - These included maximum, minimum and average values applicable at time of measurement of the following:
  - ~ Recorded data;
  - ~ Adjusted manual and recorded data for dilution ratio where applicable;
  - ~ Exhaust mass flow in Sample pipe;
  - ~ Scrubber water content;
  - ~ Water content due to combustion only;
  - ~ Oxygen mass flow (O_2); and,
  - ~ Carbon dioxide mass flow (CO_2).

- Charts - The following data was charted to permit visual observation of any variations in data with time:
  - ~ Chart, Instruments - This chart was used to display:
    D800 synchronising signal;
    Oxygen flow % w/w;
    Raw data output from - DataRam;
    DustTrak; and,
    HazDust.
  - ~ Chart, Others - displayed:
    D800 synchronising signal;
    Exhaust gas flow (dry) through the sample pipe; and,
    Oxygen flow % w/w.
  - ~ Chart, rpm-torque - displayed:
    D800 synchronising signal;
    Engine speed rpm; and,
    Engine torque Nm.
  - ~ Chart, O_2-CO_2 - displayed:
    Oxygen g/s; and,
    Carbon dioxide g/s.
  - ~ Chart, NO_x-CO - displayed:
    Oxides of nitrogen g/s; and,
    Carbon monoxide g/s.

Form C Workbook (16. 5MB)

The "Form C" workbook was designed to evaluate the data collected from the instruments under investigation, namely, DustTrak, DataRam and HazDust. One workbook was required for each test mode and it contained two worksheets:

- Instruments - This worksheet was used to allocate the recorded data according to the manual date entries in linked "Form B" workbook. Maximum, minimum and average values were determined for each time frame and dilution ratios applied to the recorded data and these returned to "Form B" workbook.
- Flows - Sample pipe flow data was obtained from linked "Gas Flows" and "ML" worksheets in workbook "Form A" and allocated to the appropriate time frame determined in the above "Instruments" worksheet. The data consisted of:
  - ~ Exhaust flow (dry) g/s;
  - ~ Total water g/s;
  - ~ Combustion water g/s;
  - ~ Exhaust oxygen content g/s; and,
  - ~ Exhaust carbon dioxide content g/s.

  The appropriate maximum, minimum and average values of these flows were returned to "Form B' workbook.

DPM Workbook (0. 6MB)

The "DPM" Workbook contained a worksheet and two charts. It is linked to Workbook "Form A" receiving "Filter ID" information and returning "Filter ID" confirmation and particulate mass collected on that filter. Only one workbook was required for each engine test containing filter data for all of the test modes.

- Worksheet 1 - The diesel particulate filter data for a given engine was manually entered into this worksheet and consisted of:
  - ~ Test mode number;
  - ~ Filter ID number;
  - ~ Filter mass (grams) prior to exposure to exhaust gas;
  - ~ Filter mass (grams) following exposure to exhaust gas. This weighing was performed three times;
  - ~ Reference filter ID number; and,
  - ~ Reference filter mass (grams). This weighing was performed a total of four times.

  The differences in mass between initial and exposed filter weighings were assessed and averaged.
- Chart 1 - This bar chart shows the mass difference for the backup filter.
- Chart 2 - Bar chart showing the mass difference for the primary filter. This is effectively the mass of particulate collected during a test run.

HazDust Workbook (4. 9MB)

The inability of the supplied HazDust instrument to communicate with the "Instruments" datalogger resulted in two alternate methods to be applied in order to salvage the data:

- Only manually obtained readings were presented in the final results for engine tests 3306 (wet) and 3306 (dry) via "Form B" workbook; and,
- A digital voltmeter with an RS232 interface was connected to a laptop computer and several readings were obtained for the following engine tests:
  - 3126 (wet);
  - Kia (wet); and,
  - 3306 (dry repeat).

  A separate "HazDust" workbook was created for each engine test containing several worksheets, one for each test mode and one as an "All mode" worksheet. The data was linked to workbook "Form B" as recorded data. In effect the HazDust workbook could be considered as a minimalist workbook "Form C" but with the inclusion of all test modes.

TEOM Workbook (5. 0MB)

The TEOM data was recorded by the D800 datalogger, however its timing was locked to the dilution tunnel particulate filter operation. A "TEOM" workbook, consisting of only one worksheet, was created for each mode to combine the data from the "D800", "Tunnel" and "Gas flows" worksheets located in workbook "Form A" and return the end results to the "Particulates" worksheet in the same workbook.

The data collected during testing was relatively easy to massage, major difficulty being limited to "spikes" present in the signal.

Although, theoretically, this could have been performed wholly within the "Form A" workbook, the resultant increase in workbook size made it impossible to do so owing to an "undocumented feature" in Excel 97/2000.

All Mode Workbook (0. 4MB)

Selected data and results for all the test modes for a single engine were combined within the "All data" workbook which contained three (3) worksheets:

- Results

  The following data/results were transferred from "Form B" for each test mode:
  - Engine speed rpm;
  - Power kW;
  - O_2 g/s;

  - CO_2 g/s;
  - Exhaust flow (wet, combustion water only); and,
  - Particulates mg/m^3;
  - OC, TC and EC for R&P; and,
  - WG" and WG'/min for NIOSH.

- Data; and,
- Calculations

  The above two worksheets were used to establish if a relationship between particulate emissions and the ratio of CO_2/O_2 irrespective of type of measurement but this proved unsuccessful.

- Charts
  However the following eight (8) charts included in workbook "All data" did show that there existed a relationship between CO_2/O_2 and particulates emission for a given method of measurement (instrument). The eight charts were all plotted against the filter mass.

  - Filters;
  - DataRam;
  - DustTrak;
  - HazDust;
  - R&P;
  - BSN;
  - JV (NIOSH); and,
  - TEOM.

  A further two (2) charts plotted the TEOM particulate emissions against the other methods of particulates measurement:

  - PM which compared:
    Filters;
    DataRam;
    DustTrak; and,
    R&P.

and

  - PM(2) comparing:
    BSN; and,
    JV (NIOSH).

Consolidation Report Workbook (1. 15MB)

All the instruments used to determine particulate emissions were compared with the dilution tunnel particulate filter adopted as reference. The data was sourced from the five (one for each engine tested) "All mode" workbooks and consisted of only CO_2/O_2 ratio and particulate emission reading in mg/m^3. The Bosch reading was not converted from BSN to mg/m^3, however the NIOSH result was adjusted from WG"/min to mg/m^3.

The "Consolidation Report" workbook summarised and presented the comparative data for final analysis and formed the platform on which conclusions and recommendations could be based. It consisted of ten (10) worksheets, one of which ("Composite") formed the link to the five "All mode" workbooks.

Eight (8) of the worksheets were used to show graphically the results for each instrument tested:

- DustTrak;
- DataRam;
- HazDust;
- NIOSH;
- R&P (EC);
- R&P (TC);
- TEOM; and,
- Bosch (Filter).

The tenth, and last, worksheet compared the Bosch (BSN) results with the TEOM results.

Each of the above nine worksheets contained the particulate emission values in five tables format and five charts. The five charts represented:

- 3306 (dry and dry repeat)
- 3306 (wet);
- 3126 (wet);
- Kia (wet);
- All engines except 3126; and
- 3126 only.

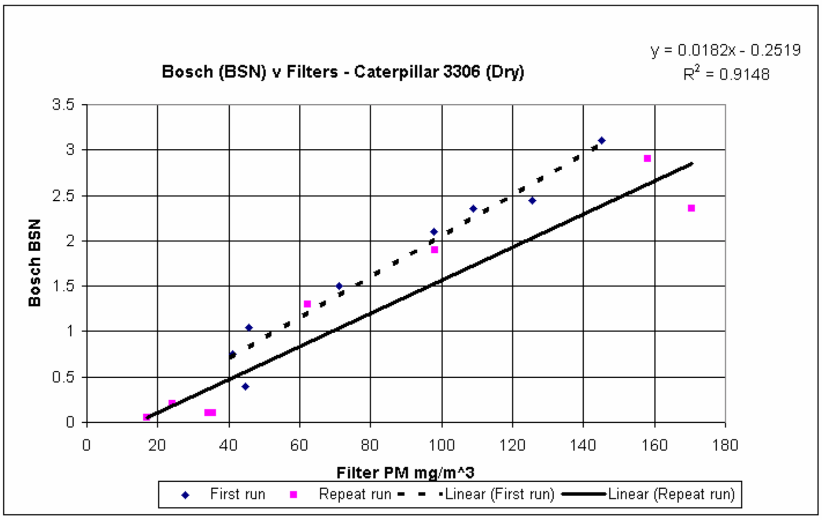
The charts also contained:

- Coefficient of determination R^2; and,
- Linear trendline equation.

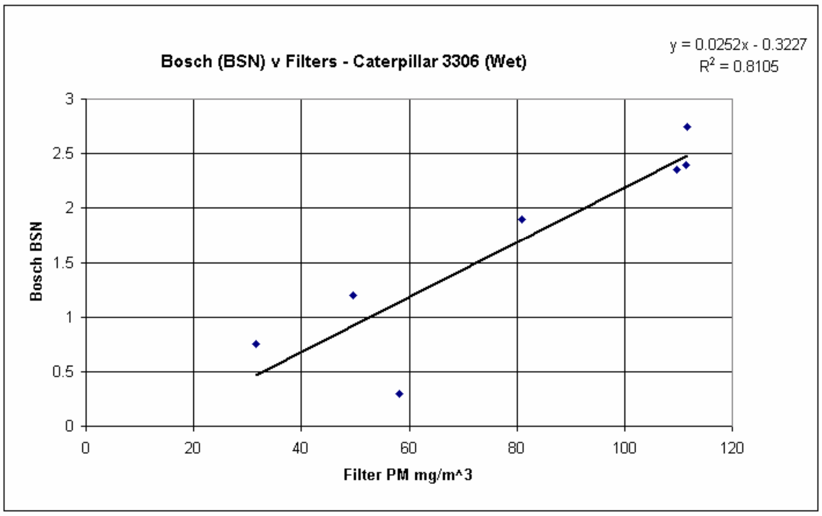
Appendix 7: Dynamometer Tests: Graphs Against Filters

Dyno Tests: Graphs showing Bosch Smoke Numbers against Tunnel Filters

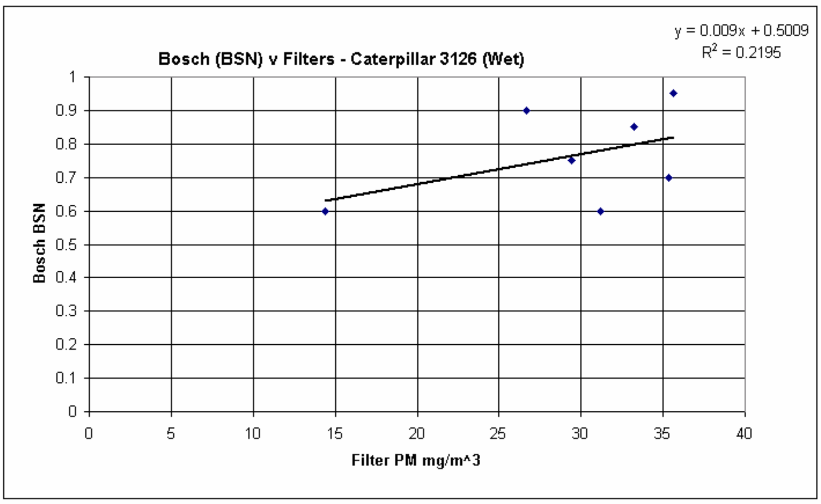
Engine	Filters mg/m^3	BSN	
First run			
3306_R_D	144.9749	3.1	1
	125.6348	2.45	2
	108.7998	2.35	3
	97.76331	2.1	4
	71.12105	1.5	5
	45.80277	1.05	6
	40.9464	0.75	7
	44.77824	0.4	8
			T
Repeat run			
3306_R-DR	158.2609	2.9	1
	170.6245	2.35	2
	97.99097	1.9	3
	62.14969	1.3	4
	34.34291	0.1	5
	24.1269	0.2	6
	16.94246	0.05	7
	35.39447	0.1	8
			T



Engine	Filters mg/m^3	BSN	
3306_R_W	111.6352	2.75	1
	109.7911	2.35	2
	111.3361	2.4	3
	80.90063	1.9	4
	49.67388	1.2	5
	31.53855	0.75	6
	58.15033	0.3	7
			T

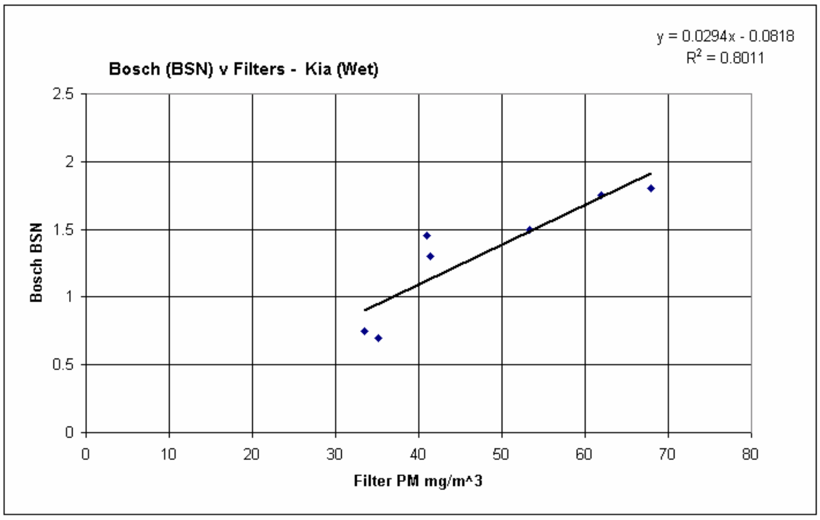


Engine	Filters mg/m^3	BSN	
3126_R_W	26.68115	0.9	1
	35.6102	0.95	2
	35.33376	0.7	3
	33.20652	0.85	4
	29.39198	0.75	5
	31.17185	0.6	6
	14.38795	0.6	7
			T

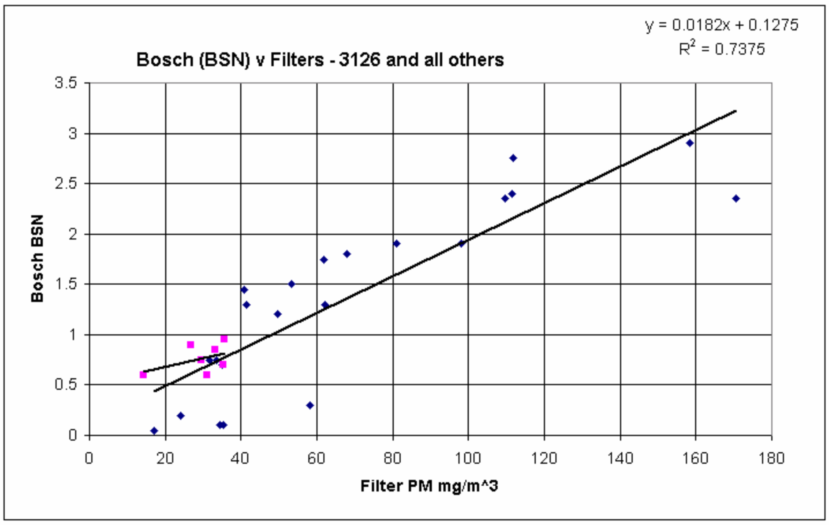


Dyno Tests: Graphs showing Bosch Smoke Numbers against Tunnel Filters (cont)

Engine	Filters mg/m^3	BSN	
Kia_R_W	67.87793	1.8	7
	61.91625	1.75	1
	53.37119	1.5	2
	40.96045	1.45	3
	35.0852	0.7	4
	41.37026	1.3	5
	33.48689	0.75	6
			T

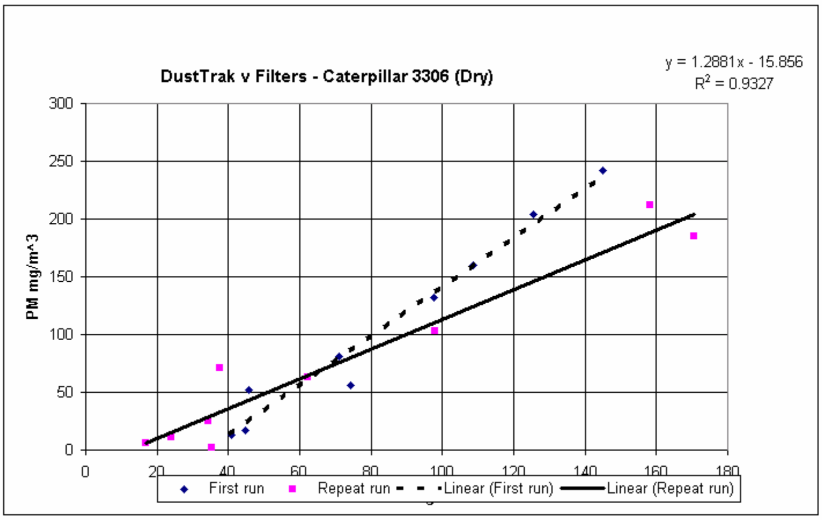


Engine All	Filters mg/m^3	BSN	
3306 dry rpt	158.2609	2.9	1
	170.6245	2.35	2
	97.99097	1.9	3
	62.14969	1.3	4
	34.34291	0.1	5
	24.1269	0.2	6
	16.94246	0.05	7
	35.39447	0.1	8
			T
3306 wet	111.6352	2.75	1
	109.7911	2.35	2
	111.3361	2.4	3
	80.90063	1.9	4
	49.67388	1.2	5
	31.53855	0.75	6
	58.15033	0.3	7
			T
Kia wet	67.87793	1.8	7
	61.91625	1.75	1
	53.37119	1.5	2
	40.96045	1.45	3
	35.0852	0.7	4
	41.37026	1.3	5
	33.48689	0.75	6
			T
3126 wet	26.68115	0.9	1
	35.6102	0.95	2
	35.33376	0.7	3
	33.20652	0.85	4
	29.39198	0.75	5
	31.17185	0.6	6
	14.38795	0.6	7
			T

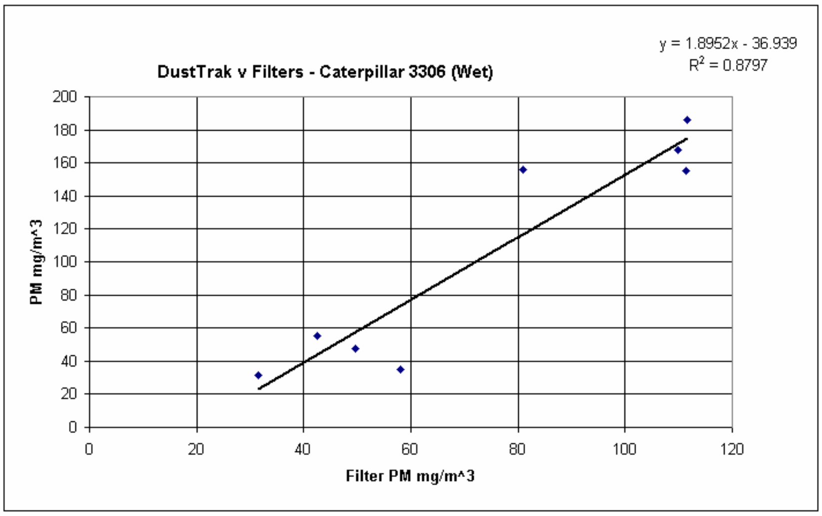


Dyno Tests: Graphs showing DustTrak Results against Tunnel Filters

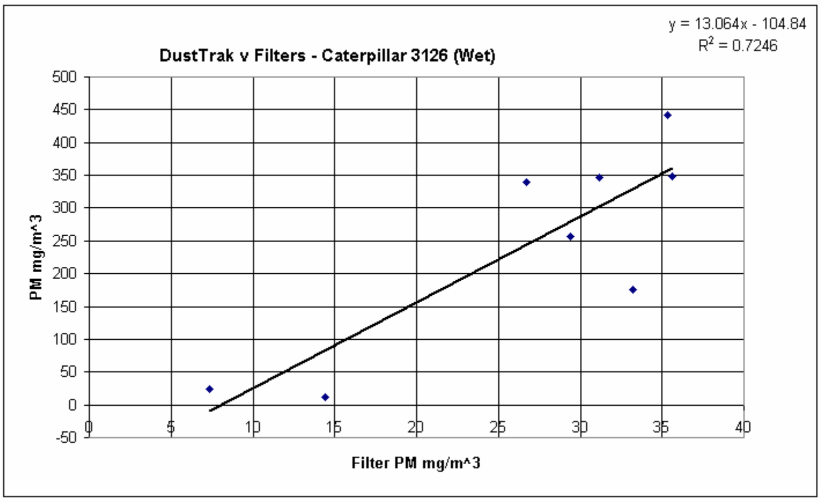
Engine	Filters mg/m^3	DustTrak mg/m^3	
First run			
3306_R_D	144.9749	241.5084	1
	125.6348	203.991	2
	108.7998	159.5278	3
	97.76331	132.4321	4
	71.12105	80.632	5
	45.80277	51.68714	6
	40.9464	13.31129	7
	44.77824	17.25526	8
	74.30658	55.64899	T
Repeat run			
3306_R-DR	158.2609	212.2241	1
	170.6245	184.5441	2
	97.99097	103.1614	3
	62.14969	62.94267	4
	34.34291	25.45973	5
	24.1269	11.01007	6
	16.94246	6.35355	7
	35.39447	2.060393	8
	37.62606	70.63699	T



Engine	Filters mg/m^3	DustTrak mg/m^3	
3306_R_W	111.6352	185.9789	1
	109.7911	167.7632	2
	111.3361	155.1764	3
	80.90063	155.6254	4
	49.67388	47.22345	5
	31.53855	31.22516	6
	58.15033	34.8477	7
	42.54411	55.36697	T

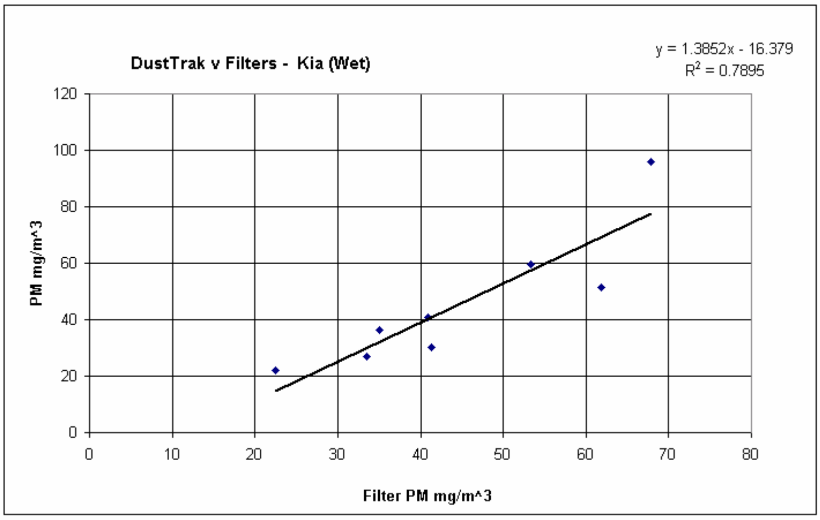


Engine	Filters mg/m^3	DustTrak mg/m^3	
3126_R_W	26.68115	340.222	1
	35.6102	348.5504	2
	35.33376	441.7406	3
	33.20652	175.8299	4
	29.39198	257.2719	5
	31.17185	345.7951	6
	14.38795	12.00911	7
	7.337469	24.1185	T

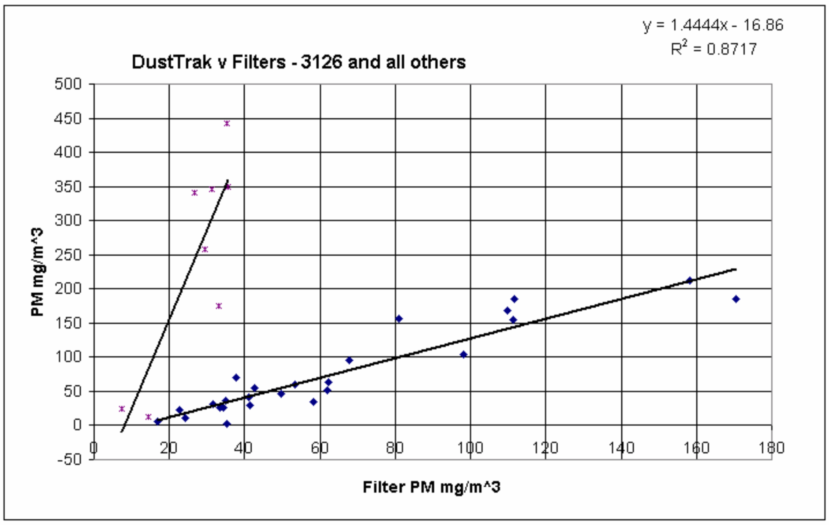


Dyno Tests: Graphs showing DustTrak Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	DustTrak mg/m^3	
Kia_R_W	67.87793	95.751	7
	61.91625	51.62022	1
	53.37119	59.43573	2
	40.96045	40.76243	3
	35.0852	36.1462	4
	41.37026	30.21423	5
	33.48689	26.86498	6
	22.54409	22.15036	T

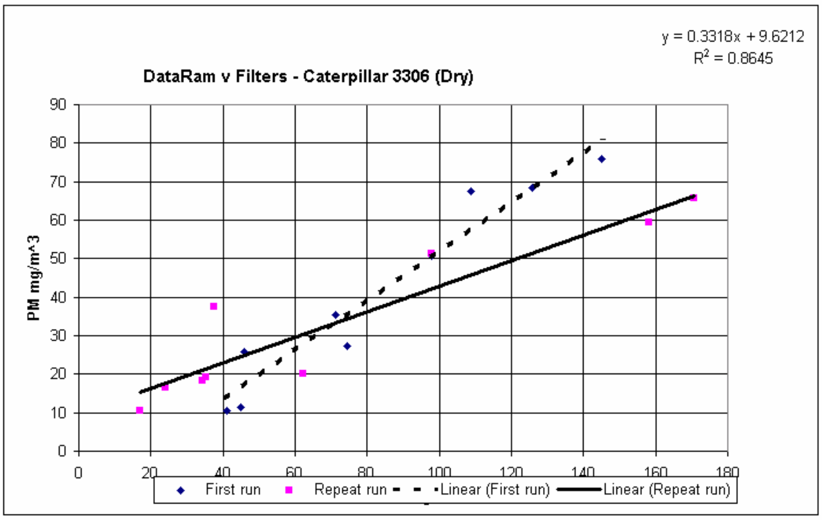


Engine All	Filters mg/m^3	DustTrak mg/m^3	
3306 dry rpt	158.2609	212.2241	1
	170.6245	184.5441	2
	97.99097	103.1614	3
	62.14969	62.94267	4
	34.34291	25.45973	5
	24.1269	11.01007	6
	16.94246	6.35355	7
	35.39447	2.060393	8
	37.62606	70.63699	T
3306 wet	111.6352	185.9789	1
	109.7911	167.7632	2
	111.3361	155.1764	3
	80.90063	155.6254	4
	49.67388	47.22345	5
	31.53855	31.22516	6
	58.15033	34.8477	7
	42.54411	55.36697	T
Kia wet	67.87793	95.751	7
	61.91625	51.62022	1
	53.37119	59.43573	2
	40.96045	40.76243	3
	35.0852	36.1462	4
	41.37026	30.21423	5
	33.48689	26.86498	6
	22.54409	22.15036	T
3126 wet	26.68115	340.222	1
	35.6102	348.5504	2
	35.33376	441.7406	3
	33.20652	175.8299	4
	29.39198	257.2719	5
	31.17185	345.7951	6
	14.38795	12.00911	7
	7.337469	24.1185	T

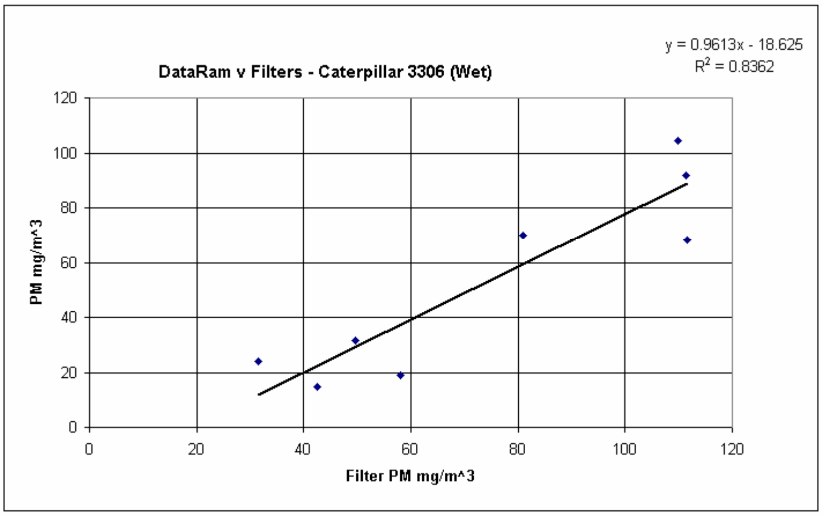


Dyno Tests: Graphs showing DataRam Results against Tunnel Filters

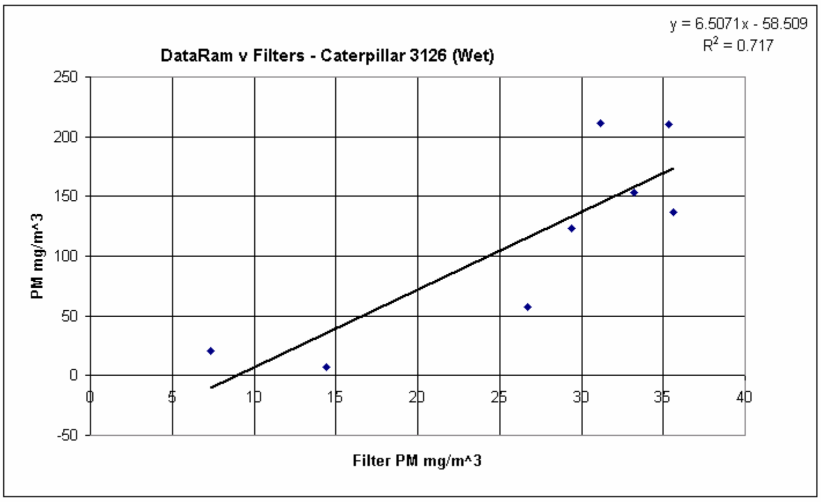
Engine	Filters mg/m^3	DataRam mg/m^3	
First run			
3306_R_D	144.9749	75.84954	1
	125.6348	68.46531	2
	108.7998	67.56721	3
	97.76331	50.67822	4
	71.12105	35.33542	5
	45.80277	25.78151	6
	40.9464	10.35274	7
	44.77824	11.39736	8
	74.30658	27.20105	T
Repeat run			
3306_R-DR	158.2609	59.29648	1
	170.6245	65.5984	2
	97.99097	51.2299	3
	62.14969	20.04363	4
	34.34291	18.27415	5
	24.1269	16.60594	6
	16.94246	10.35716	7
	35.39447	19.20607	8
	37.62606	37.49956	T



Engine	Filters mg/m^3	DataRam mg/m^3	
3306_R_W	111.6352	68.2645	1
	109.7911	104.3811	2
	111.3361	91.89956	3
	80.90063	69.71044	4
	49.67388	31.6689	5
	31.53855	24.12906	6
	58.15033	18.74461	7
	42.54411	14.74648	T

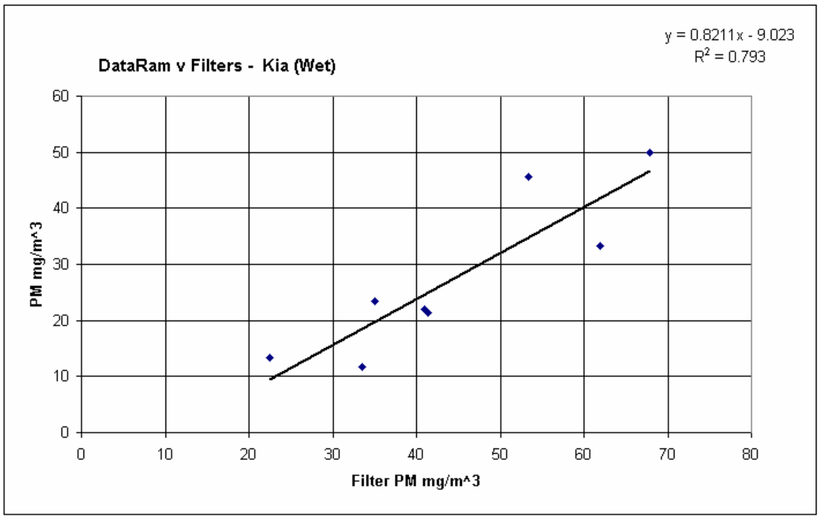


Engine	Filters mg/m^3	DataRam mg/m^4	
3126_R_W	26.68115	57.21166	1
	35.6102	136.7871	2
	35.33376	210.4515	3
	33.20652	152.8652	4
	29.39198	122.9026	5
	31.17185	211.1517	6
	14.38795	7.118454	7
	7.337469	20.22734	T

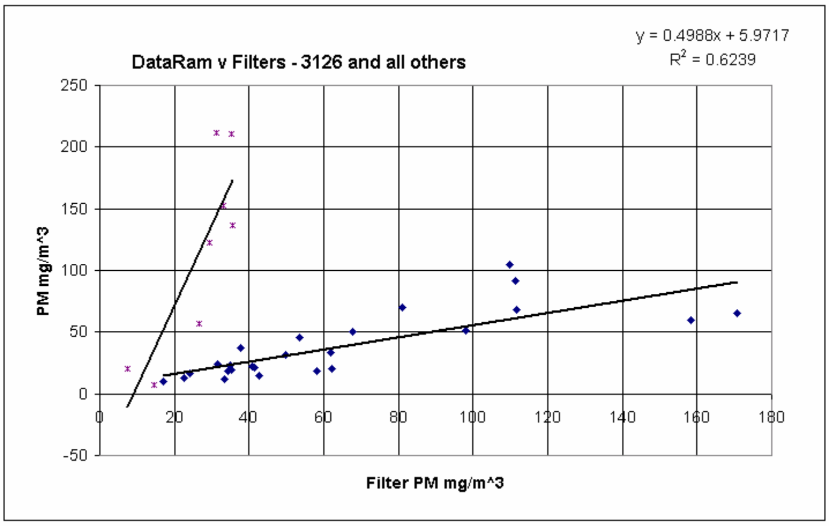


Dyno Tests: Graphs showing DataRam Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	DataRam mg/m^3	
Kia_R_W	67.87793	49.9759	7
	61.91625	33.29795	1
	53.37119	45.51422	2
	40.96045	21.94286	3
	35.0852	23.37458	4
	41.37026	21.42802	5
	33.48689	11.80993	6
	22.54409	13.27305	T

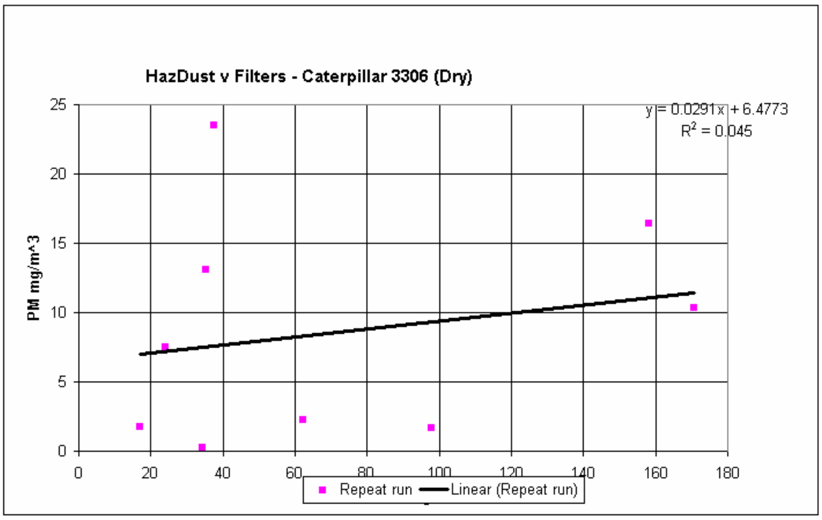


Engine All	Filters mg/m^3	DataRam mg/m^3	
3306 dry rpt	158.2609	59.29648	1
	170.6245	65.5984	2
	97.99097	51.2299	3
	62.14969	20.04363	4
	34.34291	18.27415	5
	24.1269	16.60594	6
	16.94246	10.35716	7
	35.39447	19.20607	8
	37.62606	37.49956	T
3306 wet	111.6352	68.2645	1
	109.7911	104.3811	2
	111.3361	91.89956	3
	80.90063	69.71044	4
	49.67388	31.6689	5
	31.53855	24.12906	6
	58.15033	18.74461	7
	42.54411	14.74648	T
Kia wet	67.87793	49.9759	7
	61.91625	33.29795	1
	53.37119	45.51422	2
	40.96045	21.94286	3
	35.0852	23.37458	4
	41.37026	21.42802	5
	33.48689	11.80993	6
	22.54409	13.27305	T
3126 wet	26.68115	57.21166	1
	35.6102	136.7871	2
	35.33376	210.4515	3
	33.20652	152.8652	4
	29.39198	122.9026	5
	31.17185	211.1517	6
	14.38795	7.118454	7
	7.337469	20.22734	T



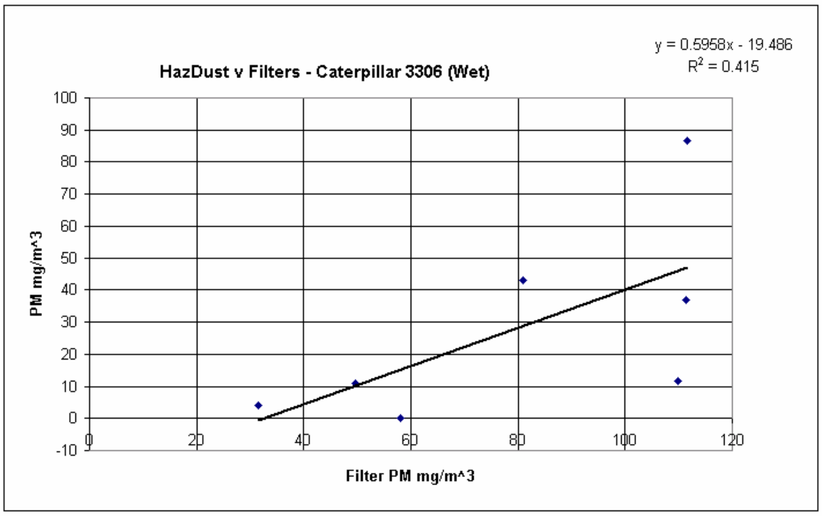
Dyno Tests: Graphs showing HazDust Results against Tunnel Filters

Engine	Filters mg/m^3	HazDust mg/m^3	
First run			
3306_R_D	144.9749	ND	1
	125.6348	ND	2
	108.7998	ND	3
	97.76331	ND	4
	71.12105	ND	5
	45.80277	ND	6
	40.9464	ND	7
	44.77824	ND	8
	74.30658	ND	T
Repeat run			
3306_R-DR	158.2609	16.38759	1
	170.6245	10.36131	2
	97.99097	1.671488	3
	62.14969	2.240284	4
	34.34291	0.279179	5
	24.1269	7.54114	6
	16.94246	1.781591	7
	35.39447	13.047	8
	37.62606	23.52806	T

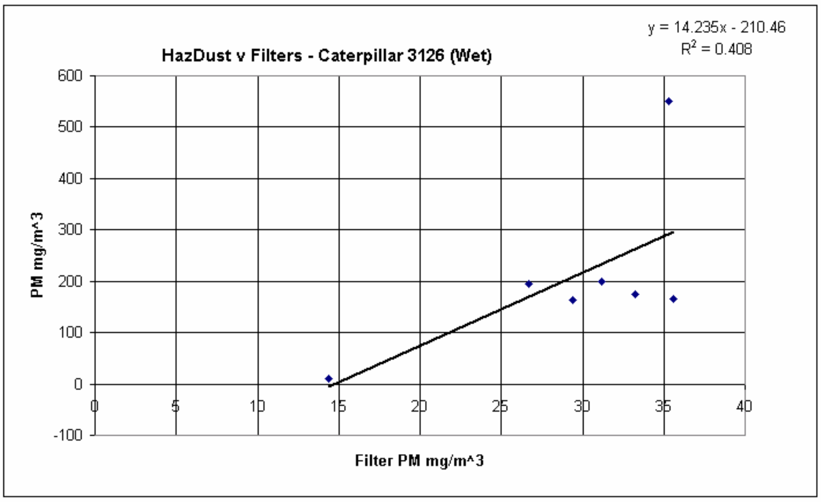


Engine	Filters mg/m^3	HazDust mg/m^3	
3306_R_W	111.6352	86.5865	1
	109.7911	11.466	2
	111.3361	36.99641	3
	80.90063	42.97475	4
	49.67388	10.92	5
	31.53855	4.16325	6
	58.15033	ND	7
			8
	42.54411	ND	T

Note: Manual data

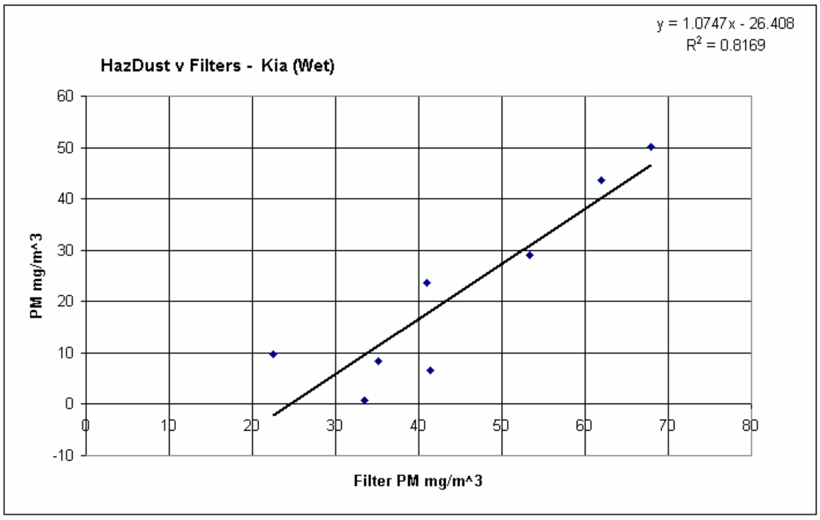


Engine	Filters mg/m^3	HazDust mg/m^4	
3126_R_W	26.68115	195.5948	1
	35.6102	165.2135	2
	35.33376	549.6141	3
	33.20652	174.1073	4
	29.39198	162.396	5
	31.17185	198.7178	6
	14.38795	10.52315	7
			8
	7.337469	7.774245	T

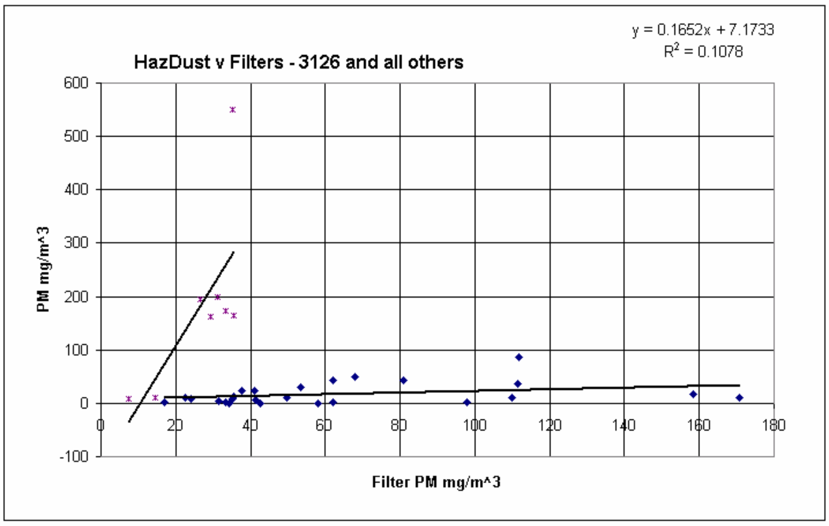


Dyno Tests: Graphs showing HazDust Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	HazDust mg/m^3	
Kia_R_W	67.87793	50.11812	1
	61.91625	43.55641	2
	53.37119	29.04339	3
	40.96045	23.59807	4
	35.0852	8.448855	5
	41.37026	6.532137	6
	33.48689	0.866602	7
			8
	22.54409	9.840692	T

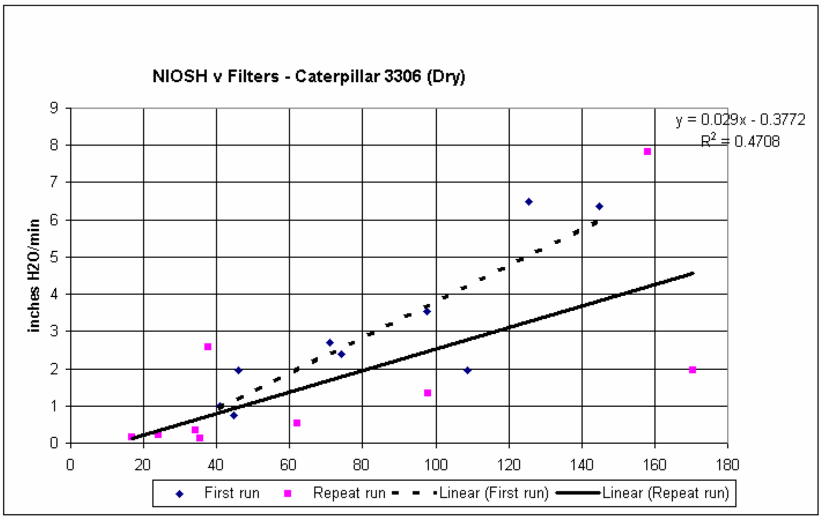


Engine All	Filters mg/m^3	HazDust mg/m^3	
3306 dry rpt	158.2609	16.38759	1
	170.6245	10.36131	2
	97.99097	1.671488	3
	62.14969	2.240284	4
	34.34291	0.279179	5
	24.1269	7.54114	6
	16.94246	1.781591	7
	35.39447	13.047	8
	37.62606	23.52806	T
3306 wet	111.6352	86.5865	1
	109.7911	11.466	2
	111.3361	36.99641	3
	80.90063	42.97475	4
	49.67388	10.92	5
	31.53855	4.16325	6
	58.15033	ND	7
	42.54411	ND	T
Kia wet	67.87793	50.11812	1
	61.91625	43.55641	2
	53.37119	29.04339	3
	40.96045	23.59807	4
	35.0852	8.448855	5
	41.37026	6.532137	6
	33.48689	0.866602	7
	22.54409	9.840692	T
3126 wet	26.68115	195.5948	1
	35.6102	165.2135	2
	35.33376	549.6141	3
	33.20652	174.1073	4
	29.39198	162.396	5
	31.17185	198.7178	6
	14.38795	10.52315	7
	7.337469	7.77	T

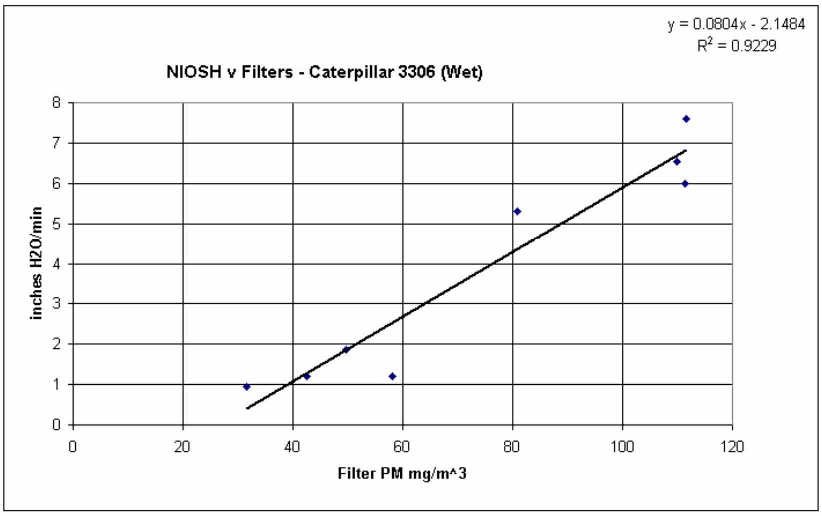


Dyno Tests: Graphs showing NIOSH dP Results against Tunnel Filters

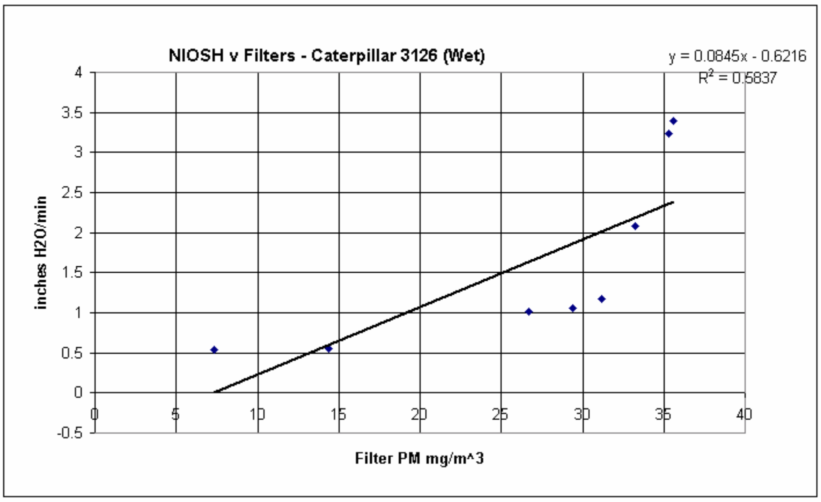
Engine	Filters mg/m^3	NIOSH inches H2O/min	
First run			
3306_R_D	144.9749	6.36	1
	125.6348	6.475	2
	108.7998	1.945	3
	97.76331	3.55	4
	71.12105	2.71	5
	45.80277	1.953333	6
	40.9464	1.003333	7
	44.77824	0.756667	8
	74.30658	2.403333	T
Repeat run			
3306_R-DR	158.2609	7.81	1
	170.6245	1.956667	2
	97.99097	1.345	3
	62.14969	0.533333	4
	34.34291	0.356667	5
	24.1269	0.21	6
	16.94246	0.17	7
	35.39447	0.12	8
	37.62606	2.58	T



Engine	Filters mg/m^3	NIOSH inches H2O/min	
3306_R_W	111.6352	7.606667	1
	109.7911	6.55	2
	111.3361	6.003333	3
	80.90063	5.306667	4
	49.67388	1.873333	5
	31.53855	0.936667	6
	58.15033	1.213333	7
	42.54411	1.213333	T

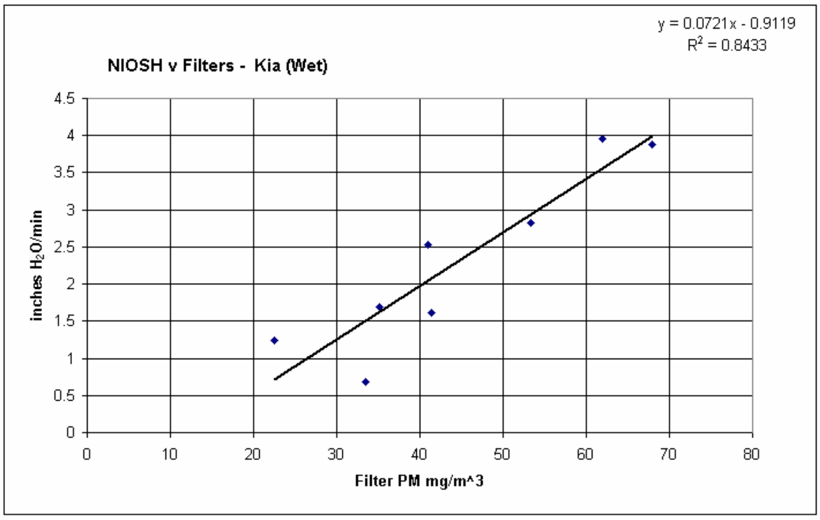


Engine	Filters mg/m^3	NIOSH mg/m^4	
3126_R_W	26.68115	1.013333	1
	35.6102	3.393	2
	35.33376	3.236667	3
	33.20652	2.076667	4
	29.39198	1.056667	5
	31.17185	1.17	6
	14.38795	0.55	7
	7.337469	0.536667	T

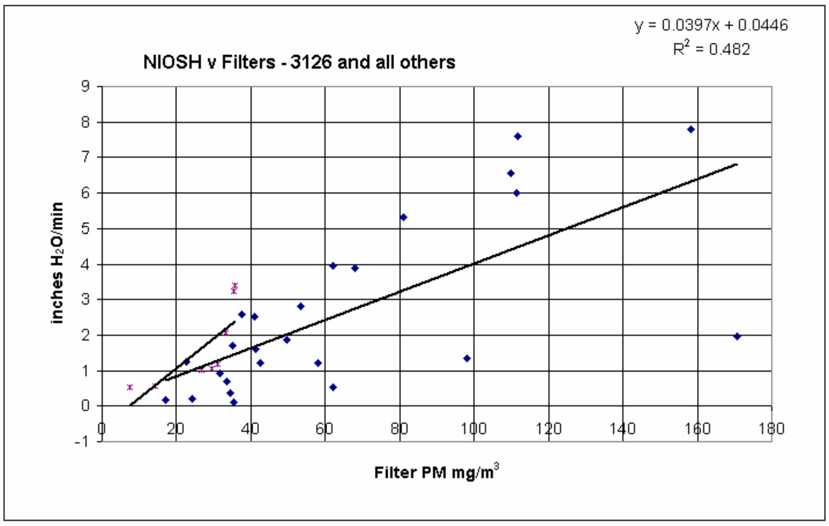


Dyno Tests: Graphs showing NIOSH dP Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	NIOSH inches H2O/min	
Kia_R_W	67.87793	3.88	7
	61.91625	3.956667	1
	53.37119	2.826667	2
	40.96045	2.526667	3
	35.0852	1.696667	4
	41.37026	1.62	5
	33.48689	0.68	6
	22.54409	1.243333	T

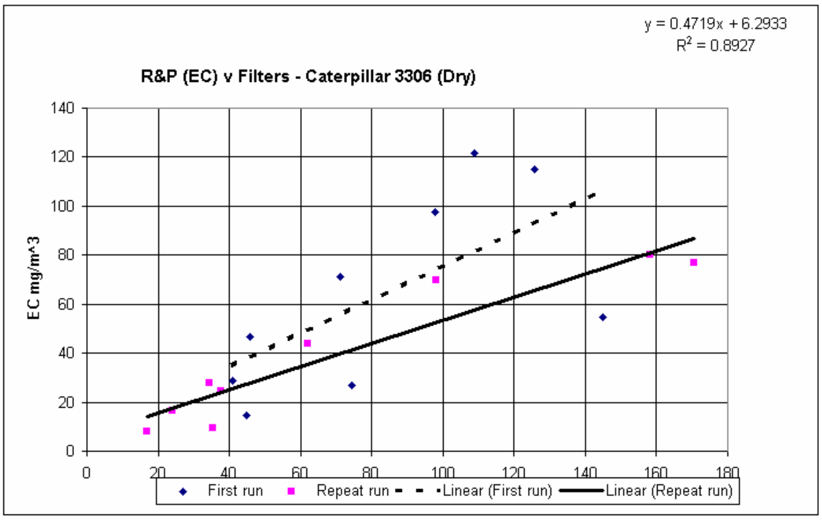


Engine All	Filters mg/m^3	NIOSH inches H2O/min	
3306 dry rpt	158.2609	7.81	1
	170.6245	1.956667	2
	97.99097	1.345	3
	62.14969	0.533333	4
	34.34291	0.356667	5
	24.1269	0.21	6
	16.94246	0.17	7
	35.39447	0.12	8
	37.62606	2.58	T
3306 wet	111.6352	7.606667	1
	109.7911	6.55	2
	111.3361	6.003333	3
	80.90063	5.306667	4
	49.67388	1.873333	5
	31.53855	0.936667	6
	58.15033	1.213333	7
	42.54411	1.213333	T
Kia wet	67.87793	3.88	7
	61.91625	3.956667	1
	53.37119	2.826667	2
	40.96045	2.526667	3
	35.0852	1.696667	4
	41.37026	1.62	5
	33.48689	0.68	6
	22.54409	1.243333	T
3126 wet	26.68115	1.013333	1
	35.6102	3.393	2
	35.33376	3.236667	3
	33.20652	2.076667	4
	29.39198	1.056667	5
	31.17185	1.17	6
	14.38795	0.55	7
	7.337469	0.536667	T

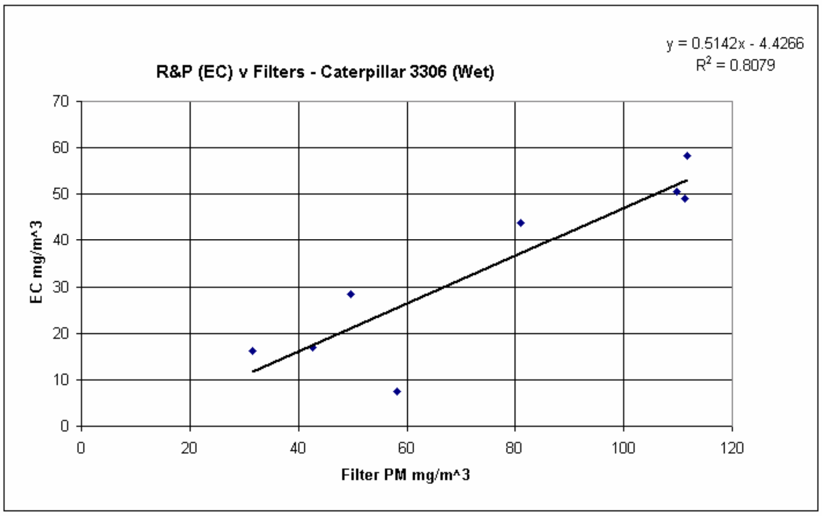


Dyno Tests: Graphs showing R&P Elemental Carbon Results against Tunnel Filters

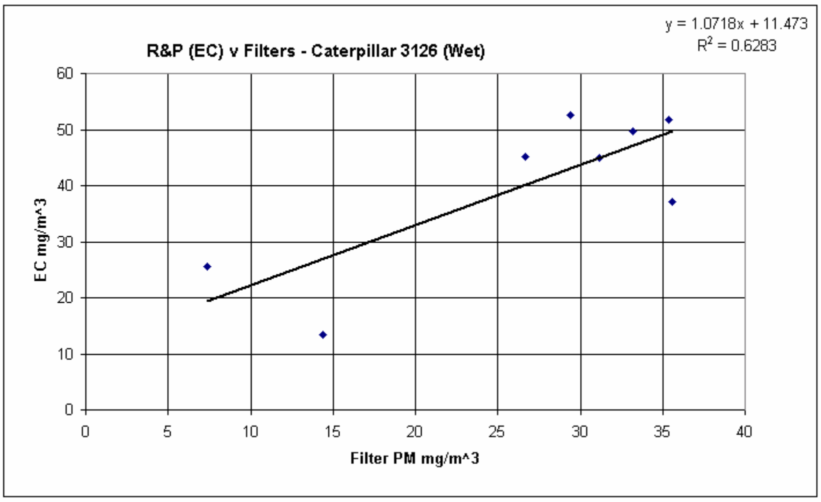
Engine	Filters mg/m^3	R&P EC mg/m^3	
First run			
3306_R_D	144.9749	54.8	1
	125.6348	115.05	2
	108.7998	121.435	3
	97.76331	97.78	4
	71.12105	71.38	5
	45.80277	46.64	6
	40.9464	28.77	7
	44.77824	14.765	8
	74.30658	27.01	T
Repeat run			
3306_R-DR	158.2609	80.335	1
	170.6245	76.785	2
	97.99097	69.99	3
	62.14969	43.86	4
	34.34291	27.89	5
	24.1269	16.6	6
	16.94246	8.015	7
	35.39447	9.41	8
	37.62606	24.595	T



Engine	Filters mg/m^3	R&P EC mg/m^3	
3306_R_W	111.6352	58.305	1
	109.7911	50.555	2
	111.3361	49.18	3
	80.90063	43.91	4
	49.67388	28.465	5
	31.53855	16.12	6
	58.15033	7.41	7
	42.54411	16.88	T

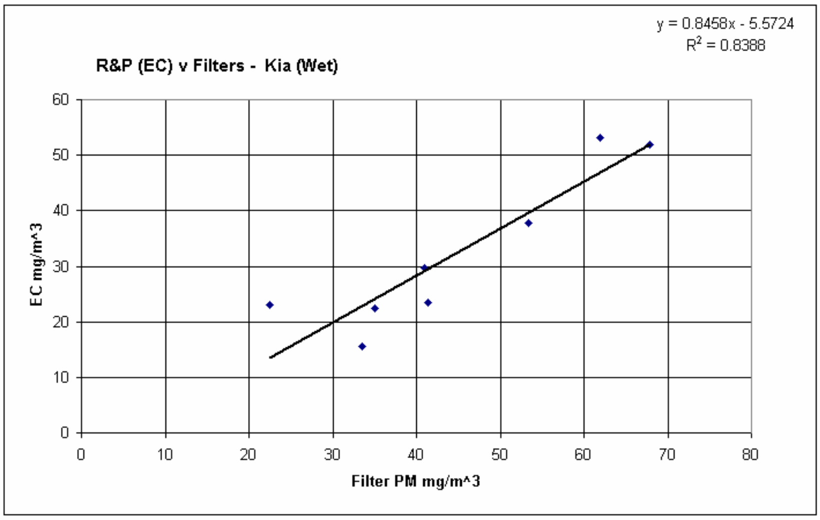


Engine	Filters mg/m^3	R&P EC mg/m^4	
3126_R_W	26.68115	45.205	1
	35.6102	37.13	2
	35.33376	51.74	3
	33.20652	49.705	4
	29.39198	52.555	5
	31.17185	45.02	6
	14.38795	13.33	7
	7.337469	25.52	T

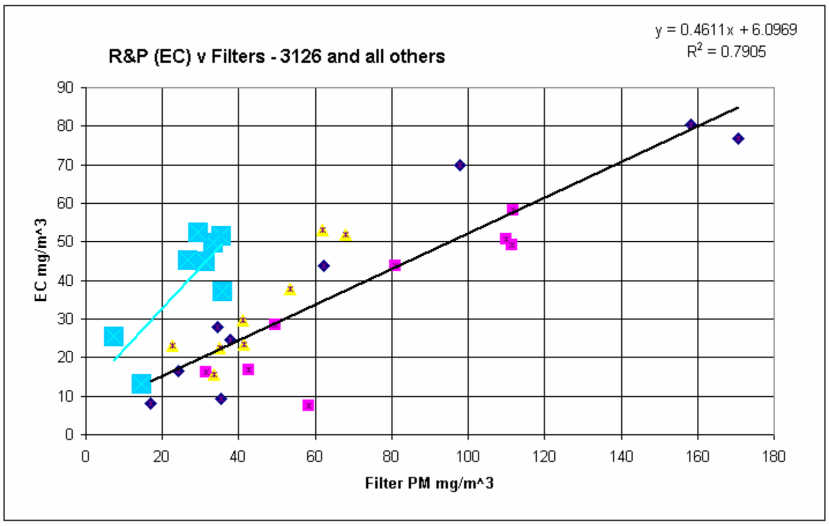


Dyno Tests: Graphs showing R&P Elemental Carbon Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	R&P EC mg/m^3	
Kia_R_W	67.87793	51.9	7
	61.91625	53.245	1
	53.37119	37.81	2
	40.96045	29.595	3
	35.0852	22.365	4
	41.37026	23.425	5
	33.48689	15.64	6
	22.54409	23.05	T

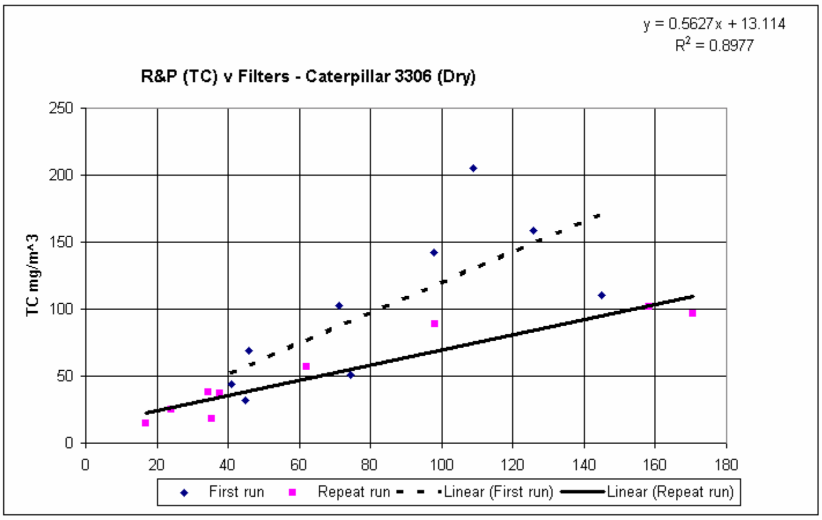


Engine All	Filters mg/m^3	R&P EC mg/m^3	
3306 dry rpt	158.2609	80.335	1
	170.6245	76.785	2
	97.99097	69.99	3
	62.14969	43.86	4
	34.34291	27.89	5
	24.1269	16.6	6
	16.94246	8.015	7
	35.39447	9.41	8
	37.62606	24.595	T
3306 wet	111.6352	58.305	1
	109.7911	50.555	2
	111.3361	49.18	3
	80.90063	43.91	4
	49.67388	28.465	5
	31.53855	16.12	6
	58.15033	7.41	7
	42.54411	16.88	T
Kia wet	67.87793	51.9	7
	61.91625	53.245	1
	53.37119	37.81	2
	40.96045	29.595	3
	35.0852	22.365	4
	41.37026	23.425	5
	33.48689	15.64	6
	22.54409	23.05	T
3126 wet	26.68115	45.205	1
	35.6102	37.13	2
	35.33376	51.74	3
	33.20652	49.705	4
	29.39198	52.555	5
	31.17185	45.02	6
	14.38795	13.33	7
	7.337469	25.52	T

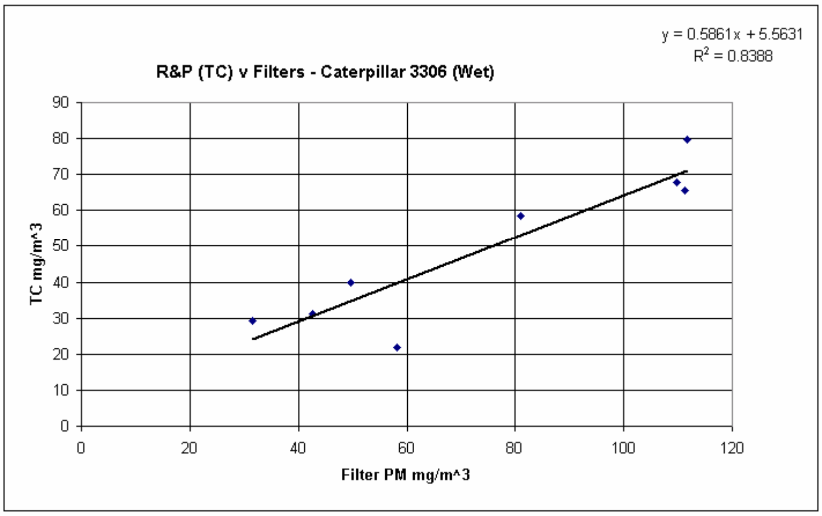


Dyno Tests: Graphs showing R&P Total Carbon Results against Tunnel Filters

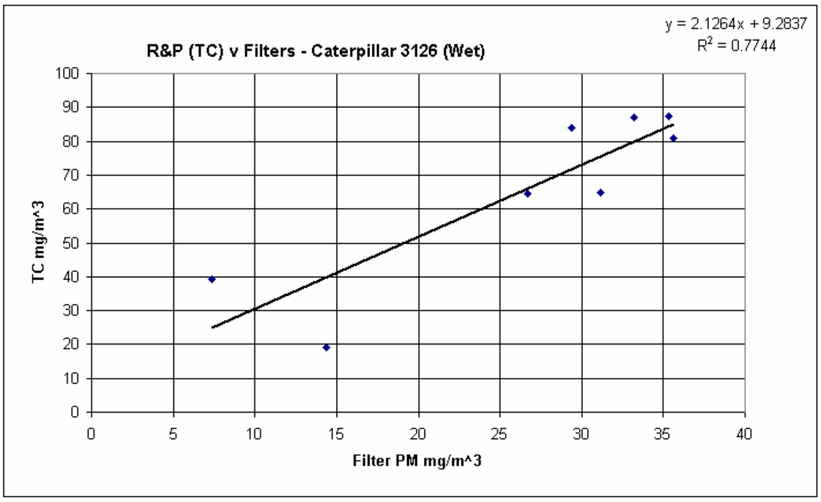
Engine	Filters mg/m^3	R&P TC mg/m^3	
First run			
3306_R_D	144.9749	110.4	1
	125.6348	158.65	2
	108.7998	205.55	3
	97.76331	142.05	4
	71.12105	102.52	5
	45.80277	69.345	6
	40.9464	44.32	7
	44.77824	31.93	8
	74.30658	51.015	T
Repeat run			
3306_R-DR	158.2609	101.715	1
	170.6245	96.955	2
	97.99097	89.11	3
	62.14969	56.72	4
	34.34291	37.67	5
	24.1269	24.955	6
	16.94246	14.84	7
	35.39447	18.015	8
	37.62606	36.73	T



Engine	Filters mg/m^3	R&P TC mg/m^3	
3306_R_W	111.6352	79.605	1
	109.7911	67.78	2
	111.3361	65.48	3
	80.90063	58.605	4
	49.67388	39.935	5
	31.53855	29.33	6
	58.15033	21.8	7
	42.54411	31.06	T

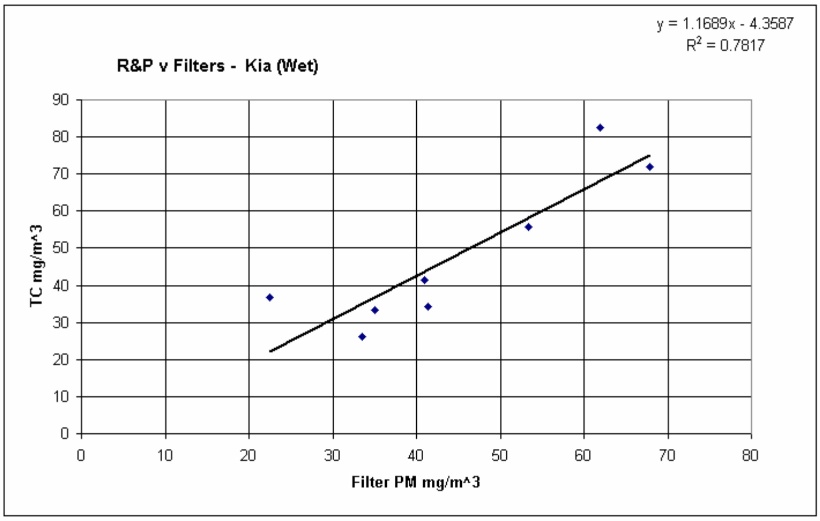


Engine	Filters mg/m^3	R&P TC mg/m^4	
3126_R_W	26.68115	64.64	1
	35.6102	81.03	2
	35.33376	87.5	3
	33.20652	87.09	4
	29.39198	84.095	5
	31.17185	64.74	6
	14.38795	19.08	7
	7.337469	39.285	T

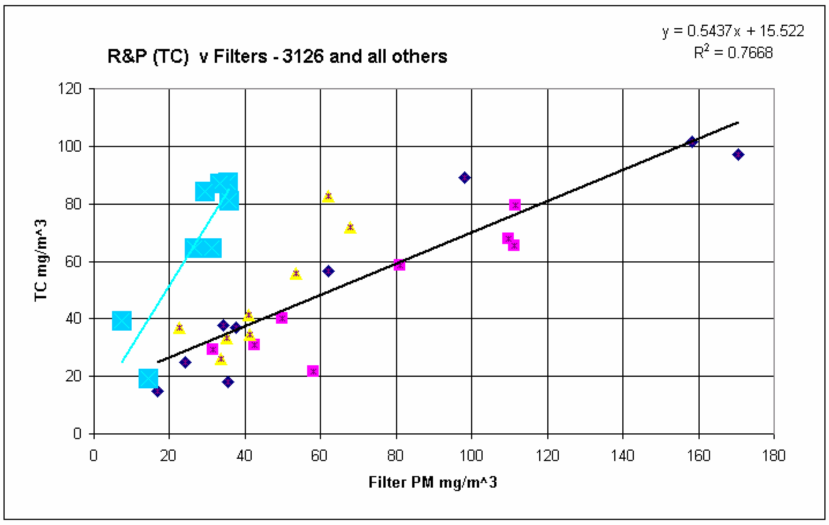


Dyno Tests: Graphs showing R&P Total Carbon Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	R&P TC mg/m^3	
Kia_R_W	67.87793	71.84	7
	61.91625	82.545	1
	53.37119	55.685	2
	40.96045	41.37	3
	35.0852	33.235	4
	41.37026	34.405	5
	33.48689	26.145	6
	22.54409	36.74	T

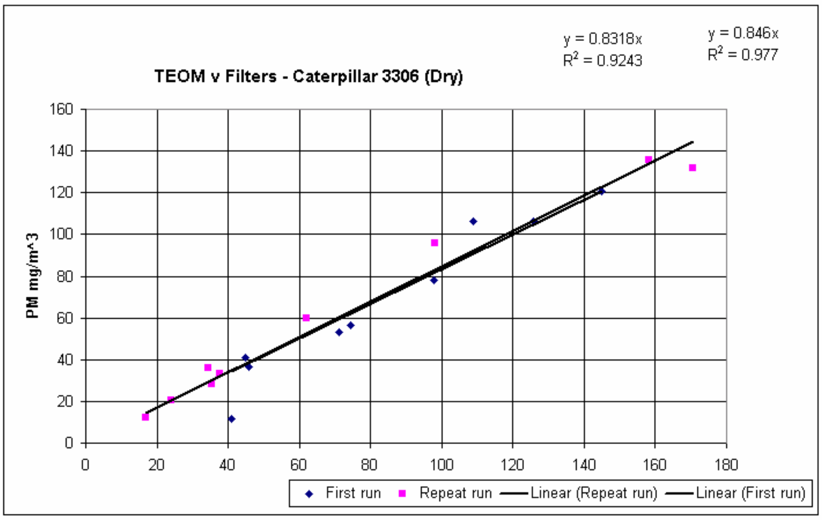


Engine	Filters	R&P TC	
All	mg/m^3	mg/m^3	
3306 dry rpt	158.2609	101.715	1
	170.6245	96.955	2
	97.99097	89.11	3
	62.14969	56.72	4
	34.34291	37.67	5
	24.1269	24.955	6
	16.94246	14.84	7
	35.39447	18.015	8
	37.62606	36.73	T
3306 wet	111.6352	79.605	1
	109.7911	67.78	2
	111.3361	65.48	3
	80.90063	58.605	4
	49.67388	39.935	5
	31.53855	29.33	6
	58.15033	21.8	7
	42.54411	31.06	T
Kia wet	67.87793	71.84	7
	61.91625	82.545	1
	53.37119	55.685	2
	40.96045	41.37	3
	35.0852	33.235	4
	41.37026	34.405	5
	33.48689	26.145	6
	22.54409	36.74	T
3126 wet	26.68115	64.64	1
	35.6102	81.03	2
	35.33376	87.5	3
	33.20652	87.09	4
	29.39198	84.095	5
	31.17185	64.74	6
	14.38795	19.08	7
	7.337469	39.285	T

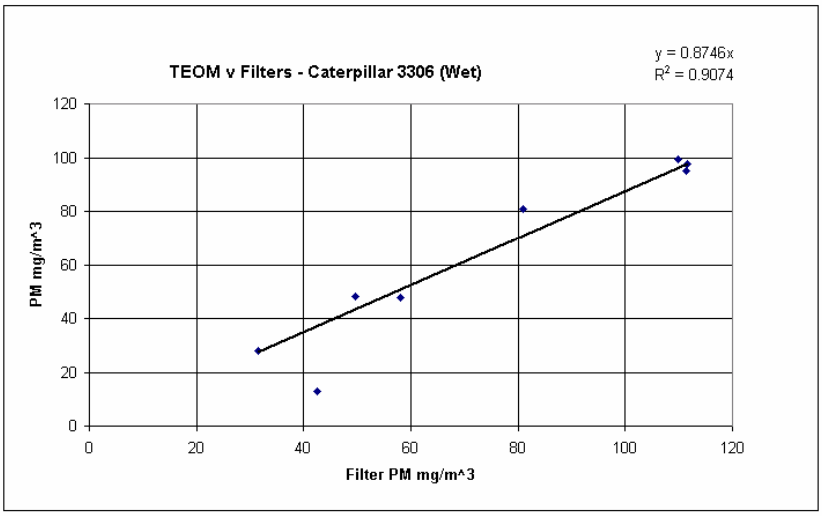


Dyno Tests: Graphs showing TEOM Results against Tunnel Filters

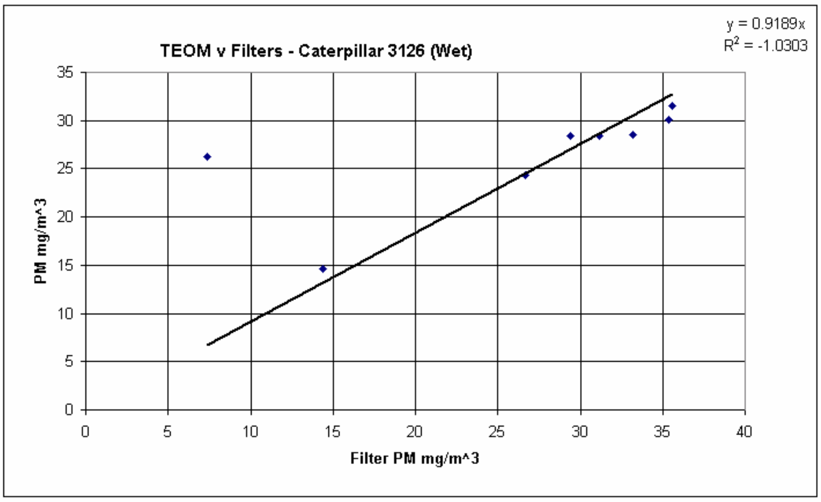
Engine	Filters mg/m^3	TEOM mg/m^3	
First run			
3306_R_D	144.9749	120.8646	1
	125.6348	106.5182	2
	108.7998	106.0881	3
	97.76331	77.85273	4
	71.12105	53.17915	5
	45.80277	36.52086	6
	40.9464	11.66417	7
	44.77824	40.72071	8
	74.30658	56.50756	T
Repeat run			
3306_R-DR	158.2609	135.4014	1
	170.6245	132.034	2
	97.99097	95.64474	3
	62.14969	59.60005	4
	34.34291	35.77171	5
	24.1269	20.39093	6
	16.94246	12.34836	7
	35.39447	28.00621	8
	37.62606	33.0964	T



Engine	Filters mg/m^3	TEOM mg/m^3	
3306_R_W	111.6352	97.7133	1
	109.7911	99.2651	2
	111.3361	95.22614	3
	80.90063	80.99951	4
	49.67388	48.29628	5
	31.53855	28.12407	6
	58.15033	47.87181	7
	42.54411	12.85835	T

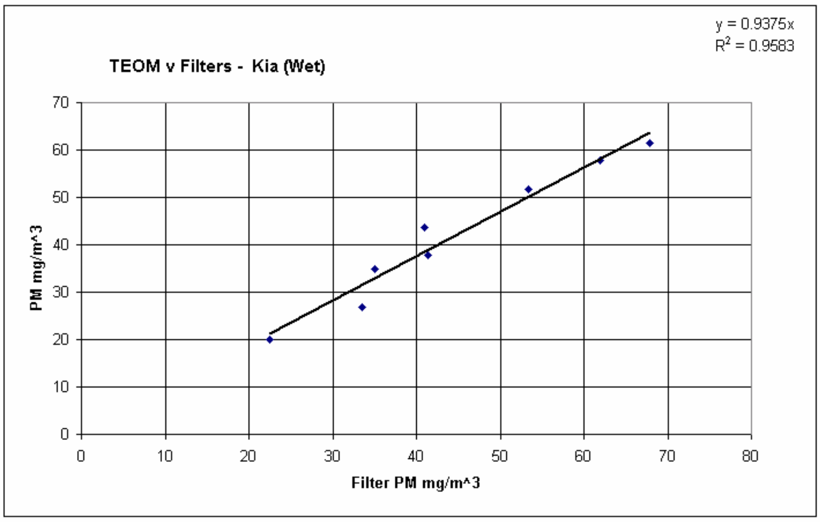


Engine	Filters mg/m^3	TEOM mg/m^4	
3126_R_W	26.68115	24.35797	1
	35.6102	31.46538	2
	35.33376	30.13713	3
	33.20652	28.4967	4
	29.39198	28.38983	5
	31.17185	28.45103	6
	14.38795	14.64098	7
	7.337469	26.23344	T

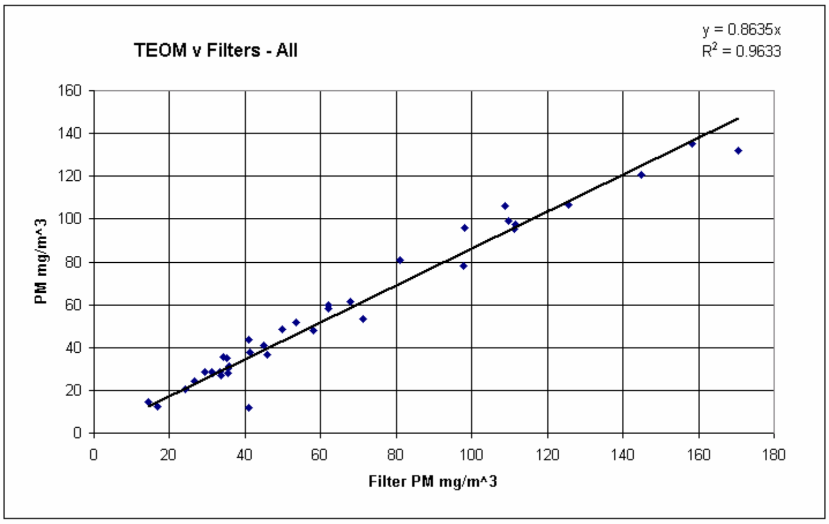


Dyno Tests: Graphs showing TEOM Results against Tunnel Filters (cont)

Engine	Filters mg/m^3	TEOM mg/m^3	
Kia_R_W	67.87793	61.56883	7
	61.91625	57.91962	1
	53.37119	51.62683	2
	40.96045	43.71323	3
	35.0852	34.89333	4
	41.37026	37.69095	5
	33.48689	26.71941	6
	22.54409	20.08407	T



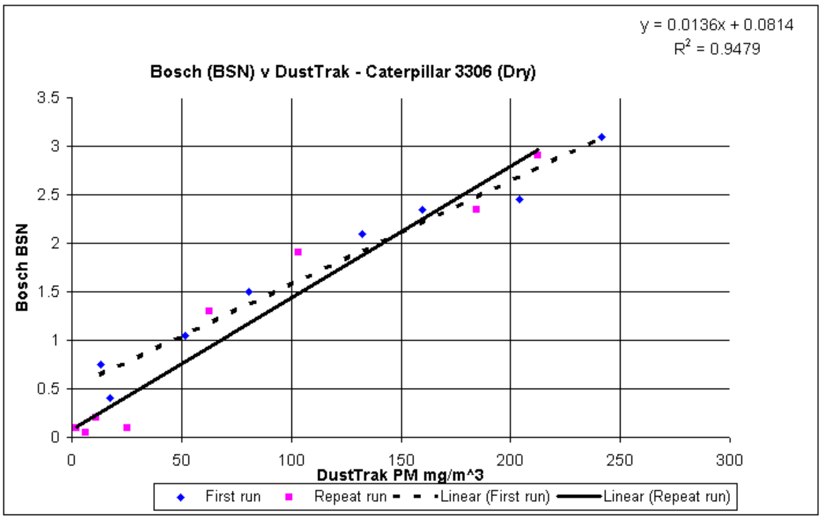
Engine All	Filters mg/m^3	TEOM mg/m^3	
3306_R_D	144.9749	120.8646	1
	125.6348	106.5182	2
	108.7998	106.0881	3
	97.76331	77.85273	4
	71.12105	53.17915	5
	45.80277	36.52086	6
	40.9464	11.66417	7
	44.77824	40.72071	8
3306 dry rpt	158.2609	135.4014	1
	170.6245	132.034	2
	97.99097	95.64474	3
	62.14969	59.60005	4
	34.34291	35.77171	5
	24.1269	20.39093	6
	16.94246	12.34836	7
	35.39447	28.00621	8
3306 wet	111.6352	97.7133	1
	109.7911	99.2651	2
	111.3361	95.22614	3
	80.90063	80.99951	4
	49.67388	48.29628	5
	31.53855	28.12407	6
	58.15033	47.87181	7
Kia wet	67.87793	61.56883	7
	61.91625	57.91962	1
	53.37119	51.62683	2
	40.96045	43.71323	3
	35.0852	34.89333	4
	41.37026	37.69095	5
	33.48689	26.71941	6
3126 wet	26.68115	24.35797	1
	35.6102	31.46538	2
	35.33376	30.13713	3
	33.20652	28.4967	4
	29.39198	28.38983	5
	31.17185	28.45103	6
	14.38795	14.64098	7



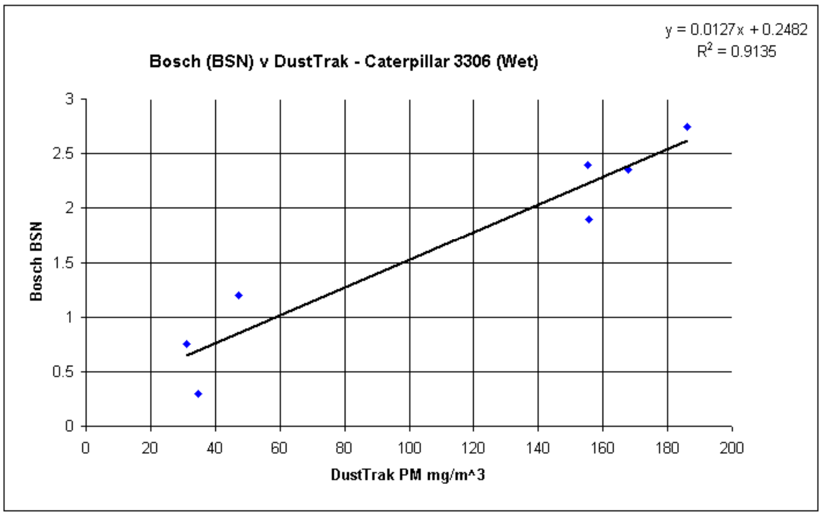
Appendix 8: Dynamometer Tests - Graphs Against DustTrak

Dyno Tests: Graphs showing Bosch Smoke Numbers against DustTrak

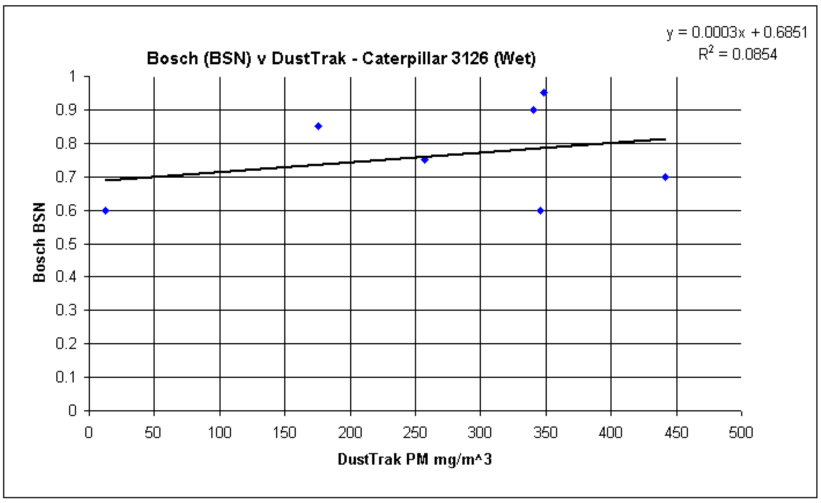
Engine	DustTrak mg/m^3	BSN	
First run			
3306_R_D	241.5084	3.1	1
	203.991	2.45	2
	159.5278	2.35	3
	132.4321	2.1	4
	80.632	1.5	5
	51.68714	1.05	6
	13.31129	0.75	7
	17.25526	0.4	8
	55.64899	ND	
Repeat run			
3306_R-DR	212.2241	2.9	1
	184.5441	2.35	2
	103.1614	1.9	3
	62.94267	1.3	4
	25.45973	0.1	5
	11.01007	0.2	6
	6.35355	0.05	7
	2.060393	0.1	8
	70.63699	ND	



Engine	DustTrak mg/m^3	BSN	
3306_R_W	185.9789	2.75	1
	167.7632	2.35	2
	155.1764	2.4	3
	155.6254	1.9	4
	47.22345	1.2	5
	31.22516	0.75	6
	34.8477	0.3	7
	55.36697	ND	

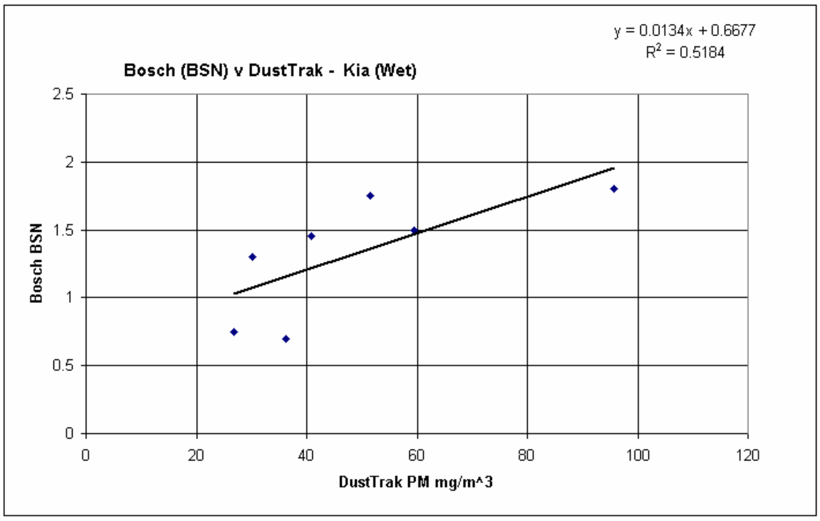


Engine	DustTrak mg/m^3	BSN	
3126_R_W	340.222	0.9	1
	348.5504	0.95	2
	441.7406	0.7	3
	175.8299	0.85	4
	257.2719	0.75	5
	345.7951	0.6	6
	12.00911	0.6	7
	24.1185		

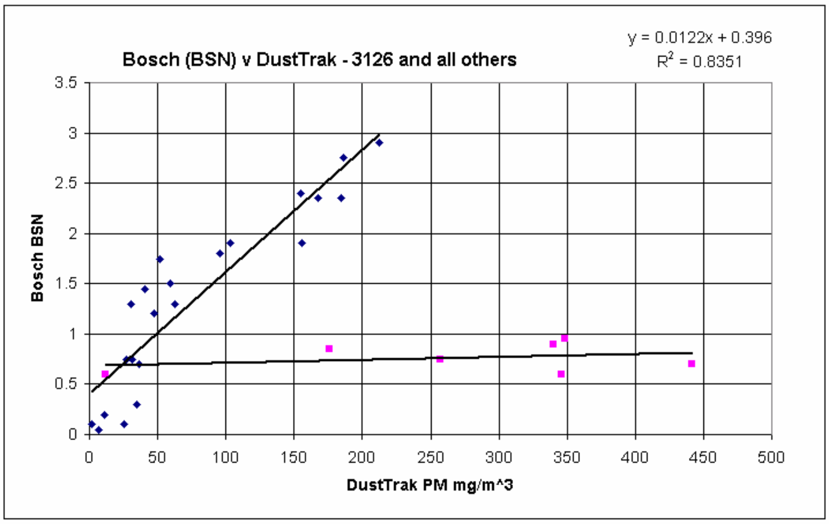


Dyno Tests: Graphs showing Bosch Smoke Numbers against DustTrak (cont)

Engine	DustTrak mg/m^3	BSN	
Kia_R_W	95.751	1.8	7
	51.62022	1.75	1
	59.43573	1.5	2
	40.76243	1.45	3
	36.1462	0.7	4
	30.21423	1.3	5
	26.86498	0.75	6
	22.15036	ND	

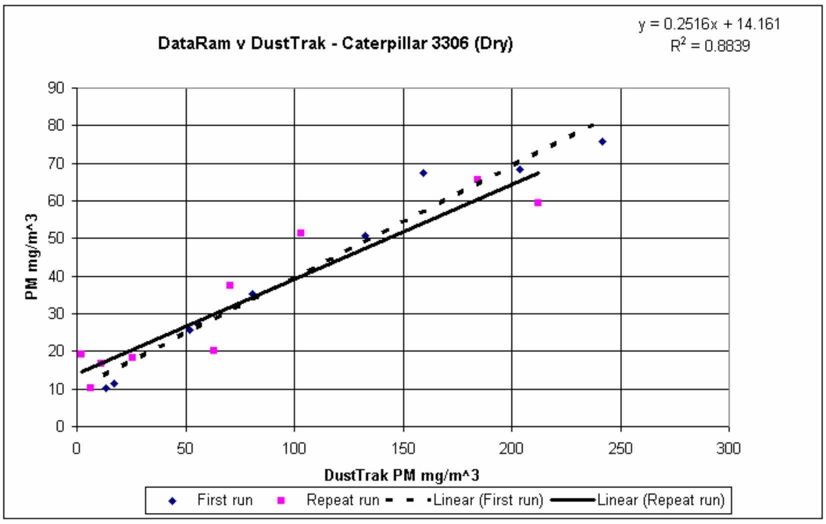


Engine All	DustTrak mg/m^3	BSN	
3306 dry rpt	212.2241	2.9	1
	184.5441	2.35	2
	103.1614	1.9	3
	62.94267	1.3	4
	25.45973	0.1	5
	11.01007	0.2	6
	6.35355	0.05	7
	2.060393	0.1	8
3306 wet	185.9789	2.75	1
	167.7632	2.35	2
	155.1764	2.4	3
	155.6254	1.9	4
	47.22345	1.2	5
	31.22516	0.75	6
	34.8477	0.3	7
Kia wet	95.751	1.8	7
	51.62022	1.75	1
	59.43573	1.5	2
	40.76243	1.45	3
	36.1462	0.7	4
	30.21423	1.3	5
	26.86498	0.75	6
3126 wet	340.222	0.9	1
	348.5504	0.95	2
	441.7406	0.7	3
	175.8299	0.85	4
	257.2719	0.75	5
	345.7951	0.6	6
	12.00911	0.6	7

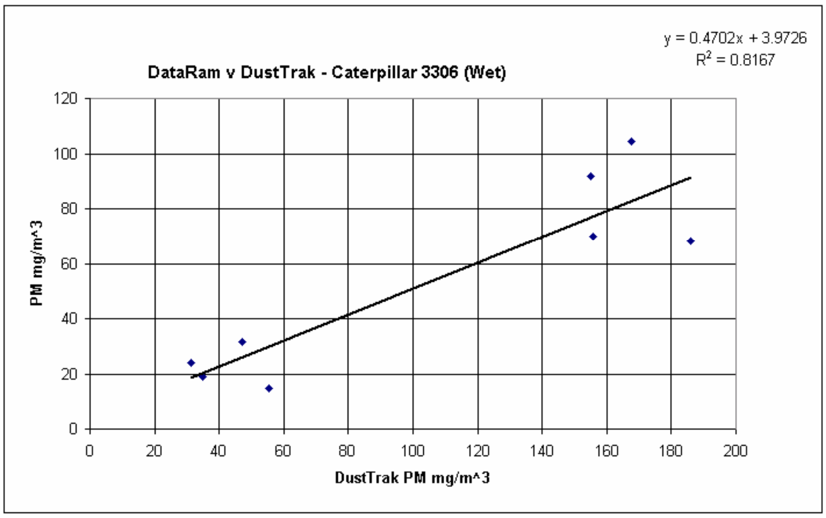


Dyno Tests: Graphs showing DataRam against DustTrak

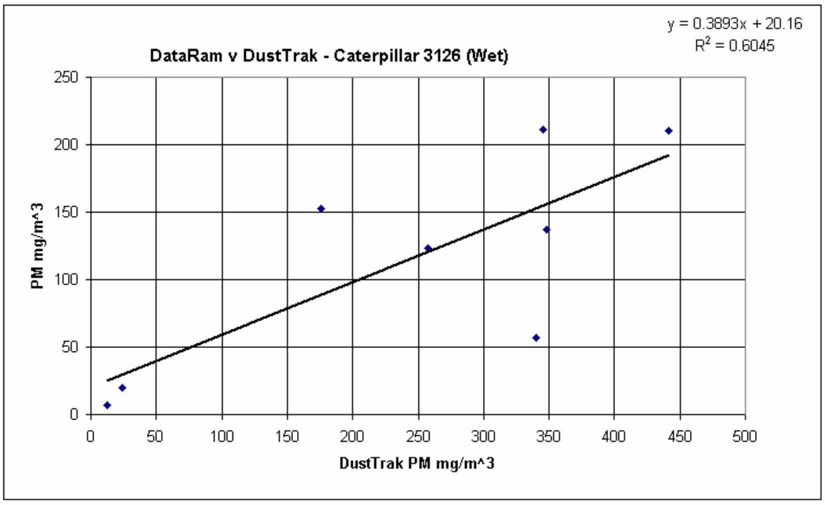
Engine	DustTrak mg/m^3	DataRam mg/m^3	
First run			
3306_R_D	241.5084	75.84954	1
	203.991	68.46531	2
	159.5278	67.56721	3
	132.4321	50.67822	4
	80.632	35.33542	5
	51.68714	25.78151	6
	13.31129	10.35274	7
	17.25526	11.39736	8
	55.64899	27.20105	T
Repeat run			
3306_R-DR	212.2241	59.29648	1
	184.5441	65.5984	2
	103.1614	51.2299	3
	62.94267	20.04363	4
	25.45973	18.27415	5
	11.01007	16.60594	6
	6.35355	10.35716	7
	2.060393	19.20607	8
	70.63699	37.49956	T



Engine	DustTrak mg/m^3	DataRam mg/m^3	
3306_R_W	185.9789	68.2645	1
	167.7632	104.3811	2
	155.1764	91.89956	3
	155.6254	69.71044	4
	47.22345	31.6689	5
	31.22516	24.12906	6
	34.8477	18.74461	7
	55.36697	14.74648	T

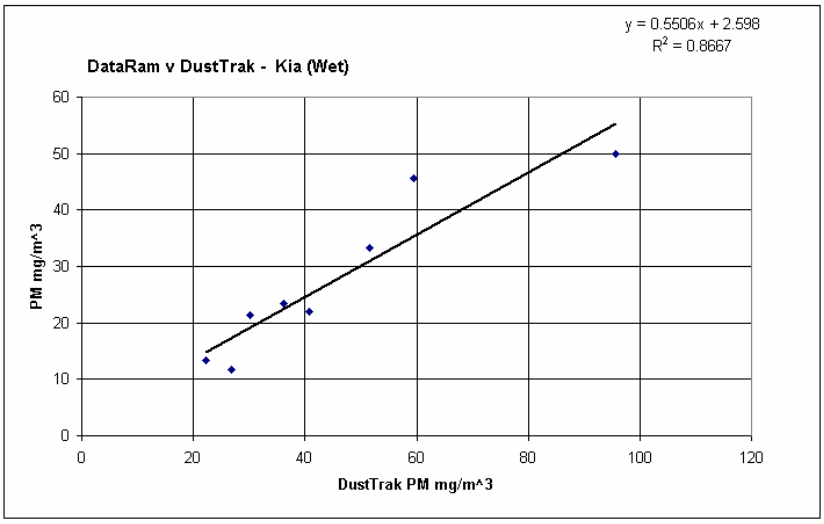


Engine	DustTrak mg/m^3	DataRam mg/m^4	
3126_R_W	340.222	57.21166	1
	348.5504	136.7871	2
	441.7406	210.4515	3
	175.8299	152.8652	4
	257.2719	122.9026	5
	345.7951	211.1517	6
	12.00911	7.118454	7
	24.1185	20.22734	T

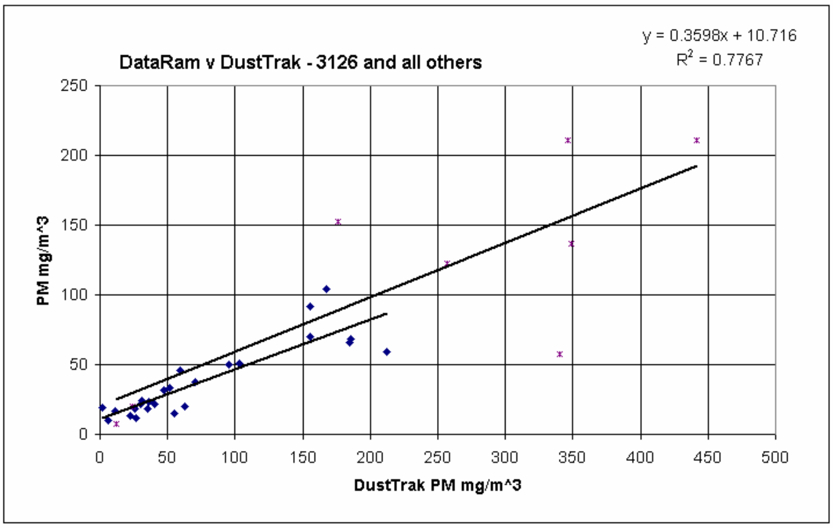


Dyno Tests: Graphs showing DataRam against DustTrak (cont)

Engine	DustTrak mg/m^3	DataRam mg/m^3	
Kia_R_W	95.751	49.9759	7
	51.62022	33.29795	1
	59.43573	45.51422	2
	40.76243	21.94286	3
	36.1462	23.37458	4
	30.21423	21.42802	5
	26.86498	11.80993	6
	22.15036	13.27305	T

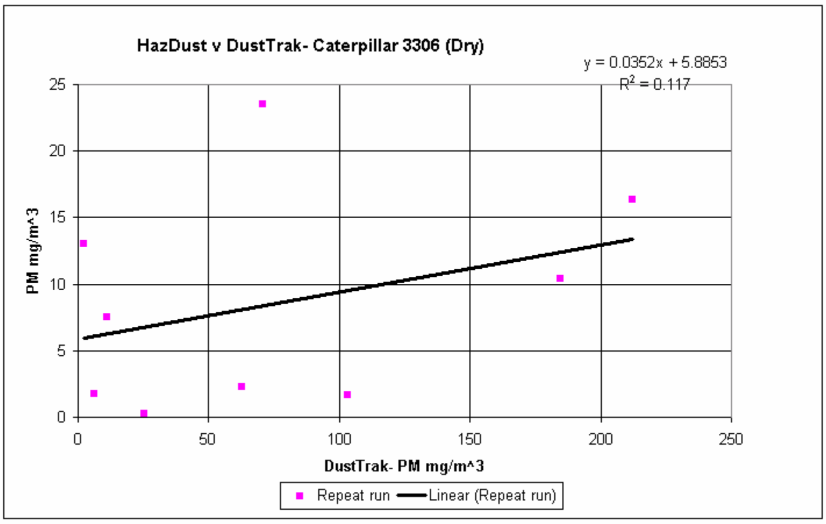


Engine All	DustTrak mg/m^3	DataRam mg/m^3	
3306 dry rpt	212.2241	59.29648	1
	184.5441	65.5984	2
	103.1614	51.2299	3
	62.94267	20.04363	4
	25.45973	18.27415	5
	11.01007	16.60594	6
	6.35355	10.35716	7
	2.060393	19.20607	8
	70.63699	37.49956	T
3306 wet	185.9789	68.2645	1
	167.7632	104.3811	2
	155.1764	91.89956	3
	155.6254	69.71044	4
	47.22345	31.6689	5
	31.22516	24.12906	6
	34.8477	18.74461	7
	55.36697	14.74648	T
Kia wet	95.751	49.9759	7
	51.62022	33.29795	1
	59.43573	45.51422	2
	40.76243	21.94286	3
	36.1462	23.37458	4
	30.21423	21.42802	5
	26.86498	11.80993	6
	22.15036	13.27305	T
3126 wet	340.222	57.21166	1
	348.5504	136.7871	2
	441.7406	210.4515	3
	175.8299	152.8652	4
	257.2719	122.9026	5
	345.7951	211.1517	6
	12.00911	7.118454	7
	24.1185	20.22734	T



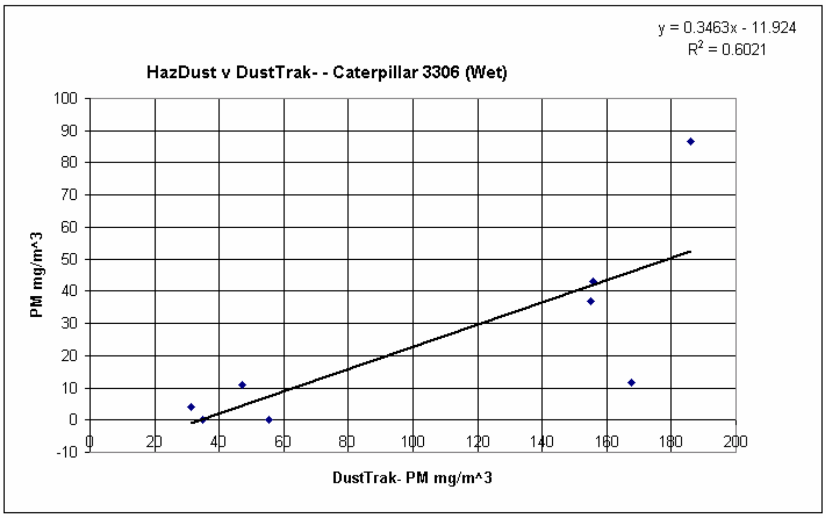
Dyno Tests: Graphs showing HazDust against DustTrak

Engine	DustTrak mg/m^3	HazDust mg/m^3	
First run			
3306_R_D	241.5084	ND	1
	203.991	ND	2
	159.5278	ND	3
	132.4321	ND	4
	80.632	ND	5
	51.68714	ND	6
	13.31129	ND	7
	17.25526	ND	8
	55.64899	ND	T
Repeat run			
3306_R-DR	212.2241	16.38759	1
	184.5441	10.36131	2
	103.1614	1.671488	3
	62.94267	2.240284	4
	25.45973	0.279179	5
	11.01007	7.54114	6
	6.35355	1.781591	7
	2.060393	13.047	8
	70.63699	23.52806	T

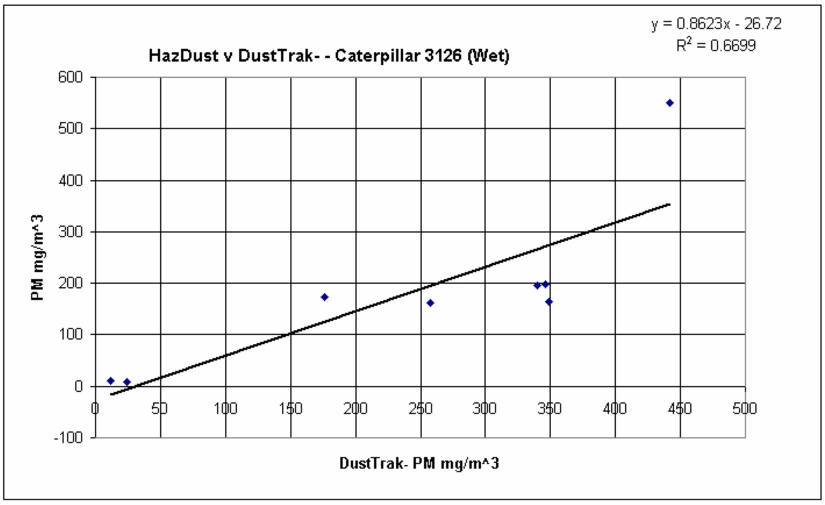


Engine	DustTrak mg/m^3	HazDust mg/m^3	
3306_R_W	185.9789	86.5865	1
	167.7632	11.466	2
	155.1764	36.99641	3
	155.6254	42.97475	4
	47.22345	10.92	5
	31.22516	4.16325	6
	34.8477	ND	7
	55.36697	ND	T

Note: Manual data

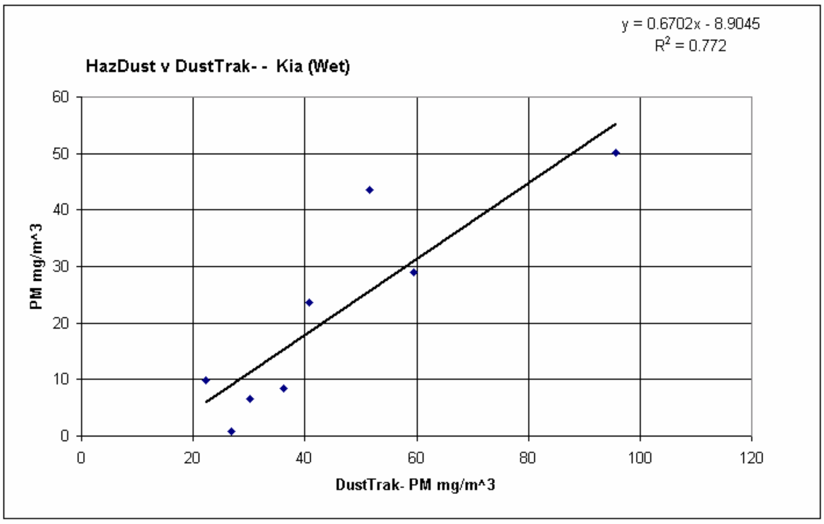


Engine	DustTrak mg/m^3	HazDust mg/m^4	
3126_R_W	340.222	195.5948	1
	348.5504	165.2135	2
	441.7406	549.6141	3
	175.8299	174.1073	4
	257.2719	162.396	5
	345.7951	198.7178	6
	12.00911	10.52315	7
	24.1185	7.774245	T

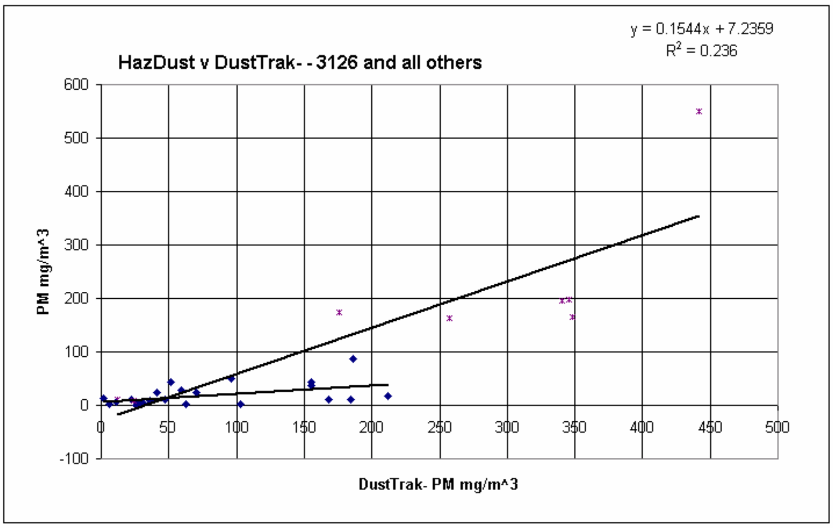


Dyno Tests: Graphs showing HazDust against DustTrak (cont)

Engine	DustTrak mg/m^3	HazDust mg/m^3	
Kia_R_W	95.751	50.11812	7
	51.62022	43.55641	1
	59.43573	29.04339	2
	40.76243	23.59807	3
	36.1462	8.448855	4
	30.21423	6.532137	5
	26.86498	0.866602	6
	22.15036	9.840692	T

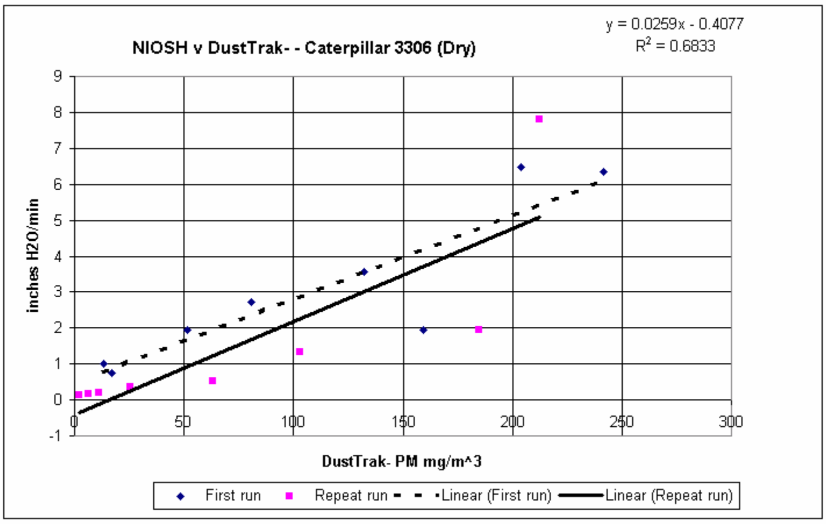


Engine All	DustTrak mg/m^3	HazDust mg/m^3	
3306 dry rpt	212.2241	16.38759	1
	184.5441	10.36131	2
	103.1614	1.671488	3
	62.94267	2.240284	4
	25.45973	0.279179	5
	11.01007	7.54114	6
	6.35355	1.781591	7
	2.060393	13.047	8
	70.63699	23.52806	T
3306 wet	185.9789	86.5865	1
	167.7632	11.466	2
	155.1764	36.99641	3
	155.6254	42.97475	4
	47.22345	10.92	5
	31.22516	4.16325	6
Kia wet	95.751	50.11812	7
	51.62022	43.55641	1
	59.43573	29.04339	2
	40.76243	23.59807	3
	36.1462	8.448855	4
	30.21423	6.532137	5
	26.86498	0.866602	6
	22.15036	9.840692	T
3126 wet	340.222	195.5948	1
	348.5504	165.2135	2
	441.7406	549.6141	3
	175.8299	174.1073	4
	257.2719	162.396	5
	345.7951	198.7178	6
	12.00911	10.52315	7
	24.1185	7.77	T

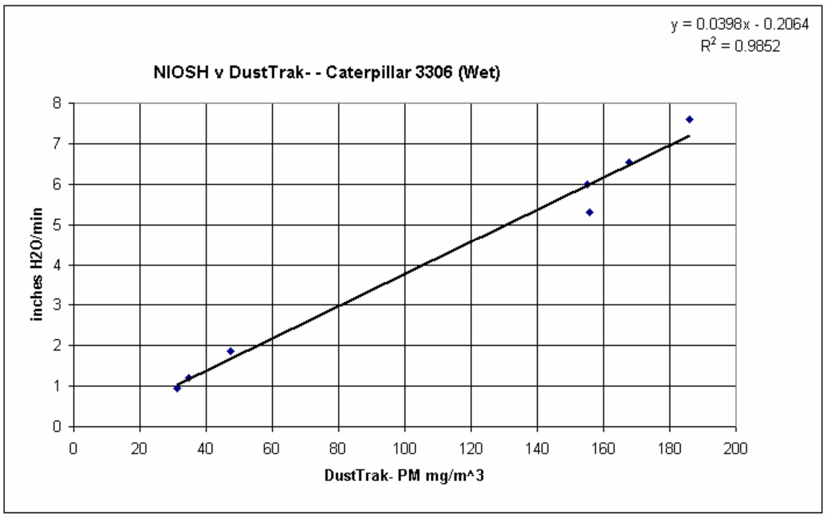


Dyno Tests: Graphs showing NIOSH against DustTrak

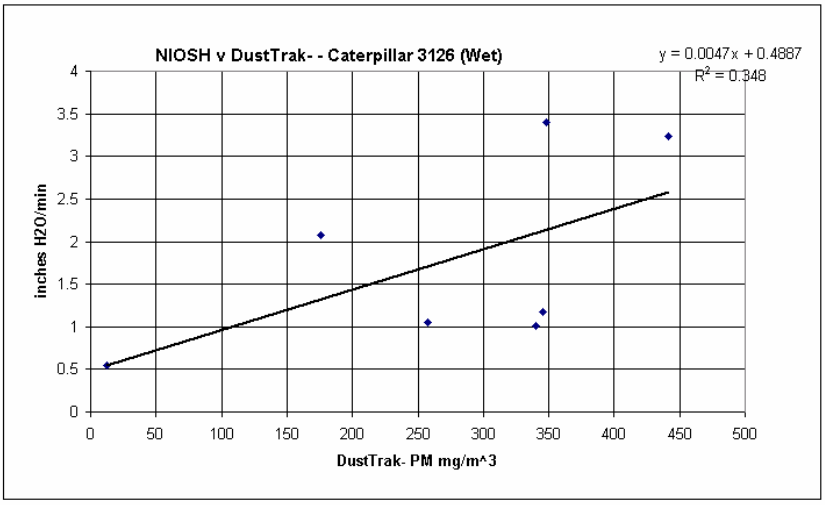
Engine	DustTrak mg/m^3	NIOSH inches H2O/min
First run		
3306_R_D	241.5084	6.36
	203.991	6.475
	159.5278	1.945
	132.4321	3.55
	80.632	2.71
	51.68714	1.953333
	13.31129	1.003333
	17.25526	0.756667
	55.64899	2.403333
Repeat run		
3306_R-DR	212.2241	7.81
	184.5441	1.956667
	103.1614	1.345
	62.94267	0.533333
	25.45973	0.356667
	11.01007	0.21
	6.35355	0.17
	2.060393	0.12
	70.63699	2.58



Engine	DustTrak mg/m^3	NIOSH inches H2O/min
3306_R_W	185.9789	7.606667
	167.7632	6.55
	155.1764	6.003333
	155.6254	5.306667
	47.22345	1.873333
	31.22516	0.936667
	34.8477	1.213333
	55.36697	1.213333

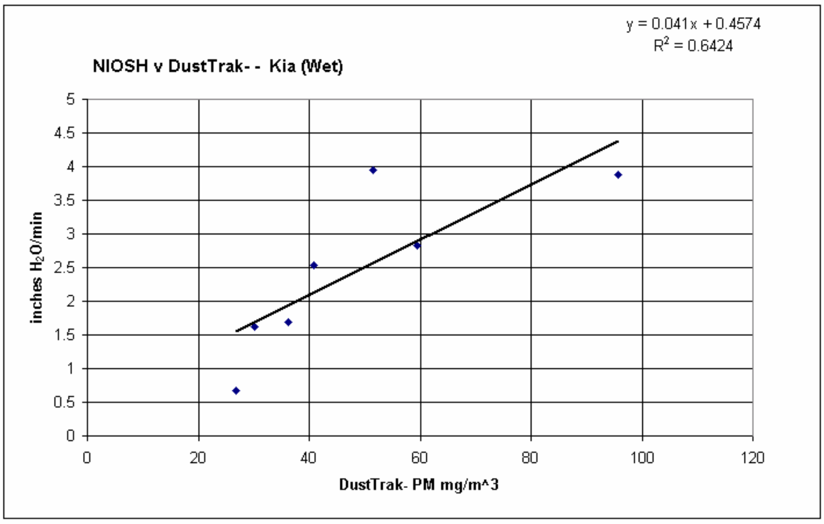


Engine	DustTrak mg/m^3	NIOSH mg/m^4
3126_R_W	340.222	1.013333
	348.5504	3.393
	441.7406	3.236667
	175.8299	2.076667
	257.2719	1.056667
	345.7951	1.17
	12.00911	0.55
	24.1185	

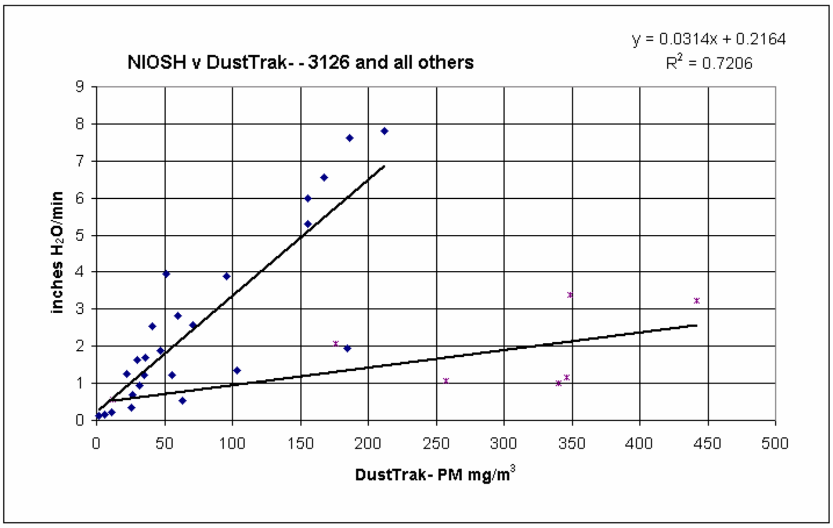


Dyno Tests: Graphs showing NIOSH against DustTrak (cont)

Engine	DustTrak mg/m^3	NIOSH inches H2O/min
Kia_R_W	95.751	3.88
	51.62022	3.956667
	59.43573	2.826667
	40.76243	2.526667
	36.1462	1.696667
	30.21423	1.62
	26.86498	0.68
	22.15036	1.243333



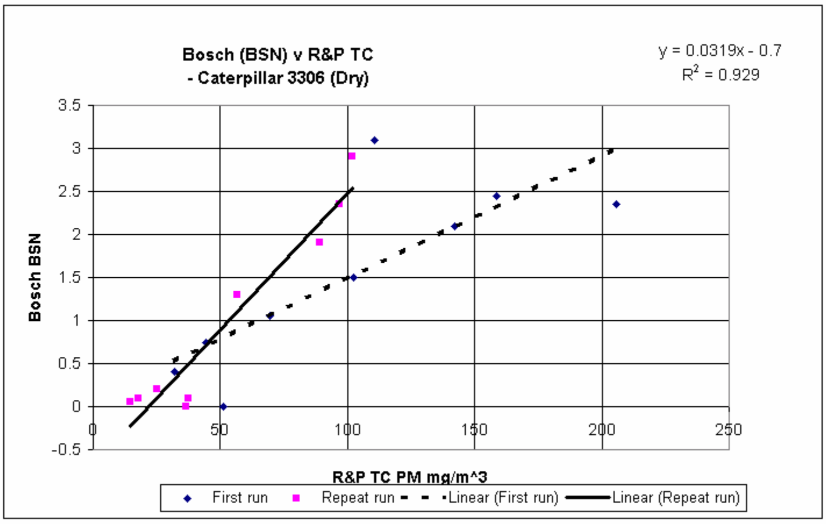
Engine All	DustTrak mg/m^3	NIOSH inches H2O/min
3306 dry rpt	212.2241	7.81
	184.5441	1.956667
	103.1614	1.345
	62.94267	0.533333
	25.45973	0.356667
	11.01007	0.21
	6.35355	0.17
	2.060393	0.12
	70.63699	2.58
3306 wet	185.9789	7.606667
	167.7632	6.55
	155.1764	6.003333
	155.6254	5.306667
	47.22345	1.873333
	31.22516	0.936667
	34.8477	1.213333
	55.36697	1.213333
Kia wet	95.751	3.88
	51.62022	3.956667
	59.43573	2.826667
	40.76243	2.526667
	36.1462	1.696667
	30.21423	1.62
	26.86498	0.68
	22.15036	1.243333
3126 wet	340.222	1.013333
	348.5504	3.393
	441.7406	3.236667
	175.8299	2.076667
	257.2719	1.056667
	345.7951	1.17
	12.00911	0.55
	24.1185	0.536667



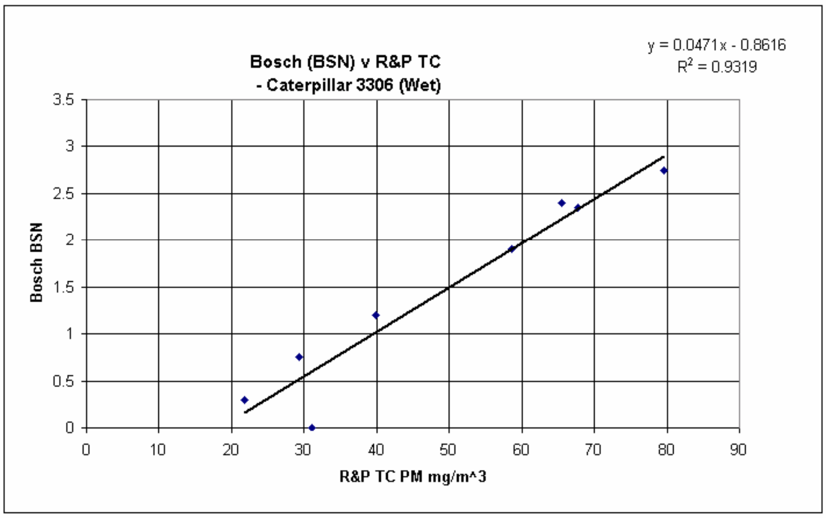
Appendix 9:Dynamometer Tests - Graphs Against R&P TC

Dyno Tests: Graphs showing Bosch Smoke Number against R&P TC

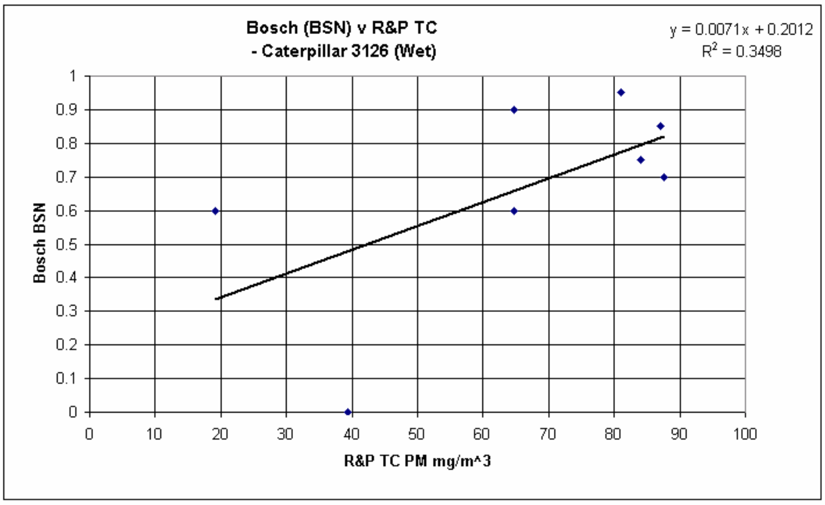
Engine	R&P TC mg/m^3	BSN	
First run			
3306_R_D	110.4	3.1	1
	158.65	2.45	2
	205.55	2.35	3
	142.05	2.1	4
	102.52	1.5	5
	69.345	1.05	6
	44.32	0.75	7
	31.93	0.4	8
	51.015 ND		ND
Repeat run			
3306_R-DR	101.715	2.9	1
	96.955	2.35	2
	89.11	1.9	3
	56.72	1.3	4
	37.67	0.1	5
	24.955	0.2	6
	14.84	0.05	7
	18.015	0.1	8
	36.73 ND		T



Engine	R&P TC mg/m^3	BSN	
3306_R_W	79.605	2.75	1
	67.78	2.35	2
	65.48	2.4	3
	58.605	1.9	4
	39.935	1.2	5
	29.33	0.75	6
	21.8	0.3	7
	31.06 ND		T

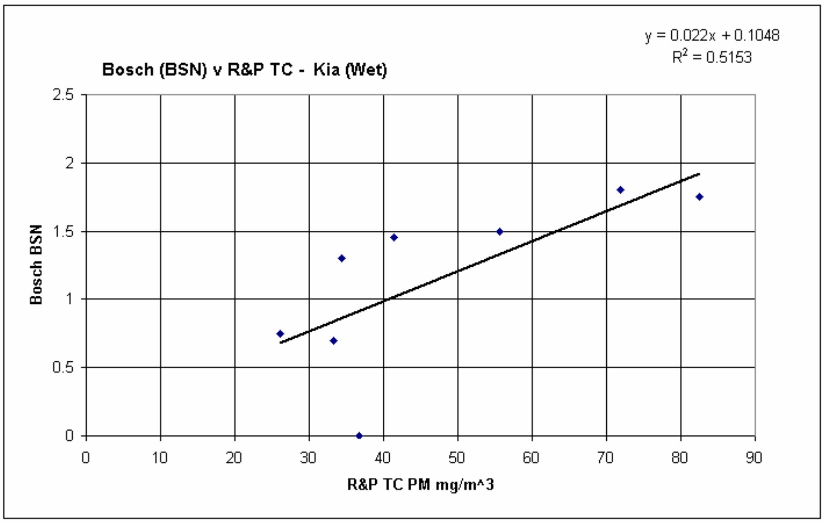


Engine	R&P TC mg/m^3	BSN	
3126_R_W	64.64	0.9	1
	81.03	0.95	2
	87.5	0.7	3
	87.09	0.85	4
	84.095	0.75	5
	64.74	0.6	6
	19.08	0.6	7
	39.285 ND		T

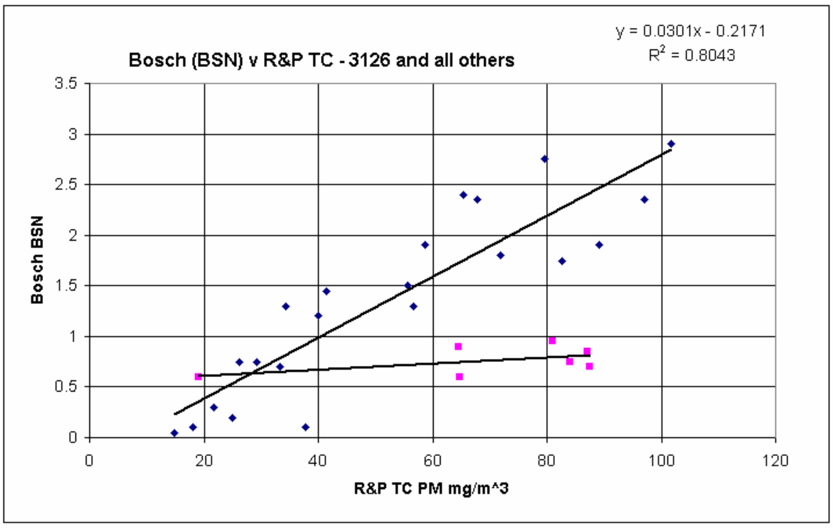


Dyno Tests: Graphs showing Bosch Smoke Number against R&P TC (cont)

Engine	R&P TC mg/m^3	BSN	
Kia_R_W	71.84	1.8	7
	82.545	1.75	1
	55.685	1.5	2
	41.37	1.45	3
	33.235	0.7	4
	34.405	1.3	5
	26.145	0.75	6
	36.74 ND		ND

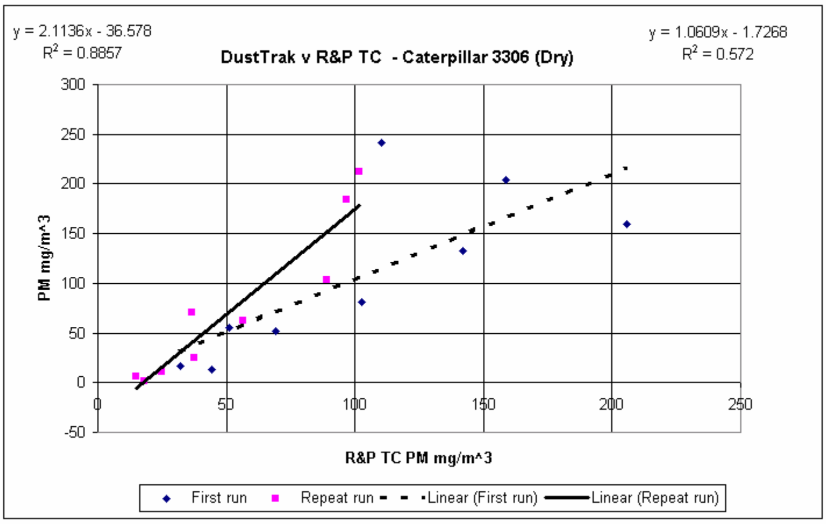


Engine All	R&P TC mg/m^3	BSN	
3306 dry rpt	101.715	2.9	1
	96.955	2.35	2
	89.11	1.9	3
	56.72	1.3	4
	37.67	0.1	5
	24.955	0.2	6
	14.84	0.05	7
	18.015	0.1	8
3306 wet	79.605	2.75	1
	67.78	2.35	2
	65.48	2.4	3
	58.605	1.9	4
	39.935	1.2	5
	29.33	0.75	6
	21.8	0.3	7
Kia wet	71.84	1.8	7
	82.545	1.75	1
	55.685	1.5	2
	41.37	1.45	3
	33.235	0.7	4
	34.405	1.3	5
	26.145	0.75	6
3126 wet	64.64	0.9	1
	81.03	0.95	2
	87.5	0.7	3
	87.09	0.85	4
	84.095	0.75	5
	64.74	0.6	6
	19.08	0.6	7

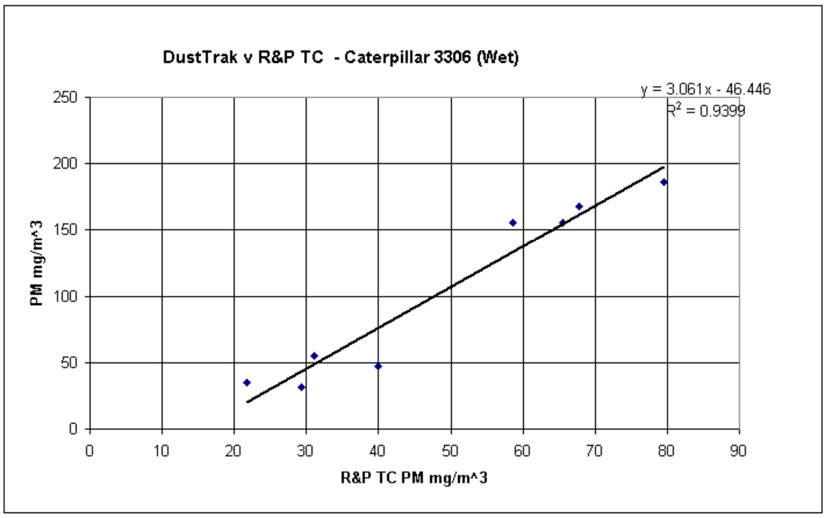


Dyno Tests: Graphs showing DustTrak against R&P Total Carbon

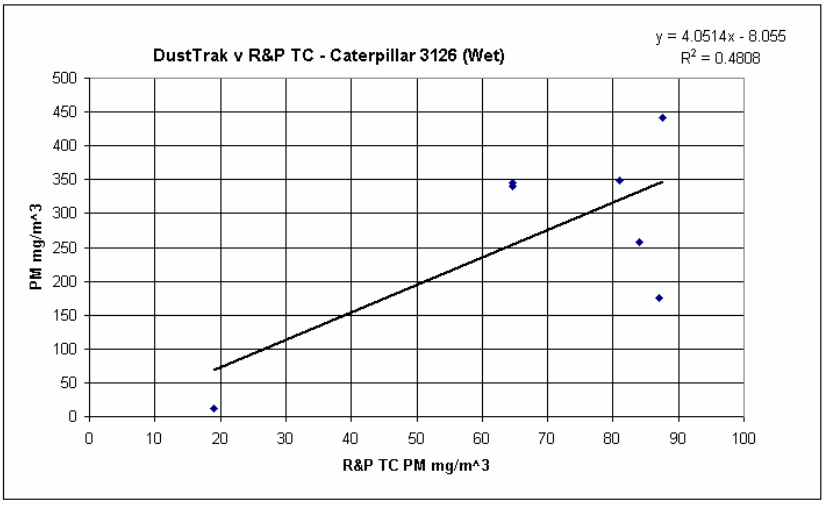
Engine	R&P TC mg/m^3	DustTrak mg/m^3	
First run			
3306_R_D	110.4	241.5084	1
	158.65	203.991	2
	205.55	159.5278	3
	142.05	132.4321	4
	102.52	80.632	5
	69.345	51.68714	6
	44.32	13.31129	7
	31.93	17.25526	8
	51.015	55.64899	T
Repeat run	R&P TC	DustTrak	
3306_R-DR	101.715	212.2241	1
	96.955	184.5441	2
	89.11	103.1614	3
	56.72	62.94267	4
	37.67	25.45973	5
	24.955	11.01007	6
	14.84	6.35355	7
	18.015	2.060393	8
	36.73	70.63699	T



Engine	R&P TC mg/m^3	DustTrak mg/m^3	
3306_R_W	79.605	185.9789	1
	67.78	167.7632	2
	65.48	155.1764	3
	58.605	155.6254	4
	39.935	47.22345	5
	29.33	31.22516	6
	21.8	34.8477	7
	31.06	55.36697	T

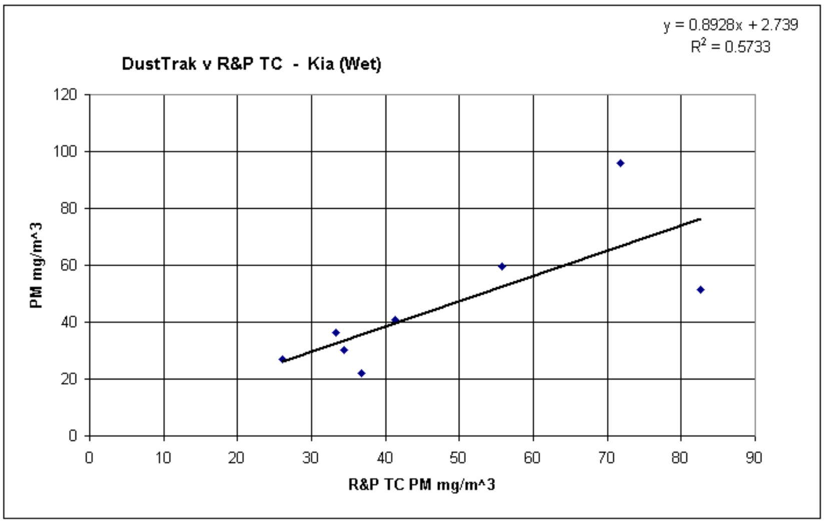


Engine	R&P TC mg/m^3	DustTrak mg/m^3	
3126_R_W	64.64	340.222	1
	81.03	348.5504	2
	87.5	441.7406	3
	87.09	175.8299	4
	84.095	257.2719	5
	64.74	345.7951	6
	19.08	12.00911	7
	39.285	24.1185	T

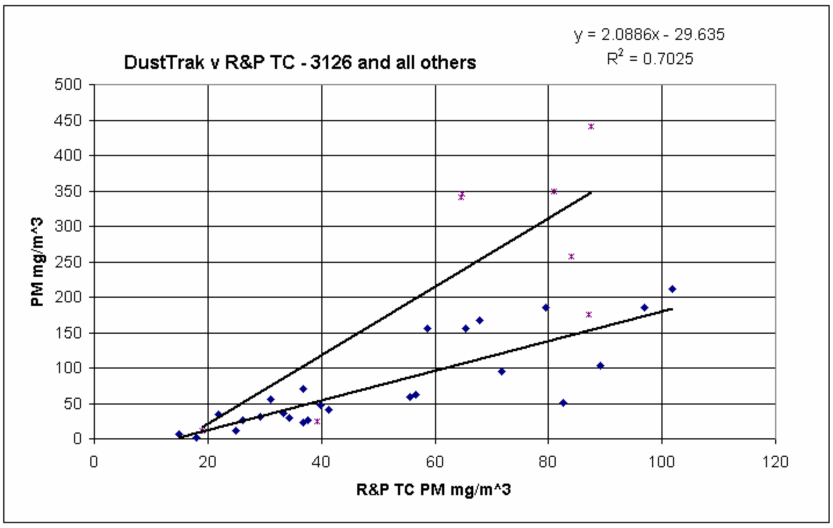


Dyno Tests: Graphs showing DustTrak against R&P Total Carbon (cont)

Engine	R&P TC mg/m^3	DustTrak mg/m^3	
Kia_R_W	71.84	95.751	7
	82.545	51.62022	1
	55.685	59.43573	2
	41.37	40.76243	3
	33.235	36.1462	4
	34.405	30.21423	5
	26.145	26.86498	6
	36.74	22.15036	T

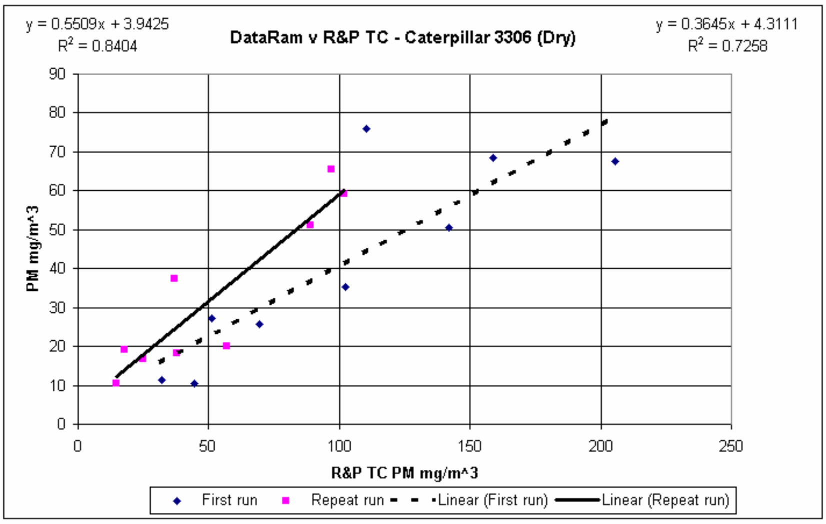


Engine All	R&P TC mg/m^3	DustTrak mg/m^3	
3306 dry rpt	101.715	212.2241	1
	96.955	184.5441	2
	89.11	103.1614	3
	56.72	62.94267	4
	37.67	25.45973	5
	24.955	11.01007	6
	14.84	6.35355	7
	18.015	2.060393	8
	36.73	70.63699	T
3306 wet	79.605	185.9789	1
	67.78	167.7632	2
	65.48	155.1764	3
	58.605	155.6254	4
	39.935	47.22345	5
	29.33	31.22516	6
	21.8	34.8477	7
	31.06	55.36697	T
Kia wet	71.84	95.751	7
	82.545	51.62022	1
	55.685	59.43573	2
	41.37	40.76243	3
	33.235	36.1462	4
	34.405	30.21423	5
	26.145	26.86498	6
	36.74	22.15036	T
3126 wet	64.64	340.222	1
	81.03	348.5504	2
	87.5	441.7406	3
	87.09	175.8299	4
	84.095	257.2719	5
	64.74	345.7951	6
	19.08	12.00911	7
	39.285	24.1185	T

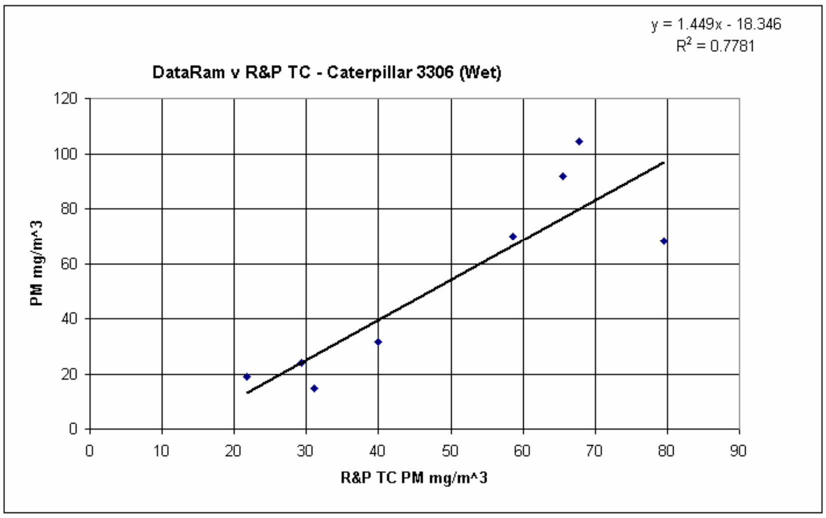


Dyno Tests: Graphs showing DataRam against R&P Total Carbon

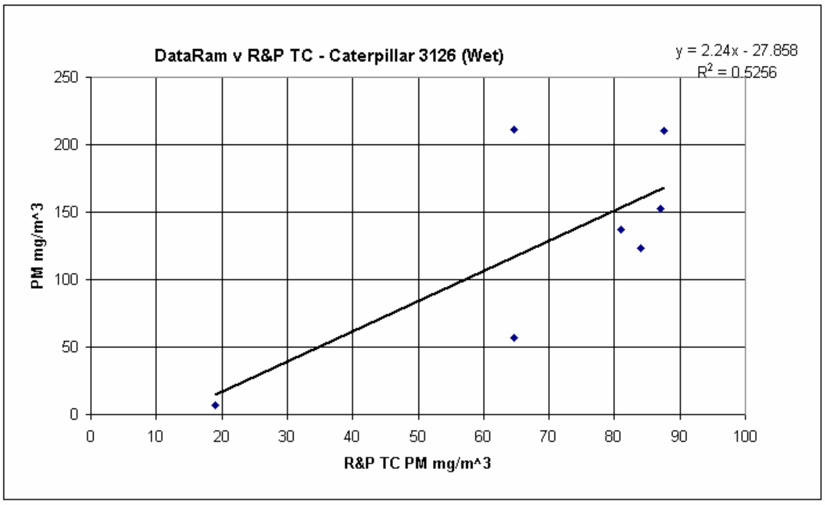
Engine	R&P TC mg/m^3	DataRam mg/m^3	
First run			
3306_R_D	110.4	75.84954	1
	158.65	68.46531	2
	205.55	67.56721	3
	142.05	50.67822	4
	102.52	35.33542	5
	69.345	25.78151	6
	44.32	10.35274	7
	31.93	11.39736	8
	51.015	27.20105	T
Repeat run			
3306_R-DR	101.715	59.29648	1
	96.955	65.5984	2
	89.11	51.2299	3
	56.72	20.04363	4
	37.67	18.27415	5
	24.955	16.60594	6
	14.84	10.35716	7
	18.015	19.20607	8
	36.73	37.49956	T



Engine	R&P TC mg/m^3	DataRam mg/m^3	
3306_R_W	79.605	68.2645	1
	67.78	104.3811	2
	65.48	91.89956	3
	58.605	69.71044	4
	39.935	31.6689	5
	29.33	24.12906	6
	21.8	18.74461	7
	31.06	14.74648	T

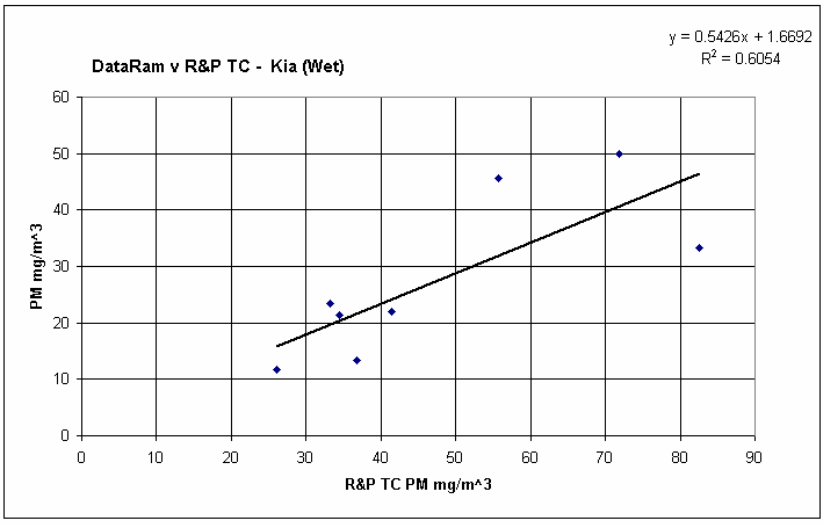


Engine	R&P TC mg/m^3	DataRam mg/m^4	
3126_R_W	64.64	57.21166	1
	81.03	136.7871	2
	87.5	210.4515	3
	87.09	152.8652	4
	84.095	122.9026	5
	64.74	211.1517	6
	19.08	7.118454	7
	39.285	20.22734	T

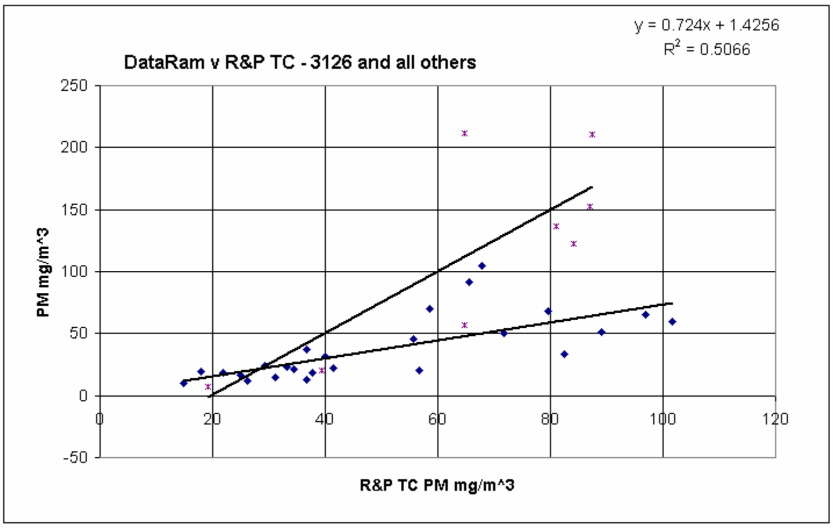


Dyno Tests: Graphs showing DataRam against R&P Total Carbon (cont)

Engine	R&P TC mg/m^3	DataRam mg/m^3	
Kia_R_W	71.84	49.9759	7
	82.545	33.29795	1
	55.685	45.51422	2
	41.37	21.94286	3
	33.235	23.37458	4
	34.405	21.42802	5
	26.145	11.80993	6
	36.74	13.27305	T

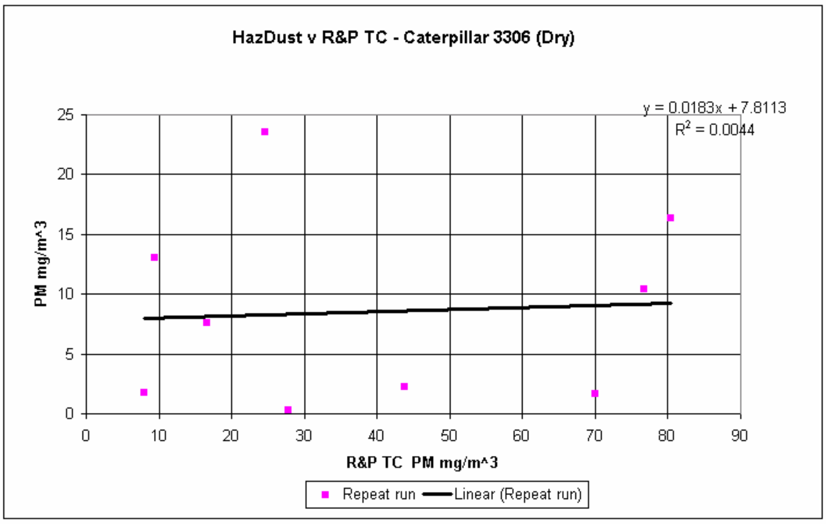


Engine All	R&P TC mg/m^3	DataRam mg/m^3	
3306 dry rpt	101.715	59.29648	1
	96.955	65.5984	2
	89.11	51.2299	3
	56.72	20.04363	4
	37.67	18.27415	5
	24.955	16.60594	6
	14.84	10.35716	7
	18.015	19.20607	8
	36.73	37.49956	T
3306 wet	79.605	68.2645	1
	67.78	104.3811	2
	65.48	91.89956	3
	58.605	69.71044	4
	39.935	31.6689	5
	29.33	24.12906	6
	21.8	18.74461	7
	31.06	14.74648	T
Kia wet	71.84	49.9759	7
	82.545	33.29795	1
	55.685	45.51422	2
	41.37	21.94286	3
	33.235	23.37458	4
	34.405	21.42802	5
	26.145	11.80993	6
	36.74	13.27305	T
3126 wet	64.64	57.21166	1
	81.03	136.7871	2
	87.5	210.4515	3
	87.09	152.8652	4
	84.095	122.9026	5
	64.74	211.1517	6
	19.08	7.118454	7
	39.285	20.22734	T



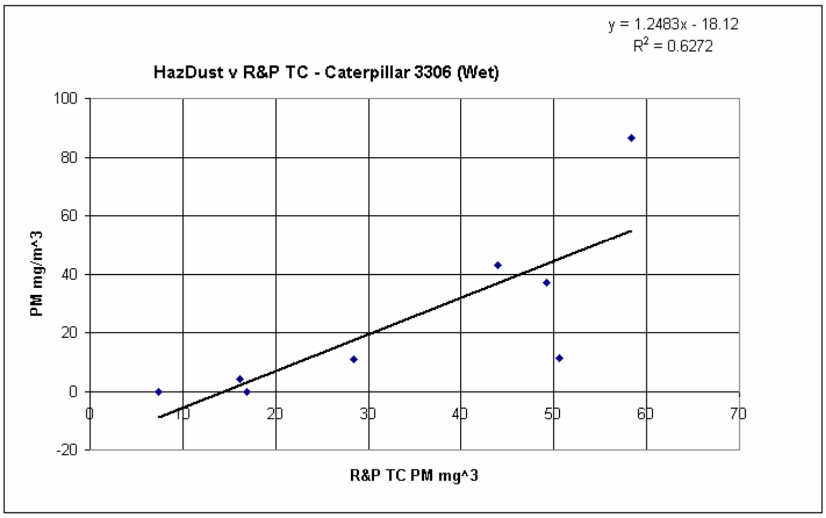
Dyno Tests: Graphs showing HazDust against R&P Total Carbon

Engine	R&P EC mg/m^3	HazDust mg/m^3	
First run			
3306_R_D	54.8	ND	1
	115.05	ND	2
	121.435	ND	3
	97.78	ND	4
	71.38	ND	5
	46.64	ND	6
	28.77	ND	7
	14.765	ND	8
	27.01	ND	T
Repeat run			
3306_R-DR	80.335	16.38759	1
	76.785	10.36131	2
	69.99	1.671488	3
	43.86	2.240284	4
	27.89	0.279179	5
	16.6	7.54114	6
	8.015	1.781591	7
	9.41	13.047	8
	24.595	23.52806	T

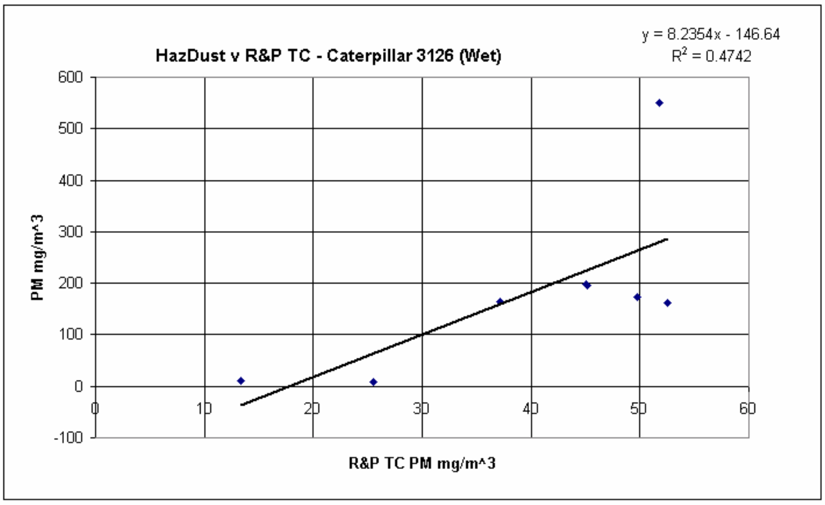


Engine	R&P EC mg/m^3	HazDust mg/m^3	
3306_R_W	58.305	86.5865	1
	50.555	11.466	2
	49.18	36.99641	3
	43.91	42.97475	4
	28.465	10.92	5
	16.12	4.16325	6
	7.41	ND	7
	16.88	ND	T

Note: Manual data

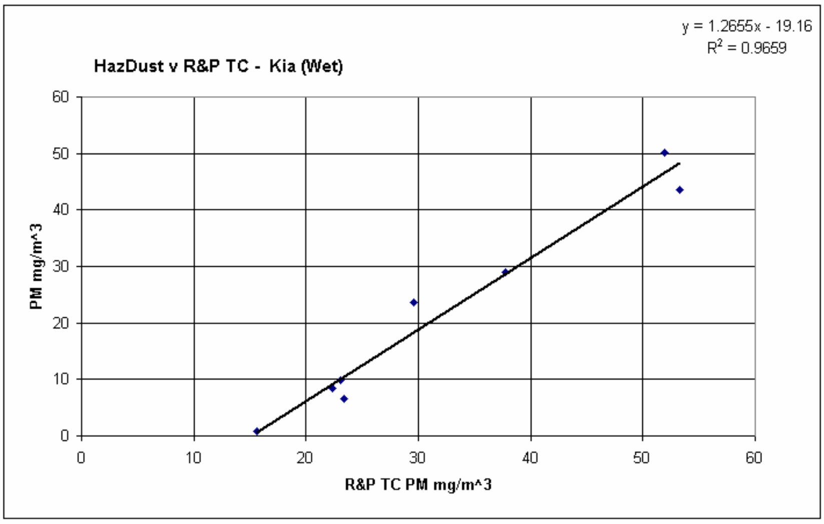


Engine	R&P EC mg/m^3	HazDust mg/m^4	
3126_R_W	45.205	195.5948	1
	37.13	165.2135	2
	51.74	549.6141	3
	49.705	174.1073	4
	52.555	162.396	5
	45.02	198.7178	6
	13.33	10.52315	7
	25.52	7.774245	T

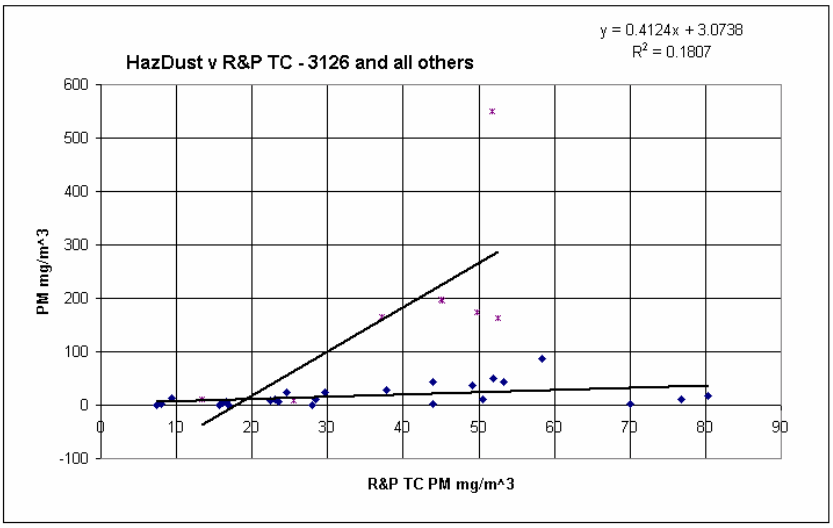


Dyno Tests: Graphs showing HazDust against R&P Total Carbon (cont)

Engine	R&P EC mg/m^3	HazDust mg/m^3	
Kia_R_W	51.9	50.11812	7
	53.245	43.55641	1
	37.81	29.04339	2
	29.595	23.59807	3
	22.365	8.448855	4
	23.425	6.532137	5
	15.64	0.866602	6
	23.05	9.840692	T

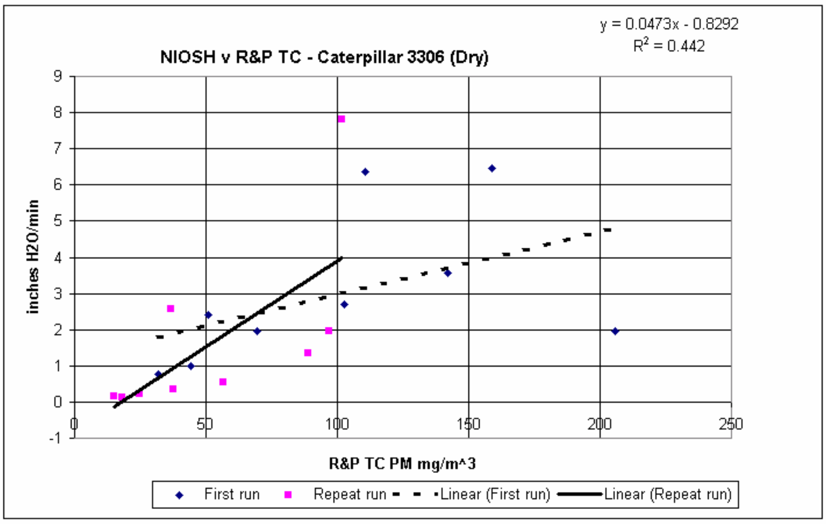


Engine All	R&P EC mg/m^3	HazDust mg/m^3	
3306 dry rpt	80.335	16.38759	1
	76.785	10.36131	2
	69.99	1.671488	3
	43.86	2.240284	4
	27.89	0.279179	5
	16.6	7.54114	6
	8.015	1.781591	7
	9.41	13.047	8
	24.595	23.52806	T
3306 wet	58.305	86.5865	1
	50.555	11.466	2
	49.18	36.99641	3
	43.91	42.97475	4
	28.465	10.92	5
	16.12	4.16325	6
	7.41	ND	7
	16.88	ND	T
Kia wet	51.9	50.11812	7
	53.245	43.55641	1
	37.81	29.04339	2
	29.595	23.59807	3
	22.365	8.448855	4
	23.425	6.532137	5
	15.64	0.866602	6
	23.05	9.840692	T
3126 wet	45.205	195.5948	1
	37.13	165.2135	2
	51.74	549.6141	3
	49.705	174.1073	4
	52.555	162.396	5
	45.02	198.7178	6
	13.33	10.52315	7
	25.52	7.77	T

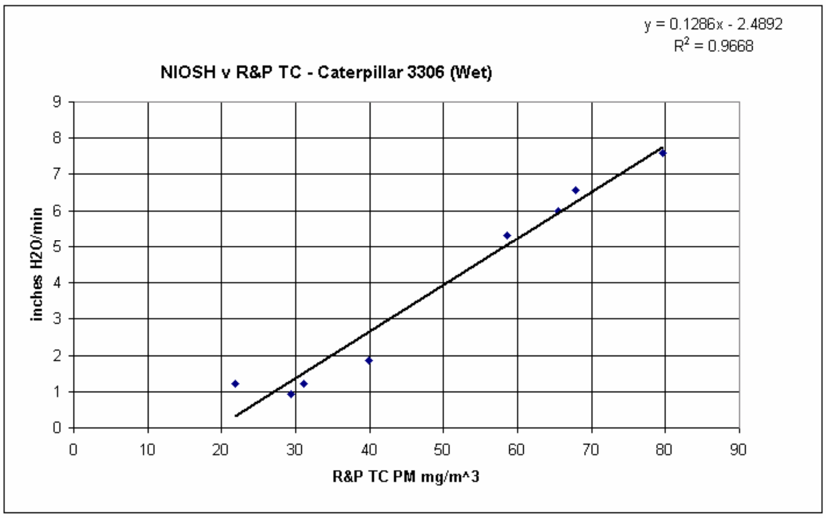


Dyno Tests: Graphs showing NIOSH against R&P Total Carbon

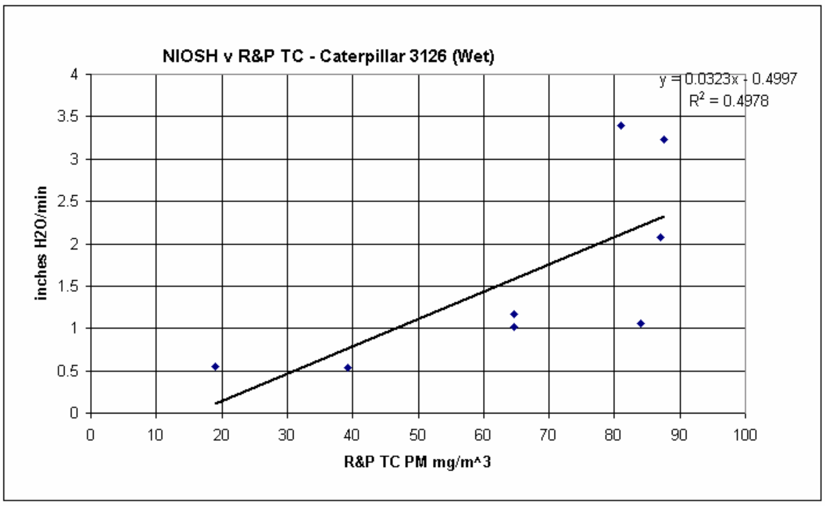
Engine	R&P TC mg/m^3	NIOSH inches H2O/min	
First run			
3306_R_D	110.4	6.36	1
	158.65	6.475	2
	205.55	1.945	3
	142.05	3.55	4
	102.52	2.71	5
	69.345	1.953333	6
	44.32	1.003333	7
	31.93	0.756667	8
	51.015	2.403333	T
Repeat run			
3306_R-DR	101.715	7.81	1
	96.955	1.956667	2
	89.11	1.345	3
	56.72	0.533333	4
	37.67	0.356667	5
	24.955	0.21	6
	14.84	0.17	7
	18.015	0.12	8
	36.73	2.58	T



Engine	R&P TC mg/m^3	NIOSH inches H2O/min	
3306_R_W	79.605	7.606667	1
	67.78	6.55	2
	65.48	6.003333	3
	58.605	5.306667	4
	39.935	1.873333	5
	29.33	0.936667	6
	21.8	1.213333	7
	31.06	1.213333	T

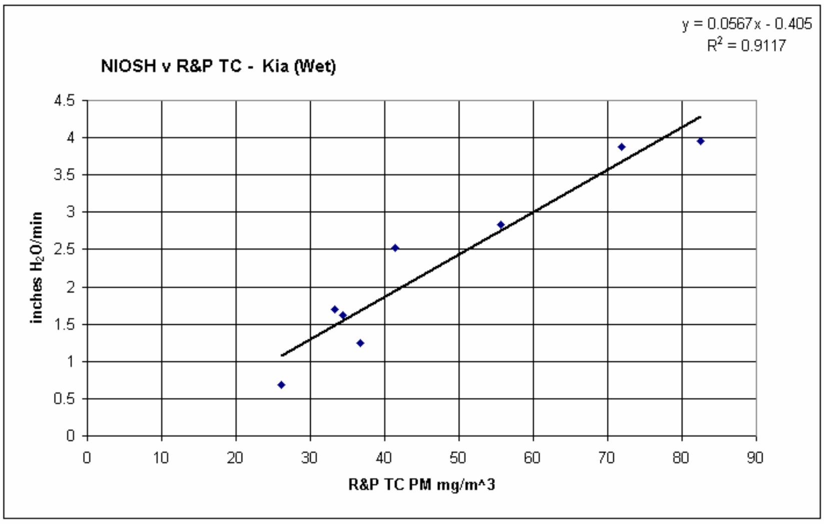


Engine	R&P TC mg/m^3	NIOSH mg/m^4	
3126_R_W	64.64	1.013333	1
	81.03	3.393	2
	87.5	3.236667	3
	87.09	2.076667	4
	84.095	1.056667	5
	64.74	1.17	6
	19.08	0.55	7
	39.285	0.536667	T

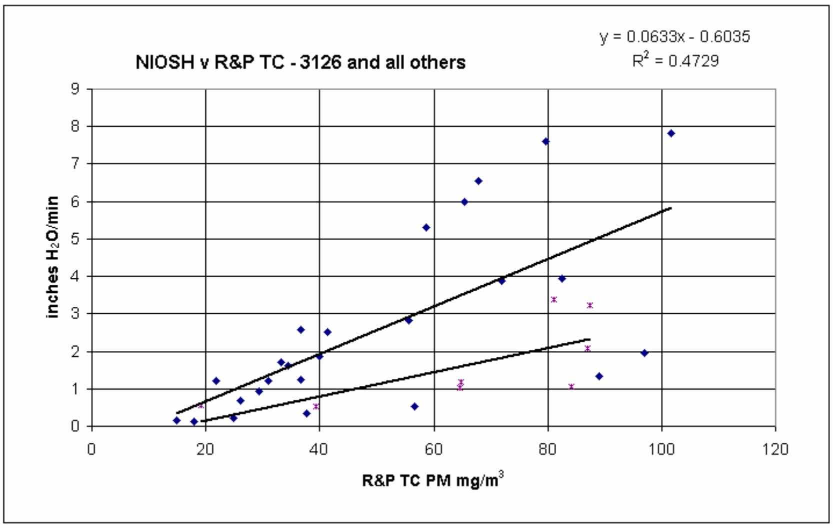


Dyno Tests: Graphs showing NIOSH against R&P Total Carbon (cont)

Engine	R&P TC mg/m^3	NIOSH inches H2O/min	
Kia_R_W	71.84	3.88	7
	82.545	3.956667	1
	55.685	2.826667	2
	41.37	2.526667	3
	33.235	1.696667	4
	34.405	1.62	5
	26.145	0.68	6
	36.74	1.243333	T

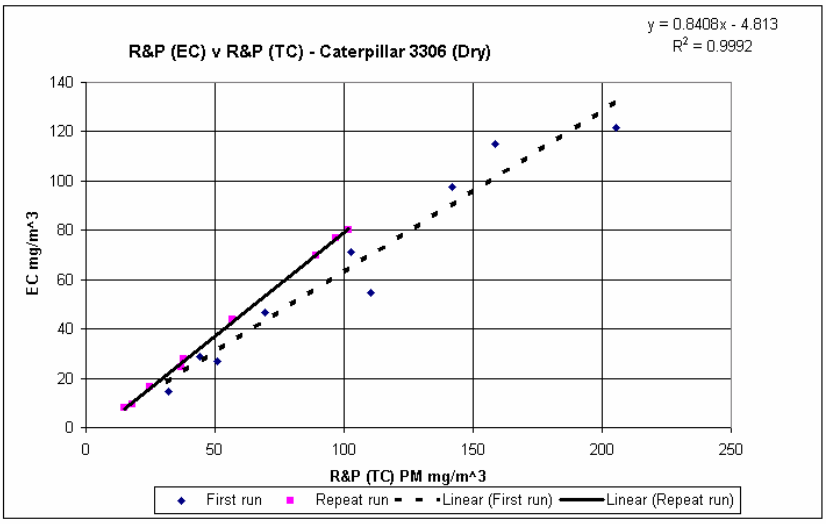


Engine All	R&P TC mg/m^3	NIOSH inches H2O/min	
3306 dry rpt	101.715	7.81	1
	96.955	1.956667	2
	89.11	1.345	3
	56.72	0.533333	4
	37.67	0.356667	5
	24.955	0.21	6
	14.84	0.17	7
	18.015	0.12	8
	36.73	2.58	T
3306 wet	79.605	7.606667	1
	67.78	6.55	2
	65.48	6.003333	3
	58.605	5.306667	4
	39.935	1.873333	5
	29.33	0.936667	6
	21.8	1.213333	7
	31.06	1.213333	T
Kia wet	71.84	3.88	7
	82.545	3.956667	1
	55.685	2.826667	2
	41.37	2.526667	3
	33.235	1.696667	4
	34.405	1.62	5
	26.145	0.68	6
	36.74	1.243333	T
3126 wet	64.64	1.013333	1
	81.03	3.393	2
	87.5	3.236667	3
	87.09	2.076667	4
	84.095	1.056667	5
	64.74	1.17	6
	19.08	0.55	7
	39.285	0.536667	T

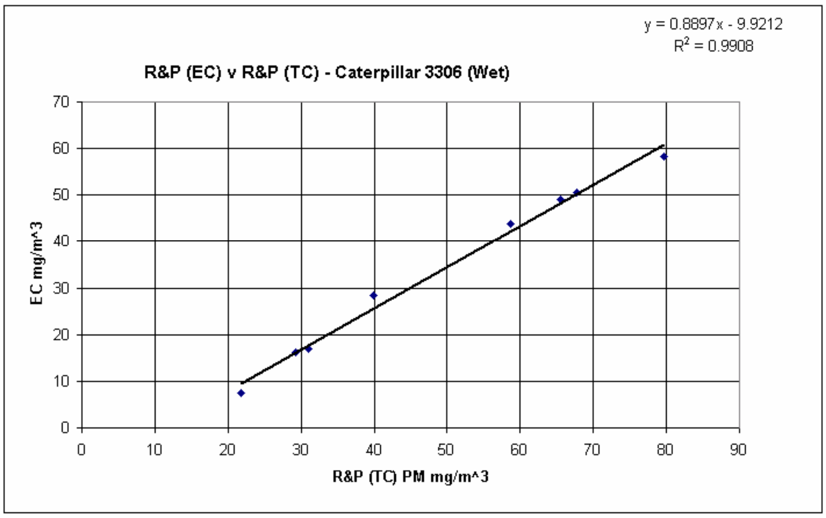


Dyno Tests: Graphs showing R&P Elemental Carbon against R&P Total Carbon

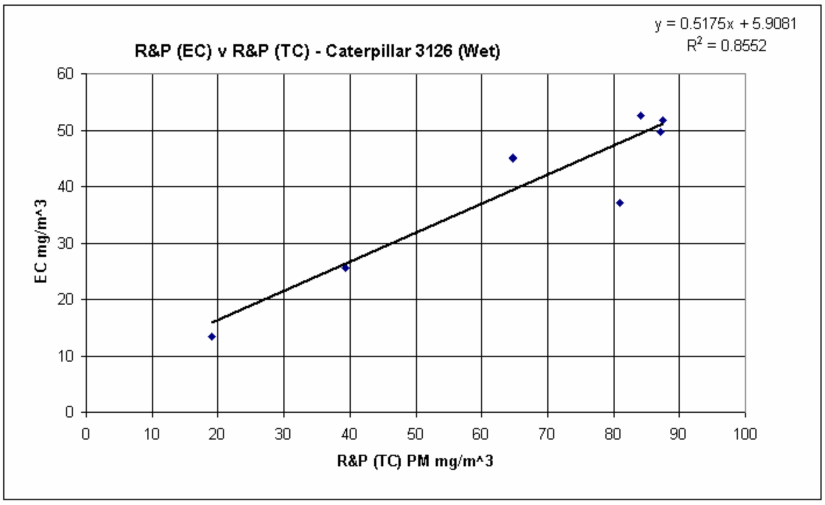
Engine	R&P TC mg/m^3	R&P EC mg/m^3	
First run			
3306_R_D	110.4	54.8	1
	158.65	115.05	2
	205.55	121.435	3
	142.05	97.78	4
	102.52	71.38	5
	69.345	46.64	6
	44.32	28.77	7
	31.93	14.765	8
	51.015	27.01	T
Repeat run			
3306_R-DR	101.715	80.335	1
	96.955	76.785	2
	89.11	69.99	3
	56.72	43.86	4
	37.67	27.89	5
	24.955	16.6	6
	14.84	8.015	7
	18.015	9.41	8
	36.73	24.595	T



Engine	R&P TC mg/m^3	R&P EC mg/m^3	
3306_R_W	79.605	58.305	1
	67.78	50.555	2
	65.48	49.18	3
	58.605	43.91	4
	39.935	28.465	5
	29.33	16.12	6
	21.8	7.41	7
	31.06	16.88	T

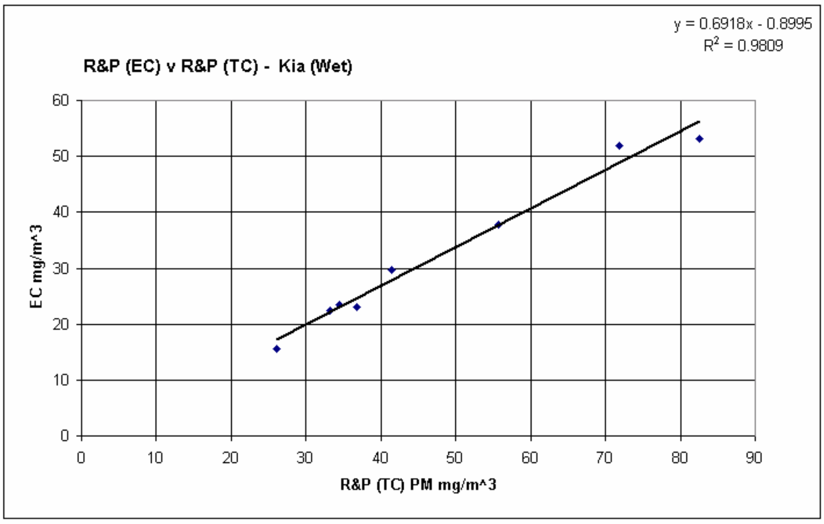


Engine	R&P TC mg/m^3	R&P EC mg/m^4	
3126_R_W	64.64	45.205	1
	81.03	37.13	2
	87.5	51.74	3
	87.09	49.705	4
	84.095	52.555	5
	64.74	45.02	6
	19.08	13.33	7
	39.285	25.52	T

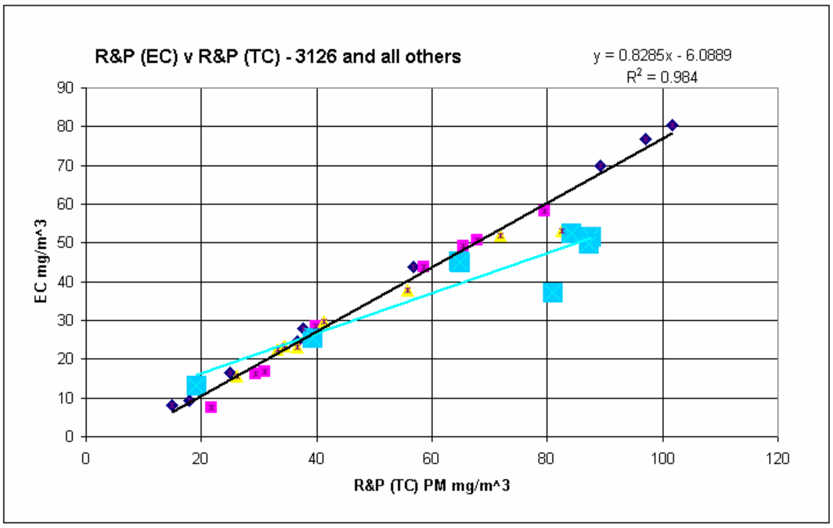


Dyno Tests: Graphs showing R&P EC against R&P TC (cont)

Engine	R&P TC mg/m^3	R&P EC mg/m^3	
Kia_R_W	71.84	51.9	7
	82.545	53.245	1
	55.685	37.81	2
	41.37	29.595	3
	33.235	22.365	4
	34.405	23.425	5
	26.145	15.64	6
	36.74	23.05	T



Engine All	R&P TC mg/m^3	R&P EC mg/m^3	
3306 dry rpt	101.715	80.335	1
	96.955	76.785	2
	89.11	69.99	3
	56.72	43.86	4
	37.67	27.89	5
	24.955	16.6	6
	14.84	8.015	7
	18.015	9.41	8
	36.73	24.595	T
3306 wet	79.605	58.305	1
	67.78	50.555	2
	65.48	49.18	3
	58.605	43.91	4
	39.935	28.465	5
	29.33	16.12	6
	21.8	7.41	7
	31.06	16.88	T
Kia wet	71.84	51.9	7
	82.545	53.245	1
	55.685	37.81	2
	41.37	29.595	3
	33.235	22.365	4
	34.405	23.425	5
	26.145	15.64	6
	36.74	23.05	T
3126 wet	64.64	45.205	1
	81.03	37.13	2
	87.5	51.74	3
	87.09	49.705	4
	84.095	52.555	5
	64.74	45.02	6
	19.08	13.33	7
	39.285	25.52	T



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