Advances in technologies for sampling, measuring and monitoring coal dust and related emissions along the rail corridor

Melita Keywood and Paul Selleck

29 March 2016

Report commissioned for the Office of the NSW Chief Scientist & Engineer

Important disclaimer

Contents

Figures

Tables

Acronyms

Aerosol	Particle suspended in the atmosphere
AMS	Aerosol mass spectrometer
APS	Aerosol particle sizer
BAM	Beta attenuation monitor
BC	Black carbon - light absorbing substance made up of carbonaceous particles
CGA	Coal grain analysis
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation particle counter
DustTrak	DustTrack
EC	Elemental Carbon- carbonaceous fraction of particulate matter that can only be vaporised by oxidation at temperatures above 340˚C.
E-Sampler	E-Sampler
FDMS	Filter dynamics measurement system
FIDAS	Fine dust monitoring and ambient air measuring system
FEM	Federal equivalent method
FRM	Federal reference method
NEPM	National environmental protection (ambient air quality) measure
NOAA	National oceanic and atmospheric administration (U.S.)
MAAP	Multi angle absorption photometer
OSIRIS	Optical Scattering Instantaneous Respirable Dust Indication System
PASS	Photo acoustic soot spectrometer
PM	Particulate matter
PM_1	PM with an equivalent aerodynamic diameter of 1 micron or less
$PM_{2.5}$	PM with an equivalent aerodynamic diameter of 2.5 micron or less
PM_{10}	PM with an equivalent aerodynamic diameter of 10 micron or less
$PM_{2.5\text{-}10}$	PM with an equivalent aerodynamic diameter of 2.5 to 10 micron
Q-ACSM	Aerosol chemical speciation monitor
SP2	Single particle soot photometer
SP-AMS	Soot Particle Aerosol Mass Spectrometer
TAP	Tricolour absorption photometer
TEOM	Tapered element oscillating microbalance
ToF-ACSM	Time of flight aerosol chemical speciation monitor
TSP	Total suspended particles
UAV	Un-manned aerial vehicles
US EPA	United States environmental protection agency

1 Introduction

CSIRO has been contracted by the Office of the NSW Chief Scientist and Engineer (OCSE) to produce an information paper that provides an overview of current and emerging monitoring, measurement and sensor technologies that could be used for sampling and monitoring coal dust and related emissions from the coal chain in the rail corridor. This Information Paper will form part of the “Review of rail coal dust emissions management practices in the NSW coal chain”.

The rail corridor is defined as the region between the loading activities at the mine site (where the train or other transport is filled with coal) and the location where the train unloads the coal at the export terminal or power plant (OCSE 2015).

In this review we focus on the measurement of coal dust and emissions associated with the rail corridor. The review will focus on air-borne particles associated with these sources.

Sources of coal dust include:

- The surface of loaded coal wagons
- Leakage from doors of loaded or unloaded coal wagons
- Dust emissions re-entrained from spilled coal in the corridor
- Residual coal in unloaded wagons
- Parasitic load (e.g. coal caught on lips and shelves outside of the carriage)
- Coal dust due to induced turbulence from two trains passing.

Other emissions associated with the rail corridor include:

- Diesel exhaust emissions from the locomotives
- Other train emissions (e.g. brake dust)
- Re-suspended dust from other sources (e.g. soil, sea salt etc.) caused by trains passing through the corridor.

1.1 Factors that determine how to measure particles in the rail corridor of the coal chain

Particles are a complex mixture of chemical components and sizes. This means there is no single method that is able to quantify all the properties of particles and most often one or a number of properties of the particles are measured and used as proxies along with valid assumptions to quantify the particles.

Particle properties of relevance to this review that can be measured are:

- Size distribution
- Concentration of particle mass
- Concentration of the number of particles
- Optical properties including absorption and scattering

- Chemical composition of particles.

Both the chemical composition and size of particles are dependent on the source of the particles and their formation process. For example, coal dust is generated by air blowing over a surface containing coal (e.g. a coal pile) and this mechanical formation process results in a particle mass size distribution dominated by coarse particles (greater than 2.5 µm in diameter). Vehicle emissions on the other hand are the result of combustion of fossil fuel (diesel in this case) and are dominated by fine particles (less than 2.5 µm). Resuspended dust along the rail corridor effectively results from wind produced as the train passes through the corridor so also produces particle mass dominated by coarse particles.

Literature on the size distribution of airborne coal dust particles is scarce. Warren et al (2015) have reported on use of CSIRO’s Coal Grain Analysis system to quantify coal dust in urban dust samples collected in a town with coal ports and associated rail networks for the transportation of coal. The study estimated that coal particles comprised 31.2% of the total particles based on particle size with 4.3% between 2.5 µm and 10 µm in diameter, and 26.9% between 10 and 30 µm in diameter. Further refinements of the technique are expected to enable measurements of particles down to 1 µm in diameter.

Figure 1 compares the number and mass size distribution of particles generated by resuspension of brown coal under experimental conditions. The figure on the left shows that a significant number of the particles are likely to extend below 1 µm in diameter, while the mass of the particles (figure on the right) is dominated by particles around 10 µm (Civiš and Hovorka 2010). Figure 2 compares the number size distribution of particles generated by the resuspension of roadside dust under experimental conditions and shows that the number size distribution is dominated by particles less than 3 µm, while the mass size distribution has peaks at about 10 and 3 µm. Figure 3 shows the particle number and black carbon mass distributions for fresh diesel emissions. Both distributions are dominated by particles less than 1 µm in diameter.

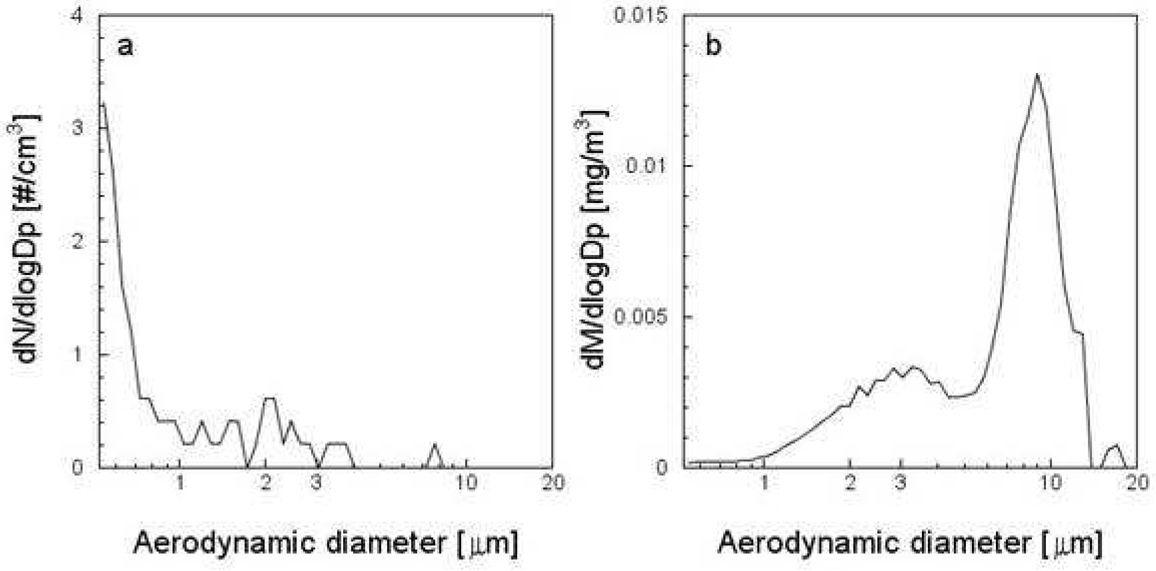

Figure 1 size distribution of a) number and b) particle mass of particles generated from the resuspension of brown coal dust in experimental conditions (Civiš and Hovorka 2010).

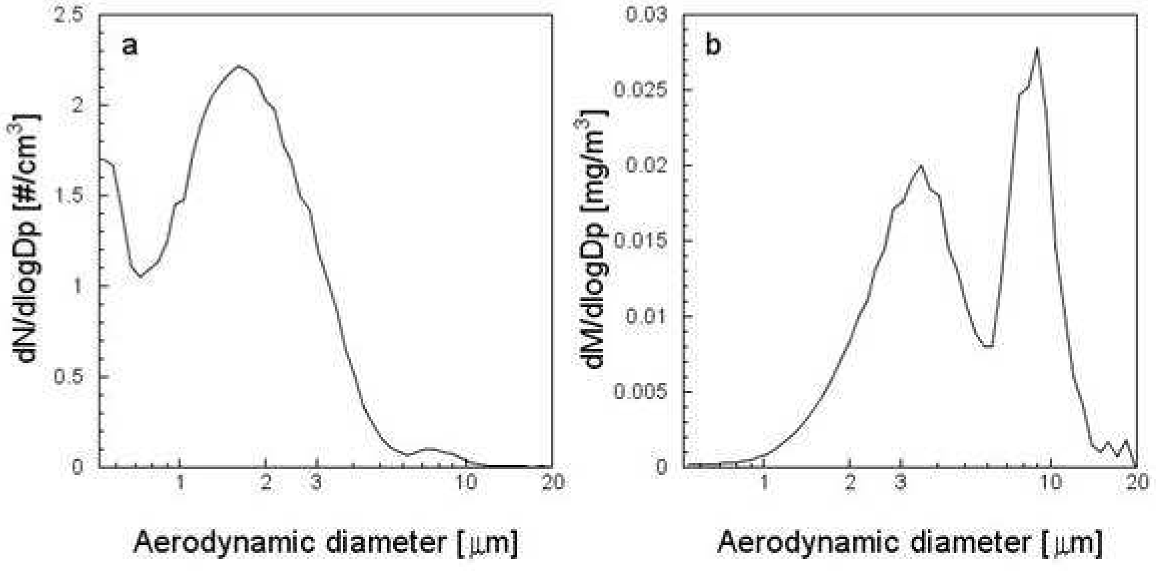

Figure 2 Size distribution of a) number and b) particle mass of particles generated from the resuspension of road dust in experimental conditions (Civiš and Hovorka 2010).

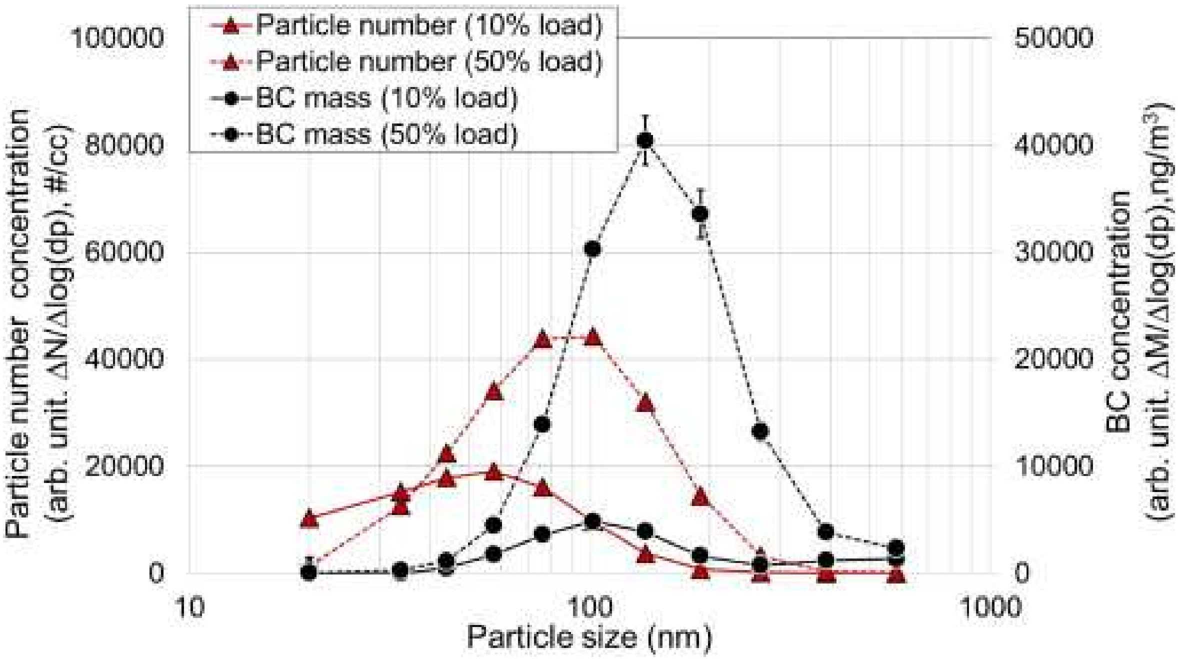

Figure 3 Particle number and black carbon mass size distributions from diesel engine emissions under experimental conditions (from Ning et al., 2013)

Both coal dust and diesel airborne particles are comprised of black carbon (BC) that is able to absorb light. In addition components of resuspended dust such as resuspended coal and soil are also able to absorb light. Light absorption is routinely used to determine the BC concentration of atmospheric aerosol in air quality and climate research. The ability of a particle to absorb light however is affected by the size of the particle and the wavelength at which the absorption is measured. For example Figure 4 shows that particles around 1 µm in diameter most efficiently absorb and scatter light at 550 nm. A size-dependent mass absorption coefficient can be used to calculate BC concentration from light absorption data if the particle size distribution is understood.

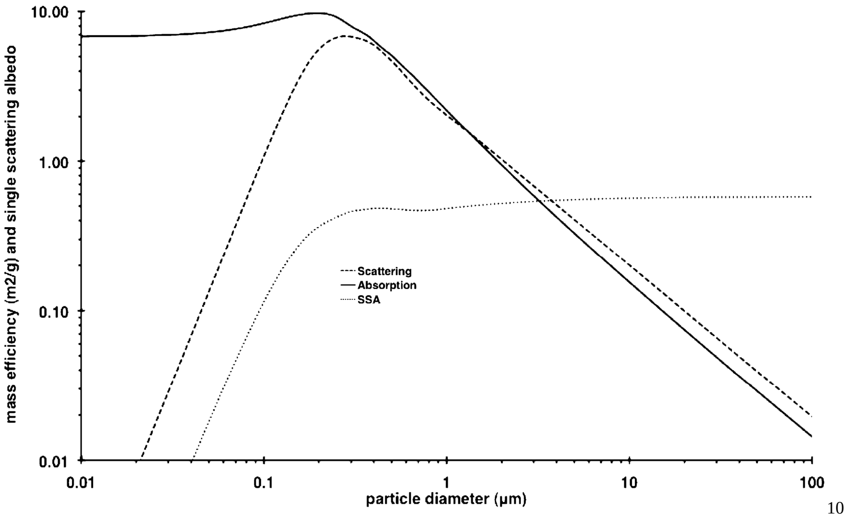

Figure 4 Mass scattering and absorption efficiency as a function of particle diameter for a spherical BC particle with a density of 1.8 g cm^{-3} calculated from theory at 550 nm. From Moosmuller et al (2009)

The chemical composition of particles can be used to determine the source of particles, particularly if the source has a unique tracer component e.g. levoglucosan as a tracer for biomass burning (Jordan et al., 2006). In the case of coal dust, the coal grain analysis methods commonly applied to dust samples have recently been adapted to airborne particles collected on filters (see Section 4.3). Diesel particles are mostly comprised of elemental carbon (EC) and organic compounds, so analysis of elemental carbon (EC) and organic species such as polycyclic aromatic hydrocarbons may indicate the presence of diesel emissions in the aerosol. Supporting information on gaseous volatile organic compound speciation and indicators of combustion such as carbon monoxide (CO) and carbon dioxide (CO_2) may also be used to indicate the presence of diesel emissions. Resuspended road dust is comprised of a number of different aerosol sources and arises when these particles have been deposited on the road. Sources include sea-salt, soil dust and in this case coal dust. Sea-salt and soil dust chemical markers include soluble ions such as sodium and chloride, soil dust markers include insoluble elements such as silicon, iron and aluminium. Traditionally large sample volumes and complex analytical methodologies are required to make these measurements and source receptor models are used to extract source information from the data sets.

In summary, a framework of particle properties can be measured to maximise information available to identify the impact of emissions from the rail corridor of the coal chain on particle loadings in the vicinity of the corridor. These include particle concentration, particle size distribution, optical properties (absorption and scattering) and chemical composition. This report describes current and emerging monitoring sensor technologies capable of measuring these properties. Section 1 describes currently available methodologies routinely used in other atmospheric measurement applications. Section 2 describes methodologies that have already been used in Australian studies and Section 3 describes emerging technologies that have the potential for application to this issue.

2 Currently available methodologies

In this section we describe currently available technologies that are used routinely in atmospheric measurement programs and could be applied to determine emissions from the rail corridor of the coal chain. The technologies are divided into methods that measure particle concentration, particle size distribution, absorption and chemical composition. These are summarised in Table 1.

Table 1 Summary of currently available methodologies for the measurement of and characterisation of particle emissions from the rail corridor

Property	Property measured	Methods available
Particle concentration	Gravimetric mass Scattering coefficient	• Samples collected on to filters through size selective inlets (PM_{10}, $PM_{2.5}$ and PM_1) and weighed e.g. HiVol and Partisol. • Beta attenuation monitor (BAM) • Tapered Element Oscillating Microbalance (TEOM) • Light scattering device i.e. photometers that measure intensity of light reaching a photodetector such as the Optical Scattering Instantaneous Respirable Dust Indication System (OSIRIS), DusTrak, E-Sampler, Fine dust monitoring and ambient air measuring system (FIDAS)
Particle Size Distribution	Particle number and mass size distribution. Large particles may be from coal dust. Fine particles may be from diesel emissions	• Scanning Mobility Particle Sizer (SMPS), Aerosol Particle Sizer (APS) (number distribution) continuous • Cascade impactor (mass distribution) integrated (can carry out chemical composition analysis with sufficient sample volume and analytical detection limits) • Size selective inlets (PM_{10}, $PM_{2.5}$ and PM_1) on aerosol samplers • Light scattering devices (both optical particle counters and photometers)
Absorption	Strongly absorbing particles may be from BC (coal dust or diesel emissions), moderately absorbing may be from soil/resuspended rail dust	• Multi-Angle Absorption Photometer (MAAP)(1 wavelength) • Aethelometer (up to 7 wavelengths), Tricolour Absorption Photometer (TAP) (3 wavelengths)
Chemical composition	Coal grain,BC, EC, Organic Carbon(OC) organic compounds, soluble ions, elements.	• Samples collected with aerosol samplers with size selective inlets (PM_{10}, $PM_{2.5}$ and PM_1) and analysed offline for chemical composition by specialised analytical methods

2.1 Particle concentration

Technologies for determining the concentration of particle mass can be grouped into methods that collect samples offline for gravimetric analysis, and methods that continuously determine particulate concentrations. Gravimetric methods are the only type that meet the United States Environmental Protection Agency (US EPA) Federal Reference Method (FRM) requirements and can be used for the reporting of National Environmental Protection Measure for Ambient Air Quality (NEPM) PM_{10} standards and $PM_{2.5}$ advisory standards. The continuous methods can be divided into techniques that measure gravimetric mass specifically and methods that measure a proxy such as light scattering of particles that require a calibration to determine a mass scattering coefficient for the calculation of mass.

2.1.1 Size selective sample collection

Particles can be collected on filters using particulate samplers and the mass on the filter gravimetrically determined (i.e. filters are weighed). Air is drawn at a constant flow rate through a size selective inlet filter (e.g. PM_{10}, $PM_{2.5}$, PM_1) and through a filter that has been pre-weighed. The size selective inlet removes from the air stream particles larger than the size determined by the size selective inlet, so that only particles smaller than these sizes are collected on the filter. Dichotomous samplers separate the incoming PM_{10} air stream into its fine ($PM_{2.5}$) and coarse components ($PM_{2.5-10}$).

At the end of sampling, the filter is weighed and the mass of particles and volume of air sampled are used to determine the concentration of particles. Samples are collected for a period of time (usually 24 hours) to ensure sufficient mass on the filter for gravimetric determination. A number of different particulate samplers are commonly used. High Volume samplers sample at 1000 L/min, low volume samplers typically sample at 3 or 16.7 L/min. Size selective inlets can operate on the principal of inertial impaction or centrifugal classification (cyclones). Australian standards relevant to the collection and gravimetric determination of particulate mass concentration are listed in Table 2.

The advantages of size selective sample collection are:

- Meets NEPM reporting requirements
- Australian standard exists
- Collected samples can also be used for chemical composition and thus source identification
- Sampling equipment moderately priced
- Low volume samplers are quiet and require less power
- High volume sampler collect enough material for most chemical analyses

The disadvantages of size selective sample collection are:

- Off line gravimetric mass measurement requires infrastructure and equipment
- Relatively time intensive
- Sample collected over a period of time (usually 24 hours) so that time resolution is poor i.e. only one data point every 24 hours.
- Low volume samplers may not collect enough material for some analyses

Table 2 Australian standards for the measurement of particles

Standard	Measurement
AS/NZ 3850.9.9:2006	Determination of suspended particulate matter –PM_{10} low volume sampler gravimetric method
AS/NZ 3850.9.9:2006	Determination of suspended particulate matter –$PM_{2.5}$ low volume sampler gravimetric method
AS/NZ 3850.9.6:2015	Determination of suspended particulate matter –PM_{10} high volume sampler with size selective inlet –gravimetric method
AS/NZ 3850.9.14:2013	Determination of suspended particulate matter –$PM_{2.5}$ high volume sampler with size selective inlet –gravimetric method
AS/NZ 3850.9.7:2009	Determination of suspended particulate matter –Dichotomous sampler (PM_{10}, coarse PM and $PM_{2.5}$–gravimetric method
AS/NZ 3850.9.8:2008	Determination of suspended particulate matter –PM_{10} continuous direct mass method using a tapered element oscillating microbalance analyser
AS/NZ 3850.9.13:2013	Determination of suspended particulate matter –$PM_{2.5}$ continuous direct mass method using a tapered element oscillating microbalance analyser
AS/NZ 3850.9.11:2008	Determination of suspended particulate matter –PM_{10} beta attenuation monitors
AS/NZ 3850.9.12:2013	Determination of suspended particulate matter –$PM_{2.5}$ beta attenuation monitors
AS/NZ 3850.12.1:2015	Determination of light scattering— Integrating nephelometer method

2.1.2 Beta Attenuation

Beta attenuation is the absorption of beta radiation by solid particles and is only dependent on the mass of the particle (i.e. not density, chemical composition or optical or electrical properties (Jaklevic et al., 1991). Air is drawn through a filter at a known rate for a known period of time (generally 1 hour) and attenuation of a beta ray signal (generated from a small source such as carbon-14) is measured with a scintillation detector. This is compared with a measurement of the beta attenuation on the unexposed filter (determined before sample collection commenced) to determine the volumetric concentration of particulate matter in ambient air.

Beta attenuation monitors (BAM) can be operated with size selective inlets (e.g. PM_{10}, $PM_{2.5}$, PM_1). A number of BAM instruments are commercially available and in some instruments the 1 hour measurement resolution is increased to minute resolution by including a light scattering measurement (e.g. nephelometer) that is calibrated using the hourly BAM mass measurement. Australian standards for the measurement of PM_{10} and $PM_{2.5}$ using BAM's currently exist (Table 2).

The advantages of BAM's are:

- Meets NEPM reporting requirements
- Australian standard exists
- Sampling equipment moderately priced
- Time resolution can be increased by inclusion of light scattering devices in some models

The disadvantage of beta attenuation monitoring is:

- Hourly time resolution means that only one data point is collected per hour

2.1.3 Tapered Element Oscillating Microbalance (TEOM)

The Tapered Element Oscillating Microbalance determines particle mass by measuring the change in frequency of an oscillating microbalance as the particle mass on the microbalance changes (Allen et al., 1997). This is only dependent on the mass of the particles (i.e. not density, chemical composition or optical or electrical properties). Air is drawn through a filter resting on a microbalance at a known flow rate and the change in frequency of the microbalance relative to the blank filter weight determines the volumetric concentration of particulate matter in ambient air. The resolution of the measurement is one data point per minute.

A Filter Dynamics Measurement System (FDMS) can be added to the TEOM that measures the aerosol mass lost due to volatilisation (the standard TEOM is operated at 50°C). The FDMS determines the mass lost by periodically drawing particle-free air through the oscillating microbalance and measuring the mass of aerosol lost from the filter as the particles equilibrate with surrounding air. The typical resolution of a TEOM is $0.5\ \mu g\ m^{-3}$.

The TEOM can be operated with size selective inlets (e.g. PM_{10}, $PM_{2.5}$, PM_1). Australian standards for the measurement of PM_{10} and $PM_{2.5}$ by TEOM currently exist (Table 2).

The advantages of the TEOM are:

- Meets NEPM reporting requirements
- Australian standard exists
- Sampling equipment moderately priced to highly priced
- High time resolution

The disadvantage of TEOM is:

- Sample heated to 50°C so volatile mass lost; this can be mitigated by use of FDMS which increases price

2.1.4 Light scattering devices

The ability of particles to scatter light can be used to measure the concentration of particles. Instruments that measure light scattering of particles draw air into an enclosed chamber, and a bright light is shone through the sample. The amount of light scattered from its original direction is measured using a photodetector and can be related to particle mass using a mass scattering coefficient determined through calibration. The value of the mass scattering coefficient varies with particle size distribution, particle composition, and relative humidity (RH), so that it should be derived for different seasons and monitoring locations. A number of commercially available photometers include a feature that allows the collection of a sample on a filter that can be used to determine the sample-period specific mass scattering coefficient. Light scattering devices can be grouped into photometers and optical particle counters.

Photometers measure the aggregate signal from a cloud of particles and are not designed to detect individual particles and thus particle size distributions. When used with size selective inlets however they will produce some information on size distributions. A number of commercially available instruments combine photometers with optical particle counters (see below) to determine particle concentration and particle size distributions. Photometers typically measure particle size ranges from 0.1 to 10 µm diameter with concentrations ranging from 0.01 to 100 mg m^{-3} or more so are better suited for applications with high particle loadings such as industrial workplace monitoring, emission testing. They are also suitable for use in ambient air monitoring.

Optical particle counters (OPC) measure particle size and number concentration by detecting the light scattered by individual particles. Single particles are drawn through a focused laser beam and produce a flash of light. The intensity of the scattered light is a complex function of the diameter, shape and refractive index of the particle as well as the wavelength of the light and geometry of the optical detector. The number concentration is determined from the count rate of photoelectric pulses and the size of the particles is estimated from the pulse height.

The measured size range is typically 0.3 to 20 µm diameter, and the number concentration is limited to a maximum of 70 particles cm^{-3}. OPCs are calibrated with perfectly uniform, spherical polystyrene latex bead particles of known refractive index. The measured size of an unknown particle is therefore the “light-scattering equivalent size” as compared to the known calibration particle. The actual physical size may be quite different from this. OPCs are best suited for environmental monitoring and clean room applications because of the low maximum concentration threshold limitation.

An integrating nephelometer is a photometer that measures light scattering from an aerosol cloud over as many angles as possible. A flashing lamp is used as the light source with a specific wavelength and models can include multiple wavelength light sources and a backscatter option (i.e. measures the light reflected back towards light source between 90° and 170°. The green (525 nm) wavelength is most sensitive for fine particles since most particles less than 2.5 µm have diameters similar to the wavelength of the incident light, resulting in maximum mass scattering coefficient for these particles. Particles larger than 2.5 µm tend to scatter light less uniformly than smaller particles, and for most a portion of the forward-scattered signal may be truncated. However the red wavelength (635 nm) interacts strongly with large particles (such as pollen, sea salt) and blue wavelength (450 nm) interacts strongly with absorbing particles (e.g. combustion aerosol). There are a number of commercially available integrating nephelometers and there is an Australian standard for the operation of the nephelometer to measure scattering coefficient (however not for the determination of mass concentration).

The last 10 years has seen a rapid increase in the number of commercially available photometers used to measure particulate mass concentration. Some of these are described below and are selected here for discussion because they have either been used to measure particles in the coal chain or have been used extensively in ambient air monitoring programs in Australia

- The Optical Scattering Instantaneous Respirable Dust Indication System (OSIRIS) was originally developed for use in the coal industry as an alternative method for the assessment of time-weighted average dust concentrations within mines. Dust concentrations are determined within a photometer that includes a collimated laser light beam and a photodetector that measures forward scattering between 12-20° (Roebuck et al. 1990).
- The E-Sampler continuously measures particle mass concentration through near-forward light scattering. A visible laser light source scatters particles in proportion to the particulate load. The instrument is calibrated using polystyrene latex spheres of known index of refraction and diameter at multiple points to validate linearity. In addition a sample can be collected on a filter simultaneously and can be used to determine the sample-period specific mass scattering coefficient.
- The DustTrak continuously measures particle mass concentration in real time through a single-channel, 90° light-scattering laser photometer. The instrument is calibrated using Arizona Road-dust and in some models a sample can be collected on a filter simultaneously and can be used to determine the sample-period specific mass scattering coefficient. The DustTrak DRX model also determines size resolved mass concentrations using propriety technology predominately based on photometric detection.
- The Fine Dust monitoring and Ambient air measuring System (FIDAS) measures continuously and simultaneously concentrations of PM $_1$, PM $_{2.5}$, PM $_4$, PM $_{10}$, total suspended particles (TSP), as well as the particle number concentration and the particle size distribution in a size range of 180 nm to 18 µm. The systems use a polychromatic LED white light source for the optical light scattering of single particles and is equipped with an optical aerosol spectrometer for particle detection. The particles are classified into 64 size bins and each size fraction (bin) is multiplied by a correlation factor to convert particle size and number into mass. A mass fraction is achieved by applying an additional separation curve to the determined particle size distribution. The FIDAS has European certification.

The advantages of light scattering devices are:

- Australian standard exists (for nephelometer although not for mass calculation)
- Sampling equipment low to moderately priced
- High time resolution

The disadvantage of light scattering devices is:

- Mass scattering coefficient needs to be determined to calculate mass from scattering coefficient

2.2 Particle size distribution

2.2.1 Scanning Mobility Particle Sizer - continuous

The Scanning Mobility Particle Sizer (SMPS) measures the concentration of particles as a function of particle diameter using the property of particle electrical mobility which is related to the size and charge of the particle. The SMPS measures the number size distribution of particles between 5 nm and 700 nm at 5 minute intervals. The SMPS is comprised of a classifier column, a neutraliser, and a condensation particle counter (CPC). Using information on the density of particles (which is dependent on the particle composition), the mass size distribution can be determined. There are a number of commercially available SMPS systems on the market.

The advantages of the SMPS are:

- Provides high quality data on particle number and mass size distribution that can be used to infer information on formation process and sources
- High time resolution (5 minute intervals)

The disadvantages of the SMPS are:

- High cost
- Health and safety considerations (includes a sealed radioactive source in the neutraliser and solvent for counting particles in the CPC)
- Only measures up to 800 nm
- Specialised training to operate and interpret data

2.2.2 Aerosol Particle Sizer - continuous

The Aerosol Particle Sizer (APS) measures the concentration of particles as a function of particle diameter by measuring the velocity of particles in an accelerating air flow through a nozzle using a time of flight spectrometer. The APS measures the number concentration of particles between 500 nm and 15 µm at 5 minute intervals.

The advantages of the APS are:

- Provides high quality data on particle number and mass size distribution
- High time resolution (5 minute intervals)

The disadvantage of the APS are:

- High cost
- Counting statistics for particles greater than 5 µm are poor

- Specialised training to interpret data

2.2.3 Light scattering devices

Both photometers and OPCs (discussed above) can be used to determine particle size distributions. Commercially available light scattering devices that produce size distribution information include the FIDAS and DustTrak (discussed above).

2.2.4 Cascade impactor- integrated

Cascade impactors are multi-stage aerosol samplers used to collect size-fractionated particle samples for chemical and gravimetric analysis. Typically size ranges can be from 10 nm up to 18 µm at flow rates from 10 to 100 L/min. Particles in discrete size ranges are collected by passing the aerosol through a series of impaction stages, with higher jet velocities in each subsequent stage ensuring collection of particles smaller than collected by the previous stage.

The advantages of cascade impactors are:

- Provides data on particle mass size distribution that can be used to infer information on formation process and sources
- Collected samples can also be used for chemical composition and thus source identification
- Sampling equipment moderately priced

The disadvantages of size cascade impactors are:

- Offline gravimetric mass measurement requires infrastructure and equipment
- Relatively time intensive
- Sample collected over a period of time (usually 24 hours) so that time resolution is poor.

2.3 Absorption

Aerosol light absorption in the atmosphere is dominated by black carbon (BC). However as noted above other aerosol including brown carbon and mineral dust are important absorbers.

The quantitative measurement of aerosol light absorption is a challenge. Aerosol light absorption can be measured after deposition of aerosols on filter media or in situ, i.e. when the aerosol is in its natural suspended state.

Filter-based techniques concentrate the deposited aerosols on filters. A significant uncertainty associated with filter based measurement is due to multiple scattering by the filter material and deposited particles that result in an absorption enhancement. However, these instruments measure in real time by including a self-advancing filter tape for sample collection, and absorption can be measured at several wavelengths so that information on particle size and composition can be inferred.

Examples of widely used filter based instruments are the particle soot absorption photometer (PSAP) (Bond et al., 1999) and the aethalometer (Hansen et al., 1984). Both single and multi-wavelength versions of PSAP and the aethalometer (up to seven wavelengths) are commercially available. In these instruments the filter substrates cause multiple scattering enhancement of particle light absorption, amplifying the signal, and thus improving the sensitivity of such measurements. However this multiple scattering in the filter substrate also complicates instrument calibration and interpretation of data. The Multi-Angle Absorption Photometer (MAAP) (Petzold et al., 2004) includes the measurement of reflectivity of the filter at two angles and a correction method for minimizing the cross sensitivity to particle scattering, removing this complication. The MAAP however operates at a single wavelength (notionally 670 nm) but includes a filter tape drive mechanism that allows for automatic advance of the filter tape. The Tricolour Absorption Photometer (TAP) is a low cost version of the filter based instrument and is the commercialised version of the absorption instrument used in the National Oceanic Atmospheric Administration aerosol network. This instrument measures absorption at three wavelengths using LEDs as the light sources.

In situ measurements of aerosol light absorption are based on the temperature increase of particles upon exposure to light. In photoacoustic methods the temperature increase results in the generation of a sound wave that is detected by a microphone. Commercially available photoacoustic instruments include the Photo-Acoustic Soot Spectrometer (PASS) that measures absorption at single or multiple wavelengths. Incandescence-based techniques use a high-intensity laser to heat the particles to very high temperatures and quantify this temperature change through measurement of their thermal emission spectrum (Tam 1986). The Single Particle Soot Photometer (SP2) is a commercially available instrument that uses this methodology (Schwarz et al., 2006). In the SP2 the peak intensity of the incandescence is proportional to the refractory mass of the incandescent particle and the ratio of broad-to-narrow band incandescence is used to calculate its boiling point. This makes it possible to measure the mass (or volume-equivalent diameter) of strongly light absorbing refractory particles and the boiling point of BC can be used to discriminate it from other incandescent particles such as soil particles.

The advantages and disadvantages of these instruments (except the TAP) are discussed in detail in Moosmüller et al (2009). In general, they are moderately to highly priced and require specialised skills to operate and analyse data. The TAP is low cost and the SP2 while being high cost, is the only instrument available that specifically identifies and quantifies BC without interference from other absorbing particles.

2.4 Chemical composition

2.4.1 Offline chemical analyses

Samples collected onto filters can be analysed for chemical composition after gravimetric analysis. The chemical composition can then be used to determine the sources of the particles. The filter material is also an important consideration in determining what type of chemical analysis can be performed. Soluble ions which can be used to identify primary sources such as sea salt particles and secondary sources such as ammonium sulfate from coal fired power stations can be analysed by ion chromatography on Teflon, polycarbonate and quartz filters. Elements that can be used to identify primary sources such as soil particles can be analysed by ion beam analysis on stretched Teflon and polycarbonate filters. Total organic carbon and elemental carbon which can help identify combustion sources and secondary organic aerosol can be measured by thermal optical techniques on quartz filters. Black carbon which can help identify combustion sources by light absorption methods can be measured on Teflon or polycarbonate filters. Carbohydrates such as levoglucosan, a unique tracer for the identification of wood smoke and arabitol which is a tracer for bioaerosols can be analysed by high performance anion exchange with pulsed amperometric detection on Teflon, polycarbonate or quartz filters. Currently the identification of coal particles by chemical analysis has proved difficult as there is no unique chemical tracer or clear ratio of elements to distinguish it from other particles. Source apportionment studies using positive matrix factorisation cannot distinguish between crustal matter containing resuspended black carbon from combustion sources or from coal sources. However a coal grain analytical method using an optical reflected light imaging and analysis system has recently been developed for aerosol samples (see below).

The advantage of offline chemical analyses are that they offer the ability to identify sources of aerosols (in some cases with unique identifiers). The limitations, however include the requirement to collect large sample volumes resulting in poor time resolution (typically 24 hours) and the artefacts that occur during and after sampling, particularly concerning volatile and semi-volatile compounds. In addition offline chemical analyses requires infrastructure and equipment and high levels of analytical skills.

2.4.2 Online Chemical analyses

Online chemical analyses can be carried out using aerosol mass spectrometer (AMS) and the aerosol chemical speciation monitor (Q-ACSM). While these are used fairly routinely in Europe and North America, these instruments are only used for research purposes in Australia. These instruments measure in real time the chemical composition and mass of non-refractory sub-micron particles. Both instruments are of high cost and are not able to measure the chemical composition of coal since coal particles are refractory (i.e. resistant to the vaporising temperature of 600 °C used in the instruments). The instruments would be most applicable to the coal chain rail corridor if used in conjunction with other instrumentation that provided information on particle mass concentration and black carbon concentration.

3 Methods Already in Use

3.1 Australian studies

The initial report on the Independent Review of Rail Coal Dust Emissions Management Practices in the NSW Coal Chain (OCSE 2015) summarises the studies that have been carried out to assess the impact of emissions from the rail corridor of the coal chain on particle loadings in the vicinity of the corridor. The report summarises relevant studies from Australia (NSW and QLD).

The measurement and sensor technologies used in these studies are listed in Table 3. Again, they can be grouped into methods that collect samples for offline gravitational and chemical analysis, and methods that continuously determine particulate concentrations by measuring light scattering of the particle. Note that a number of studies combine these methodologies, however most studies have used light scattering devices, particularly the OSIRIS and DustTrak. Two studies in Queensland have used Australian Standard methods to determine PM_{10}, $PM_{2.5}$ and dust concentrations (DSITIA , 2013 and DSITIA, 2012). Note that none of the measurement and sensor technologies used in these studies were able to specifically identify the contribution of emissions

The advantage of using the OSIRIS and DustTrack sensors in these studies include their relatively low cost. However the data produced by these instruments are proxies for particle mass concentration determined using a mass-scattering calibration factor. Unless specifically determined for the study, this factor can introduce significant uncertainty to the measurement. In addition the methodologies used to measure the air-borne particles here were unable to distinguish emissions from the coal chain from other sources of aerosol, except in the case of the dust measurements where coal grain analysis of the dust was performed.

Table 3 Methodologies applied in existing Australian studies

Instrument	Property measured	Studies used	Reference
OSIRIS	$PM_{2.5}$, PM_{10}, TSP	Pollution Reduction Program 4- Particle emissions from coal trains.	ENVIRON , 2012
OSIRIS	$PM_{2.5}$, PM_{10}, TSP	Pollution Reduction Program 4.2- Particle emissions from coal trains.	Katestone Environmental Pty Ltd, 2013
OSIRIS	PM_1, $PM_{2.5}$, PM_{10}	Coal dust in our suburbs	Rogers et al., 2013
OSIRIS	PM_1, $PM_{2.5}$, PM_{10}	Coal Train pollution signature study.	Higginbotham et al.,2013
OSIRIS	PM_1, $PM_{2.5}$, PM_{10}, TSP	Health hazard in our suburbs: particulate pollution along the South-East Queensland coal dust Corridor.	Kane , 2015

DustTrak	$PM_{2.5}$, PM_{10}	Western-metropolitan rail systems coal dust monitoring program	DSITIA, 2013
DustTrak	PM_{10}	Tennyson Dust Monitoring Investigation September to October 2012	DSITIA, 2012
Partisol	TSP	Environmental evaluation of fugitive coal dust emissions from coal trains Goonyella, Blackwater and Moura Coal Queensland rail systems.	Connell Hatch , 2008
Partisol	PM_{10} (3580.9.9:2006 Method 9.9) $PM_{2.5}$ (AS/NZS 3580.9.10:2006 Method 9.10)	Western-metropolitan rail systems coal dust monitoring program	DSITIA, 2013
Partisol	PM_{10} according to AS/NZS 3580.9.10.2006 (and US EPA FRM)	Tennyson Dust Monitoring Investigation September to October 2012.	DSITIA, 2012
Dichotomous Sampler	PM_{10}, coarse ($PM_{10-2.5}$) and $PM_{2.5}$	Western-metropolitan rail systems coal dust monitoring program	DSITIA, 2013
Dust deposition	Deposited matter according to AS/NZS3580.10.1:2003	Western-metropolitan rail systems coal dust monitoring program	DSITIA, 2013
Dust deposition	Dust deposition gauges according to AZ/NZS 3580.10.1:2003 Petri Dishes and Brush Sampling	Lower Hunter Dust Deposition Study.	AECOM , 2015
Dust deposition	Deposited matter according to AS/NZS3580.10.1:2003	Tennyson Dust Monitoring Investigation September to October 2012.	DSITIA, 2012

3.2 Other relevant study

A review of the peer reviewed literature found only one publication that describes an investigation of particle emissions along a rail corridor. Jaffe et al (2015) examined the emissions of diesel particulate matter and coal dust from trains (freight and coal) in the Columbian River Gorge in Washington State by measuring PM_1, $PM_{2.5}$, CO_2, black carbon and using video cameras to determine train type and speed. PM_1 and $PM_{2.5}$ were determined using DustTrak DRX Aerosol Monitor, CO_2 was measured using a Licor (non-dispersive infrared detection) and black carbon was measured using a two wavelength aethelometer.

They used the correlation between CO_2 and $PM_{2.5}$ to determine diesel emission factors for freight trains. Video evidence of large clouds of dust identified particle emissions from the coal trains, and this was marked by the highest $PM_{2.5}$ concentrations. While only a small fraction of the coal trains (5%) showed visible dust clouds (interestingly this fraction was higher at greater windspeeds), coal trains had statistically significant higher $PM_{2.5}$ concentrations than freight trains, and only a weak correlation between $PM_{2.5}$ and CO_2. In addition the BC/$PM_{2.5}$ ratio for coal trains was lower than that of freight trains.

Thus using CO_2 as an indicator of combustion, Jaffe et al. (2015) was able to distinguish diesel emissions from coal dust emissions. Jaffe also used the BC/$PM_{2.5}$ ratio for this distinction. The lower BC concentrations from the coal trains is most likely due to the difference in mass absorption coefficients for coal dust (large particles) and diesel (small particles) as suggested in Figure 4).

4 Emerging Methods

In this section we describe some recent advances in instrument and method developments that could be applied to the rail corridor. Adoption of these methods to the coal chain could provide high quality data that would quantify the contribution of the different sources of emissions in the rail corridor of the coal chain to the total emissions (4.1, 4.2 and 4.3) or would provide low quality high spatially resolved data that with advanced statistical analysis would quantify the spatial distribution of rail corridor emissions (4.4, 4.5). While these methods are currently research methodologies, instruments are commercially available and could be applied to the rail corridor by appropriate research providers.

4.1 Soot Particle Aerosol Mass Spectrometer

This instrument combines the SP2 and AMS, both described above. The soot particle aerosol mass spectrometer (SP-AMS) makes real time measurements of sub-micron black carbon containing particles. The SP-AMS uses laser-induced incandescence of absorbing soot particles to vaporize both the coatings and elemental carbon cores within the ionization region of the AMS, providing a unique and selective method for measuring the mass of the refractory carbon cores (i.e., black carbon mass), the mass and chemical composition of any coating material (e.g., organics, sulfates, nitrates, etc.), and particle size and morphology. The limitation of this instrument is that it only measures sub-micron particles, it is very expensive and requires skilled operators. However its time resolution and sensitivity is high and it specifically identifies and quantifies black carbon and other chemical components that can be used in a source apportionment model.

4.2 Time of flight Aerosol Chemical Speciation Monitor

The time of flight aerosol chemical speciation monitor (ToF-ACSM) made by Aerodyne is similar to the Q-ACSM except it has a time of flight mass spectrometer (the Q-ACSM has a quadrupole mass spectrometer). This results in an order of magnitude lower detection limit, and also the ability to perform high resolution peak fitting to the spectra, which can help with source identification. It is also suitable for long term sampling campaigns. Currently the aerodynamic sampling lens is for PM_1 but a $PM_{2.5}$ lens is in development. The limitations of this instrument are that it is expensive and requires skilled operators.

4.3 Coal Grain Analysis

Coal Grain Analysis (CGA) is an optical reflected light imaging and analysis system which mosaics together calibrated contiguous high resolution colour images, collected with an air objective, to enable detailed information to be obtained on individual dust particles.

The image processing software first segments the mosaicked image to enable size information (area, particle length and width) and a reflectance fingerprint to be obtained for each individual particle in the image. This reflectance fingerprint is used to discriminate the coal from non-coal particles. More details on this method are described in Warren et al. (2015).

The analysis requires at least 20 mg of total suspended particles (TSP) to be collected on a filter. A Hi-Vol sampler is need with TSP inlet to be able to collect the required mass. The filter is then weighed and the particles extracted and set in polyester resin which then undergoes CGA for coal particle identification. CGA gives information only on particles larger than 1 micron.

4.4 Network of low cost sensors

A number of low cost particle sensors are now commercially available. As stand-alone instruments these low cost sensors are unsuitable for measuring particle concentrations. However if characteristics of the sensors, including accuracy, precision, reproducibility and sensitivity are rigorously characterised, the sensors can be used in a dense network to provide information that when incorporated into advance statistical models provides robust information on particle concentrations. The advanced statistical model (e.g. the Bayesian model) uses the characteristic information and signal data from many sensors to determine a probability of a concentration, which is updated as more data becomes available. The larger the number of sensors the more rigorous the Bayesian model results. The advantage of this approach is the very low cost of the sensors and the tolerance for large uncertainties of the sensors. This type of network could involve the community in a citizen science framework.

4.5 Unmanned aerial vehicle carrying sensors

Unmanned aerial vehicles (UAV) carrying air pollution sensors provide an opportunity to measure the emissions from an individual train through the entire rail corridor. While a number of groups are developing UAVs with air pollution sensor packages (e.g. QUT Robotics Department) there are few published reports on the use of UAVs for air quality measurements. Harrison et al (2015) used an aerosol spectrometer mounted on the nose of a large remote-controlled model airplane to measure the horizontal, vertical, and temporal variability of airborne particulates within the first 150 m of the atmosphere.

One limitation appears to be weight of sensors the UAV can carry. One commercially available system is the FIDAS Fly which uses the sensor technology described above, but is battery operated and has a low total weight of only 1400 g. A myriad of low-cost sensors could also be adapted for use in UAVs again noting the need to rigorously characterise the performance of the sensors.

5 Considerations for Study Design

Table 4 summarises the advantages and disadvantages of the different methodologies discussed in this report. All of the methods discussed could be applied to understanding emissions from the rail corridor of the coal chain.

However no single method will quantify particle these emissions. The ideal method that remains elusive would involve the real time measurement of size resolved aerosol chemical composition including black carbon concentrations. While the SP-AMS discussed in Chapter 4 goes someway to achieving this, it is limited to analysing only submicron particles, so that particles greater than 1 µm (in which most of the particle mass from the emissions resides) are not characterised by this method.

Hence a combination of methods that will measure the different properties of the particles are required. Integrating information on these properties will allow identification of the contribution to the air shed of the different particle sources in the rail corridor of the coal chain. While a complete study design would require serious scoping, suggestions for the components of the most basic study design are listed below.

1. Measure continuously concentration ($PM_{2.5\text{-}10}$, PM_{10} and $PM_{2.5}$), size distribution, absorption (black carbon), CO_2, wind speed, wind direction, precipitation, camera to photograph trains with timestamp. As in the Jaffe et al. (2015) work the relationships between $PM_{2.5}$, CO_2 and BC will allow distinction of coal dust and diesel combustion particle sources. Instruments and methodologies that could be used to carry out these measurements are described in Chapter 2. The instruments should be co-located.
2. Collect samples for TSP, $PM_{2.5\text{-}10}$, PM_{10}, $PM_{2.5}$ only during the passage of coal trains and perform gravimetric mass and chemical analyses for coal grain, soil, seasalt, organic species in the aerosol that are produced from diesel emissions. The instruments and methodologies that could be used to collect these samples and the analytical methods required to determine the chemical composition of these samples are described in Chapter 2. The instruments should be co-located with instruments listed in Point 1 above.
3. Specifically calibrate any light scattering particle mass concentration measurements with gravimetric mass concentrations by co-locating instruments listed in Points 1 and 2.
4. Carry out measurements at varying distances from the rail corridor to assess the potential exposure to particles from the rail corridor as a function of distance from the corridor. This could include the instruments and methods listed in Point 1 or a subset of these instruments that are linked back to the more comprehensive suite of instruments and methods listed in Point 1.
5. Carry out measurements under upwind and downwind conditions of the rail corridor. This should include the instruments and methods listed in Chapter 1 at and upwind and a downwind location.

Design of the measurement system needs to include procedures to ensure that comparison of data from multiple instruments can be carried out. Factors to bear in mind include time synchronisation of different instruments, measurement intervals of different instruments (minute, hour, 24-hour), data loss (due to automatic calibrations and filter changes for example) and data analysis procedures.

Other more specialised components could include using state-of-the-art research grade instrumentation (e.g. SP-AMS), UAV carrying particle sensors and or a dense low cost sensor network along a length of the rail corridor.

Table 4 Summary of advantages and disadvantages of methodologies discussed in this report

Property	Advantages	Disadvantages
Particle concentration: Gravimetric mass by size selective inlet	Meets NEPM reporting requirements Australian standard exists Collected samples can also be used for chemical composition and thus source identification Sampling equipment moderately priced Low volume samplers are quiet and require less power High volume sampler collect enough material for most chemical analyses	Off line gravimetric mass measurement requires infrastructure and equipment Relatively time intensive Sample collected over a period of time (usually 24 hours) so that time resolution is poor i.e. only one data point every 24 hours. Low volume samplers may not collect enough material for some analyses
Particle concentration: Gravimetric mass by Beta attenuation Monitor	Meets NEPM reporting requirements Australian standard exists Sampling equipment moderately priced Time resolution can be increased by inclusion of light scattering devices in some models	Hourly time resolution means that only one data point is collected per hour
Particle concentration: Gravimetric mass by Tapered Element Oscillating Microbalance	Meets NEPM reporting requirements Australian standard exists Sampling equipment moderately priced to highly priced High time resolution	Sample heated to 50°C so volatile mass lost; this can be mitigated by use of FDMS which increases price
Particle concentration by light scattering (photometer and OPC)	Australian standard exists (for nephelometer although not for mass calculation) Sampling equipment low to moderately priced High time resolution	Mass scattering coefficient needs to be determined to calculate mass from scattering coefficient
Particle Size Distribution by scanning mobility particle sizer	Provides high quality data on particle number and mass size distribution that can be used to infer information on formation process and sources High time resolution (5 minute intervals)	High cost Health and safety considerations (includes a sealed radioactive source in the neutraliser and solvent for counting particles in the CPC) Only measures up to 800 nm Specialised training to operate and interpret data
Particle Size Distribution by aerosol particle sizer	Provides high quality data on particle number and mass size distribution High time resolution (5 minute intervals)	High cost Counting statistics for particles greater than 5 µm are poor Specialised training to interpret data
Particle Size Distribution by light scattering	Sampling equipment low to moderately priced High time resolution	Rely on manufacturer calibrations etc.
Particle Size Distribution by cascade impactor	Provides data on particle mass size distribution that can be used to infer information on formation process and sources Collected samples can also be used for chemical composition and thus source	Offline gravimetric mass measurement requires infrastructure and equipment Relatively time intensive Sample collected over a period of time (usually 24 hours) so that time resolution is poor

	identification Sampling equipment moderately priced	
Absorption continuous by filter based method (Aethelometer, MAAP, TAP, PSAP)	TAP Moderate cost High time resolution Information on black carbon content	Interference from other light absorbing particles e.g. soil Scattering artefact of filter interferes with measurement MAPP, Aethelometer high cost Specialised training to interpret data
Absorption continuous by acoustic based method (PASS)	High time resolution Information on black carbon content	Interference from other light absorbing particles e.g. soil High cost Specialised training to interpret data
Absorption continuous by incandescence (SP2)	High time resolution Only instrument available that specifically identifies and quantifies BC without interference from other absorbing particles	Very high cost Specialised training to interpret data
Chemical composition off line analysis	Ability to identify sources of aerosols (in some cases with unique identifiers).	Requirement to collect sufficient sample volumes resulting in poor time resolution (typically 24 hours) Artefacts that occur during and after sampling, particularly concerning volatile and semi-volatile compounds Chemical analyses requires infrastructure and equipment and high levels of analytical skills.
Chemical composition on line analysis (e.g. AMS)	High time resolution Ability to identify sources of aerosols (in some cases with unique identifiers).	Very high cost Only measure sub-micron particles Specialised training to operate instrument and interpret data
Emerging technology **SP-AMS**	High time resolution Measures chemical composition and specifically identifies and quantifies BC without interference from other absorbing particles	Extremely high cost Only measure sub-micron particles Specialised training to operate instrument and interpret data
Emerging technology **Tof-ACSM**	High time resolution Measures chemical composition	Very high cost Only measure sub-micron particles Specialised training to operate instrument and interpret data
Emerging technology **Coal grain analysis of particle samples**	Quantifies coal grain contribution to particle samples	Analysis requires large sample volumes resulting in poor time resolution (typically 24 hours) Chemical analyses requires infrastructure and equipment and high levels of analytical skills
Emerging technology **Network of low cost sensors**	Sensors are inexpensive and simple to operate	Requires careful network design Requires rigorous characterisation of sensor performance Requires high levels of statistical analytical skill
Emerging technology **Coal grain analysis of particle samples**	Quantifies coal grain contribution to particle samples	Analysis requires large sample volumes resulting in poor time resolution (typically 24 hours) Chemical analyses requires infrastructure and equipment and high levels of analytical skills
Emerging technology **Unmanned aerial vehicles**	Provides spatial data	Requires careful network design Constraints of payload size Specialised training and licencing to operate UAV

References

AECOM. (2015). Lower Hunter Dust Deposition Study - Interim Report. AECOM Australia Pty Ltd: Prepared for the NSW Environment Protection Authority. Retrieved from http://www.epa.nsw.gov.au/MediaInformation/lhddprg.htm.

Allen, G., Sioutas, C., Koutrakis, P., Reiss, R., Lurmann, F. W., & Roberts, P. T. (1997). Evaluation of the TEOM(R) method for measurement of ambient particulate mass in urban areas. *Journal of the Air & Waste Management Association, 47*(6), 682-689.

Bond, T. C., Anderson, T. L., & Campbell, D. (1999). Calibration and intercomparison of filter-based measurements of visible light absorption by aerosols. *Aerosol Science and Technology, 30*(6), 582-600.

Civiš M, & Hovorka, J. (2010). Characterization of main dust samples from a surface lignite mine using a Resuspension chamber. *Journal of Safety Research and Applications, 3*, Available from WWW: < http://www.bozpinfo.cz/josra/josra-03-04-2010/vzorky-prachu.html >. ISSN 1803-3687.

Connell Hatch. (2008). Final Report - Environmental Evaluation of Fugitive Coal Dust Emissions from Coal Trains Goonyella, Blackwater, and Moura Coal Rail Systems. Prepared by Connell Hatch (now Auricon Hatch): Queensland Rail Limited.

DSITIA. (2013). Western - Metropolitan Rail Systems Coal Dust Monitoring Program - Final Report. Queensland: Department of Science, Information Technology, Innovation and the Arts. Retrieved from www.ehp.qld.gov.au/management/coal-dust/pdf/railcoal- dust-final-report.pdf.

DSITIA. (2012). Tennyson Dust Monitoring Investigation - September to October 2012. Queensland: Department of Science, Information Technology, Innovation and the Arts. Retrieved from www.ehp.qld.gov.au/air/pdf/tennyson-dust-report.pdf.

ENVIRON. (2012). Pollution Reduction Program (PRP) 4 - Particulate Emissions from Coal Trains: Prepared by ENVIRON Australia Pty Ltd for Australian Rail Track Corporation.

Hansen, A. D. A., Rosen, H., & Novakov, T. (1984). THE AETHALOMETER - AN INSTRUMENT FOR THE REAL-TIME MEASUREMENT OF OPTICAL-ABSORPTION BY AEROSOL-PARTICLES. *Science of The Total Environment, 36*(JUN), 191-196.

Harrison, W. A., Lary, D. J., Nathan, B. J., & Moore, A. G. (2015). Using Remote Control Aerial Vehicles to Study Variability of Airborne Particulates. *Air Soil and Water Research, 8*, 43-51.

Higginbotham, N., Ewald, B., Mozeley, F., & Whelan, J. (2013). Coal train pollution signature study. Coal Terminal Action Group Dust and Health Committee: Coal Terminal Action Group.

Jaffe, D., Putz, J., Hof, G., Hof, G., Hee, J., Lommers-Johnson, D. A., et al. (2015). Diesel particulate matter and coal dust from trains in the Columbia River Gorge, Washington State, USA. *Atmospheric Pollution Research, 6*(6), 946-952.

Jaklevic, J. M., Gatti, R. C., Goulding, F. S., & Loo, B. W. (1981). A β-gauge method applied to aerosol samples. *Environmental Science and Technology, 15*(6), 680-686.

Jordan, T. B., Seen, A. J., & Jacobsen, G. E. (2006). Levoglucosan as an atmospheric tracer for woodsmoke. *Atmospheric Environment, 40*(27), 5316-5321.

Kane, M. (2015). Health Hazard in our suburbs: Particulate pollution along the South-East Queensland coal dust corridor. Queensland: Prepared for Clean Air Queensland.

Katestone Environmental Pty Ltd. (2013). Pollution Reduction Program 4.2 Particulate Emissions from Coal Trains. Queensland: Prepared for Australian Rail Track Corporation Pty Ltd.

Moosmüller, H., Chakrabarty, R. K., & Arnott, W. P. (2009). Aerosol light absorption and its measurement: A review. *Journal of Quantitative Spectroscopy and Radiative Transfer, 110*(11), 844-878.

OCSE. (2015). *Initial Report on the Independent Review of Rail Coal Dust Emissions Management Practices in the NSW Coal Chain*.

Petzold, A., & Schonlinner, M. (2004). Multi-angle absorption photometry - a new method for the measurement of aerosol light absorption and atmospheric black carbon. *Journal of Aerosol Science, 35*(4), 421-441.

Roebuck, B., Vaughan, N. P., & Chung, K. Y. K. (1990). PERFORMANCE TESTING OF THE OSIRIS DUST MONITORING-SYSTEM. [Article]. *Annals of Occupational Hygiene, 34*(3), 263-279.

Rogers, Z., Whelan, J., & Mozeley, F. (2013). Coal dust in our suburbs: a community-led study of particulate pollution in Newcastle and the Lower Hunter coal train corridor. Coal Terminal Action Group Dust and Health Steering Group: Coal Terminal Action Group.

Schwarz, J. P., Gao, R. S., Fahey, D. W., Thomson, D. S., Watts, L. A., Wilson, J. C., et al. (2006). Single-particle measurements of midlatitude black carbon and light-scattering aerosols from the boundary layer to the lower stratosphere. *Journal of Geophysical Research-Atmospheres, 111*(D16).

Warren, K., Krahenbuhl, G., Mahoney, M., O'Brien, G., & Hapugoda, P. (2015). Estimating the fusible content of individual coal grains and its application in coke making. *International Journal of Coal Geology, 152*, 3-9.

Warren, K., Krahenbuhl, G., O’Brien, G., & Hapugoda, P. (2015). Quantifying Coal Dust in Urban Samples. Paper no. 3134824 at International Conference on Coal Science & Technology, 27 Sep – 1 Oct, Melbourne.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

FOR FURTHER INFORMATION

Oceans and Atmosphere
Melita Keywood
t +61 3 9239 4596
e **melita.keywood**@csiro.au
w www.csiro.au/O&A