Coal Mines
Technical Services

COAL SERVICES HEALTH & SAFETY TRUST
RESEARCH PROJECT - PROJECT NO. 20627

Diesel particulate analysis correlation between laser light scattering devices and analysis by the NIOSH 5040 method of analysis

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EXECUTIVE SUMMARY

The aim of this research was to determine the correlation between results produced for elemental carbon (EC) BY laser light scattering (LLS) devices such as the MAHA MPM-4M and the thermo optical NIOSH 5040 filter analysis. It was also to determine whether the current correction factor used in these LLS devices is still valid.

A Coal Services Health and Safety Trust research project carried out in 2004 (Report 04/0884) by the New South Wales Department of Primary industries, Mines Safety Technical Services, looked at various methods for measuring diesel particulate matter (DPM). This work also developed a factor for use with LLS devices to convert the measured total particulate matter (TPM) to EC. The latter was based on a relatively small engine sample size and this research looks at a broader range and number of engines.

In addition to this study, recently completed research funded by the Coal Services Health and Safety Trust in relation to a practical means for the calibration of diesel particulate analysers (Dr Brian Davies, University of Wollongong, 2013) has also been undertaken.

The two studies stated above are relevant to this research as they both included the use of laser light scattering (LLS) devices for the electronic determination of TPM and EC and also the NIOSH 5040 filter analysis method for the determination of EC.

This study also looks at historical DPM correlation data between diesel engines tested using one of the original LLS devices (and considered appropriate for the analysis of diesel particulates in the raw exhausts of engines in the MDG29 Guidelines – 2008, Guidelines for the management of. diesel engine pollutants in underground environments) and the MAHA MPM-4M LLS DPM analyser.

As with the 2013 research, the chamber sampling device developed by Emission Reduction Products Engineering Pty Ltd (ERP) was used to collect samples from the engine gas manifold sampling point and was also modified prior to this study to allow simultaneous sampling of both the quartz filters for NIOSH 5040 analysis and sampling using the LLS device.

Following minor modifications that were noted following the 2013 research, the Freudenberg sampling system used in that program was also used for this work to draw the raw gas from the ERP sampling chamber.

It was considered important to carry out all testing of engines at their working site as this would be the case for normal routine gas emission and DPM testing in accordance with the NSW Department of Primary Industry MDG29 – 2008 Guidelines. Six coal mine mines site engines were used for the testing.

The results from the testing has shown a direct correlation between the EC reading produced from both diesel engine raw exhaust/manifold and results using the NIOSH 5040 filter analysis. However, based on the data analysis for this research, it would seem that the correction factors utilised in the LLS devices currently in use require updating.

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1 Introduction

Quoting from a press release from the International Agency for Research on Cancer (IARC):

"*Lyon, France, June 12, 2012 -- After a week-long meeting of international experts, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), today classified diesel engine exhaust as carcinogenic to humans (Group 1), based on sufficient evidence that exposure is associated with an increased risk for lung cancer.*"

As far back as 1988 the IARC classified diesel exhaust emissions as "*probably carcinogenic to humans (Group 2A)*" and recommended that it be re-evaluated with a high priority in 1998.

Hence there has been a focus since the late 1990s in the Australian coal mining industry on monitoring and reducing diesel engine emissions, particularly diesel particulate matter (DPM).

One of the first significant studies in relation to how to best monitor diesel emissions for DPM was the Coal Services Health and Safety Trust project conducted in 2004 by the NSW Department of Primary Industries, Mines Safety Technical Services. It investigated the capability of a number of devices that could be used for measuring DPM. Of these the laser light scattering devices (LLS) were identified as being capable of measuring DPM from the raw exhaust of diesel engines used in the coal industry. While other devices also showed promise, it was the LLS type that seemed to provide the best option at the time for practical measurement.

More recently another Coal Services Health and Safety Trust research project looked at a practical means for calibrating diesel particulate analysers (Dr Brian Davies, University of Wollongong, 2013). Dr Davies was also the Scientific Advisor for the 2004 project.

This study is relevant to both of the above projects and looks at the use of LLS devices for effectively measuring diesel engine raw exhaust emissions for DPM, whether there is a correlation with analysis using the NIOSH 5040 method and whether the correction factor that was developed in the 2004 research is still applicable.

2 Engine testing

70 diesel engines with various engine types were tested for the study. A listing of the engine types and sample size for each can be found in Table 1.

While sample numbers were not as high as preferred for some engine types, they were what the various sites provided and had available at the time of testing. The DPM data nevertheless was fairly consistent across all engine types tested in relation to a correlation with the NIOSH 5040 filter analysis method.

The testing was carried out on site in conjunction with the routine diesel engine emission testing for gaseous emissions and diesel particulates in accordance with the NSW Department of Primary Industry MDG29-2008 Guidelines.

The testing program also had to consider site operation requirements and maintenance time frames. As a result not all engines at every site were able to be tested using the ERP chamber and Freudenberg sampling system. Data for the routine gas and diesel emission testing for these additional engines were not included in the data for the 70 engines listed in Table 1.

Table 1 – Engine type, manufacturer and number of engines tested

Engine type	Manufacturer	No. tested
3126	CAT	1
3304	CAT	1
3306	CAT	3
1006-6	PERKINS	45
1104C-44	PERKINS	2
4.10 TCA	MWM	1
6V92	DETROIT	1
C7	CAT	13
D916-6	MWM	3
	Total engines tested	**70**

Initial gas emission testing for each engine (carbon monoxide, carbon dioxide and nitrous emissions) was also carried out. The initial testing was without the use of the ERP sampling chamber connected, and then with the chamber connected. This was to confirm that there was no change in gas emission levels when the device was connected and used for sampling.

Testing on all engines was carried out with exhaust filters removed. DPM testing at the exhaust using the MAHA MPM-4M LLS device was carried out after the engine scrubbers.

3 Equipment used for testing

The following equipment was used for the testing:

1. MAHA MPM-4M LLS devices (2) for measuring TPM and EC. General technical specifications provided by the manufacturer:

Measurement method:	Laser light-scattering photometry
Particle size range:	<100nm to >10 microns
Particle concentration range:	0.1 to 400 mg/m^3 (Elemental Carbon)
Resolution:	0.1 mg/m^3
Sample flow:	2.0 L/minute (nominal)
Range selection:	Auto-ranging
Pre-calibration:	Auto-zero prior to every test

Span check:	60 seconds using calibration tool supplied with instrument
Output (serial):	RS232 (up to 115,200 baud) at 5 Hz
Operating Voltage:	12V volts DC (via external adapter) (battery power optional and used when required)
Operating Current:	2.0 amp (max)
Analyser mass:	6kg (6pprox..)
Standard Accessories:	Sample hose, standard sample probe, calibration tool, 240V AC to 12V DC adaptor
Custom sample probes:	2 x 21cm probes manufactured and supplied by ERP Engineering Pty Ltd to suit sampling chamber (1 x probe to suit the MAHA device and 1 x probe for quartz filter collection)

Figure 3.1 show the typical front panel display of the MAHA MPM-4M LLS analyser and also with the exhaust sampling probe connected

Figure 3.1 – MAHA MPM-4M DPM analyser and with sampling probe attached

Source: CMTS

2. The Freudenberg Technologies Pty Ltd sample collection system. The system was used in conjunction with the ERP Engineering Pty Ltd sampling chamber to collect the quartz filter samples for the NIOSH 5040 analysis and utilises a sampling pump, timer and mass flow device to ensure accurate sample volumes are collected.

Figure 3.2 – Freudenberg portable sampling system

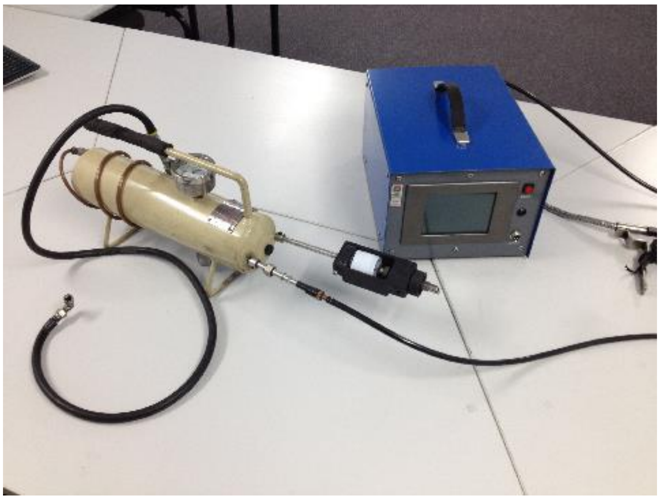
Source: CMTS

3. The ERP Engineering Pty Ltd sampling chamber was used for collecting and blending engine exhaust emission directly from engine manifolds. The chamber is directly connected to the engine manifold and uses the same sampling point as used for the routine raw gas emission sampling and analysis. It has been designed to facilitate simultaneous sampling for DPM measurement using the MAHA device and also for the collection of the quartz filter samples for the NIOSH 5040 analysis.

   When connected to the manifold sample point on an operating engine the raw exhaust is forced through a connecting pipe and into a chamber vessel via a cooling coil. Mixing of the exhaust gas occurs in the chamber vessel. A pressure gauge is fitted to the chamber vessel to ensure that when samples are collected, greater than zero back-pressure can be confirmed.

The modified version used for this study permits up to 3 sample probe positions. For this testing the two outer sampling positions were used as can be seen in Figure 3.3
There is also a drainage provision to drain any water vapour that may have condensed from the exhaust.

Figure 3.3 – ERP sampling chamber vessel with dual sampling probes



Source: CMTS

4. 21cm sampling probe with quartz filter cassette holder manufactured by ERP Engineering Pty Ltd and used in conjunction with the sampling chamber vessel for emission sampling and collection of quartz filters

Figure 3.4 – ERP 21cm sampling probe for quartz filter collection

Source: CMTS

5. 21cm sampling probe manufactured by ERP Engineering Pty Ltd and used in conjunction with the sampling chamber vessel for emission sampling using the MAHA MPM-4M LLS devices
6. Quartz filters (SKC 225-401 pre-loaded, 37mm specifically for NIOSH 5040 sampling and analysis) for engine emission collection and subsequent analysis by the NIOSH 5040 method using Sunset Laboratory Aerosol Organic Carbon-EC analysers
7. CMTS Mobile gas emission testing laboratory

4 Correlation between the original AQT LLS device and the MAHA MPM-4M LLS device

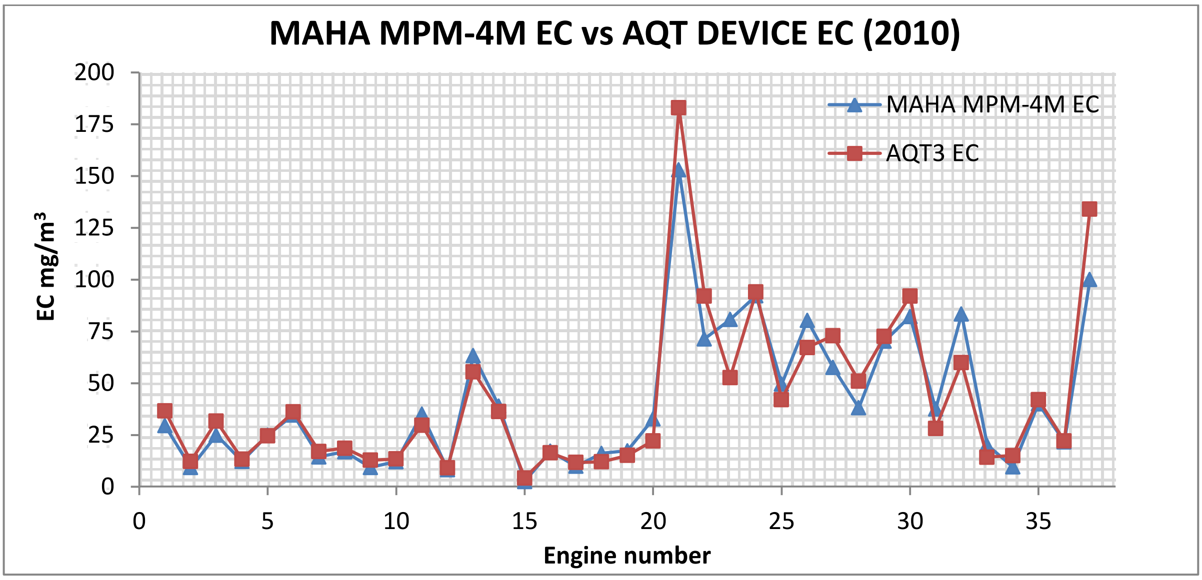
In the 2004 study the LLS devices used were the "DustTrak" and "DataRam" branded analysers. The latter, developed by Air Quality Technologies (AQT), had some additional refinements in design in relation to its dilution system. It is more commonly known as simply the AQT diesel particulate monitoring device. This became the general LLS device used by State Government licensed facilities in NSW for routine monitoring of DPM in raw engine emissions and is considered appropriate for the analysis of diesel particulates in the raw exhausts of engines as per the MDG29 Guidelines – 2008.

The MAHA MPM-4M LLS instrument was developed some years after the introduction of the AQT device and was a further refinement of the LLS system. It also has the ability to use a calibration "plug" to calibrate the instrument, an integrated sample preconditioning system, automatic inbuilt on-screen prompts to advise operators when to change engine load parameters as per the MDG29 -2008 Guidelines and other improvements.

Comparison correlation testing on 37 diesel engines carried out by Coal Mines Technical Services (CMTS) in 2010 between the then new MAHA device and the AQT device confirmed the technology for this type of DPM detection as being consistent across the two devices with good correlation. This test data is shown graphically in Figures 4.1 and 4.2. Engines with high emissions were deliberately included in the testing in order to evaluate the correlation over a wide range of DPM. EC values of less than approximately 25mg/m^3 displayed the better correlation.

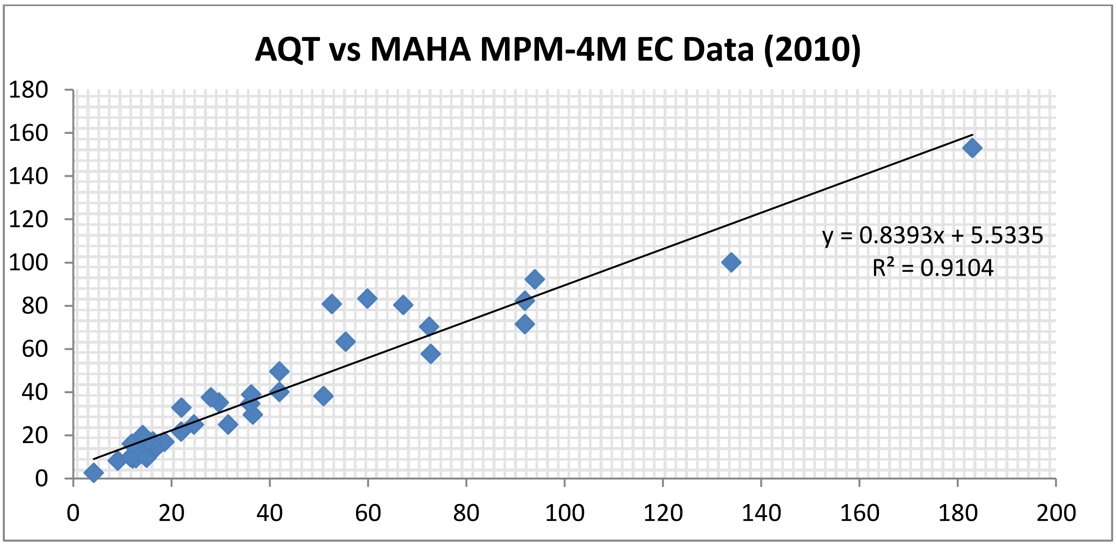
The original AQT device has also undergone refinements over the past few years and is currently being sold under the name AVT by a number of suppliers. The "5" series, or AVT 530, being the most commonly used. This particular device has a similar EC correction factor to the MAHA and original AQT of approximately 0.5.

Figure 4.1 – EC result correlation between the MAHA MPM-4M and the AQT3 analyser (2010)



Data source: CMTS

Figure 4.2 – EC linear regression correlation analysis between the MAHA MPM-4M and the AQT3 analyser (2010)



Data source: CMTS

5 Correlation of data and analysis

The data collected from the 70 engines tested using the MAHA MPM-4M and analysis from the quartz filters using the NIOSH 5040 method and incorporating the ERP sampling chamber vessel and the Freudenberg sampling system was reviewed and broken down as follows:

1. Correlation of EC data for the MAHA MPM-4M LLS device between the manifold exhaust and exhaust sample points
2. Correlation of EC data between the MAHA MPM-4M LLS device exhaust sample EC and NIOSH 5040 filter analysis EC and also with a revised correction factor for the MAHA device
3. Correlation of EC data between the MAHA MPM-4M LLS device manifold exhaust EC and NIOSH 5040 filter analysis EC and also with a revised correction factor for the MAHA device

Correlation between two sets of data is an indication of how well they are related. In addition to the use of a standard linear regression plot, the Pearson Product Moment Correlation (or PPMC) is commonly used for this purpose and often is referred simply as the Pearson Correlation. It shows the linear relationship between two sets of data. Pearson's Correlation was used for some of the statistical analysis in this study.

A positive value between 0.5 and 1.0 is considered a high correlation using the Pearson Correlation. A medium correlation using this method is regarded as being between 0.30 and 0.50.

Also of value in the statistical analysis of this type of data is the plotting of residuals. The difference between the observed value of the dependent variable and the predicted value is called the residual. If the points on a residual plot are randomly dispersed around the horizontal axis, then this indicates a linear regression model is appropriate for the data. It was used for correlation between the MAHA MPM-4M manifold/exhaust EC data and the data from the NIOSH 5040 quartz filter analysis.

5.1 Correlation of EC data for the MAHA MPM-4M between the exhaust manifold and raw exhaust sample points

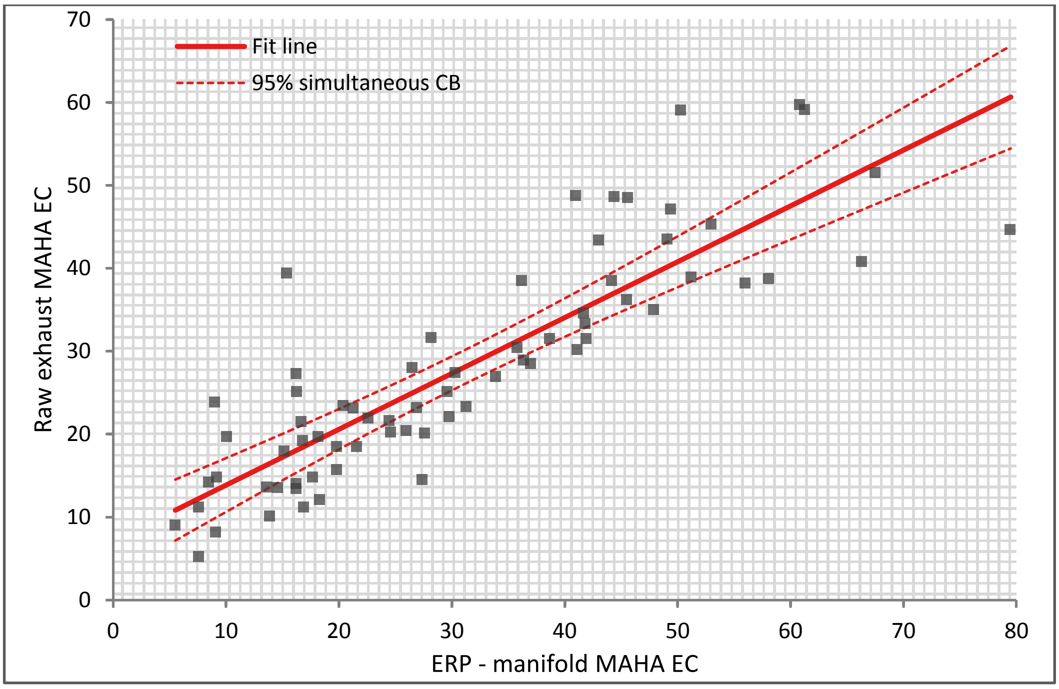
While there were sampling difficulties at times carrying our simultaneous sampling using the MAHA device at the manifold exhaust using the ERP chamber vessel and the exhaust itself (equipment availability on some occasions as two MAHA devices are required), the results still showed an acceptable correlation between the sample points.

When only a single MAHA analyser was available for testing, the exhaust was sampled first, followed by sampling using the ERP chamber at the manifold exhaust and then a re-check at the exhaust again to confirm the original readings.

Key advantages of being able to sample directly from the manifold exhaust include the reduction of moisture issues and control over probe positioning when carrying out DPM testing using LLS devices.

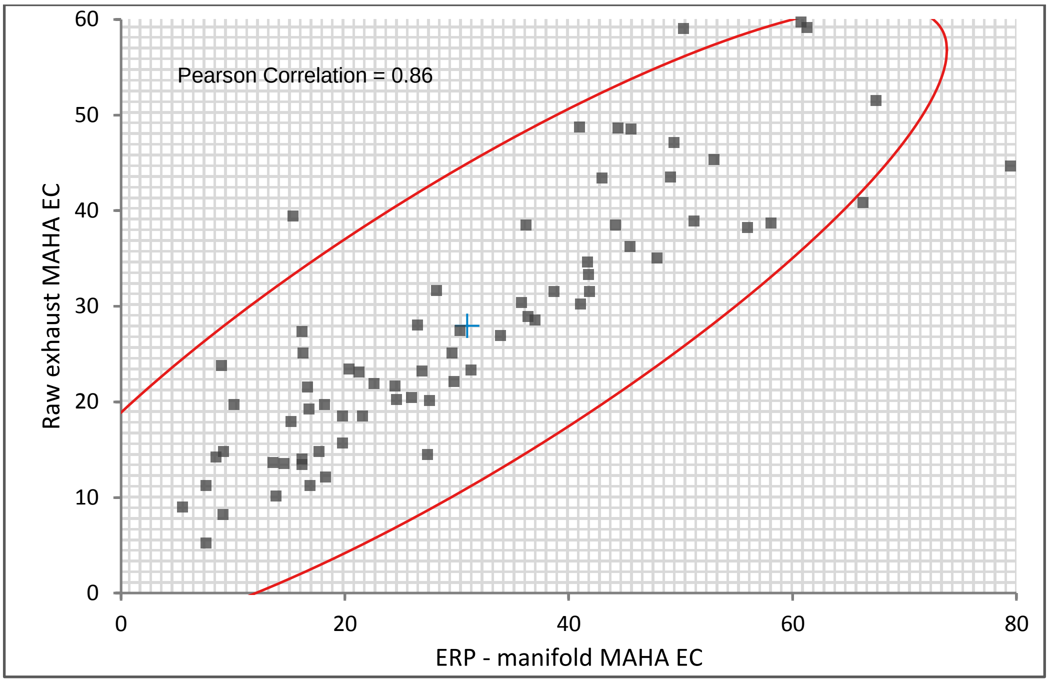
As can be seen in Figures 5.1 and 5.2, an acceptable correlation was achieved between the two sample points, with the Pearson Correlation of 0.86.

Figure 5.1 – MAHA Raw Exhaust EC vs MAHA ERP Manifold EC – Linear Regression



Data source: CMTS

Figure 5.2 – MAHA Raw Exhaust EC vs MAHA ERP Manifold EC – Pearson Correlation



Data source: CMTS

5.2 Correlation of EC data between the MAHA MPM-4M exhaust sample EC and NIOSH 5040 filter analysis EC and also with a revised correction factor for the MAHA device

Figures 5.3, 5.4 and 5.5 show the correlation between the MAHA exhaust EC analysis and the results from the quartz filter analysis using the NIOSH 5040 method.

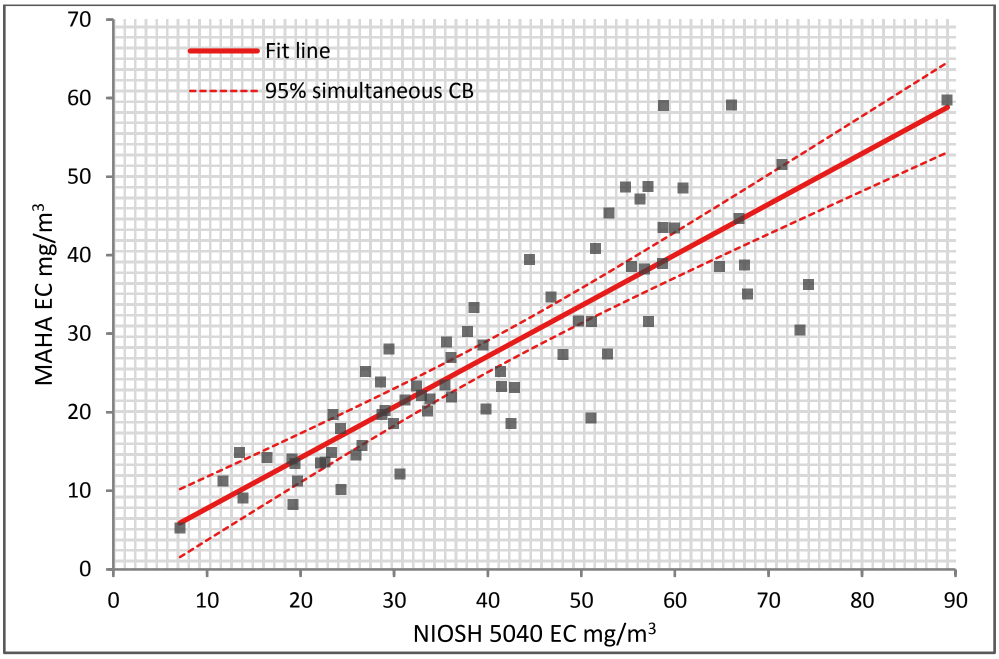
The samples for the MAHA MPM-4M and the quartz filters were collected simultaneously using the ERP collection chamber vessel connected to the exhaust manifold.

An acceptable Pearson correlation of 0.87 was achieved for the data.

The plot of residuals showed a good random dispersion above and below of the horizontal line, indicating a linear regression was appropriate for this data analysis.

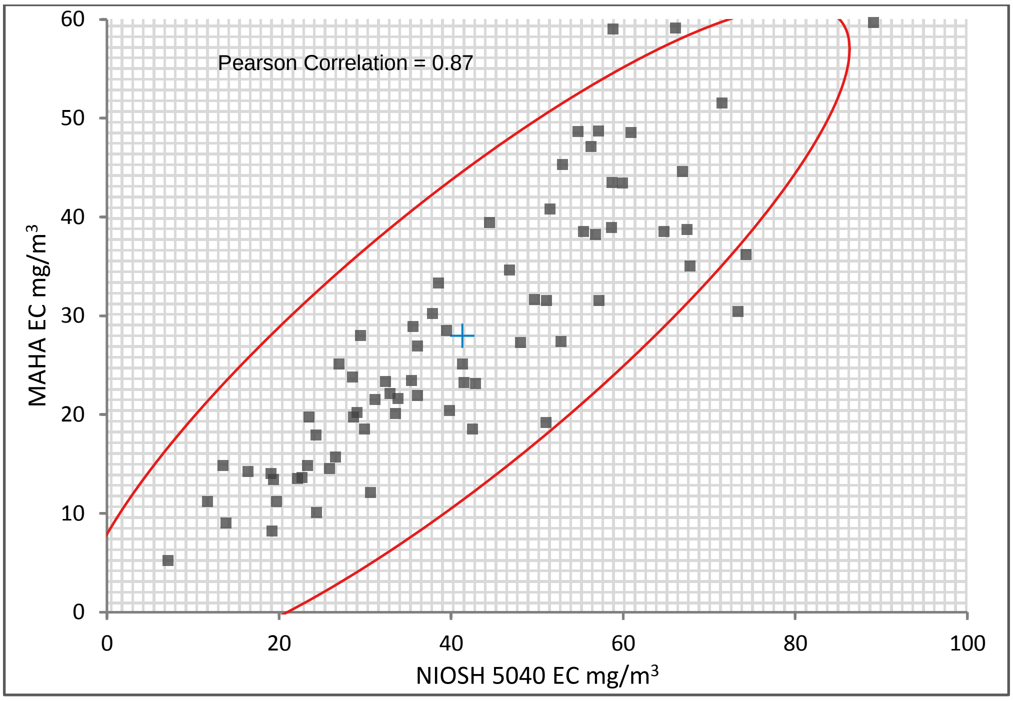
Figures 5.6 and 5.7 graph the EC values for the MAHA exhaust EC analysis and the results from the quartz filter analysis using the NIOSH 5040 method and also the corrected MAHA data using a revised correction factor. The new factor being 0.65 (MAHA MPM-4M internal pre-set factor is 0.46).

Figure 5.3 – MAHA Exhaust EC vs NIOSH 5040 EC - Linear Regression



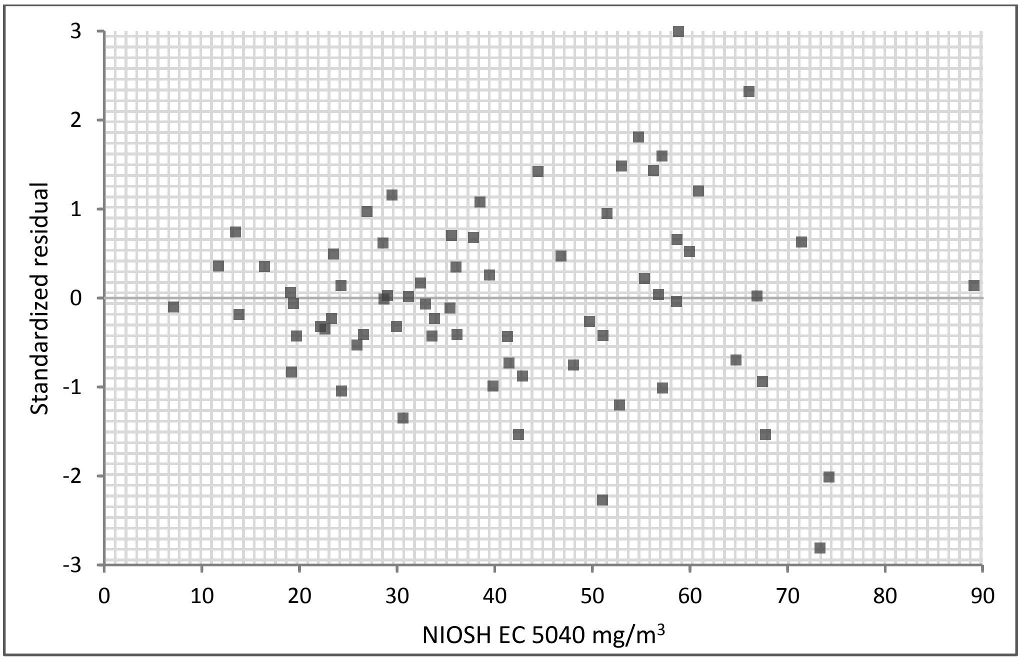
Data source: CMTS

Figure 5.4 – MAHA Exhaust EC vs NIOSH 5040 EC – Pearson Correlation



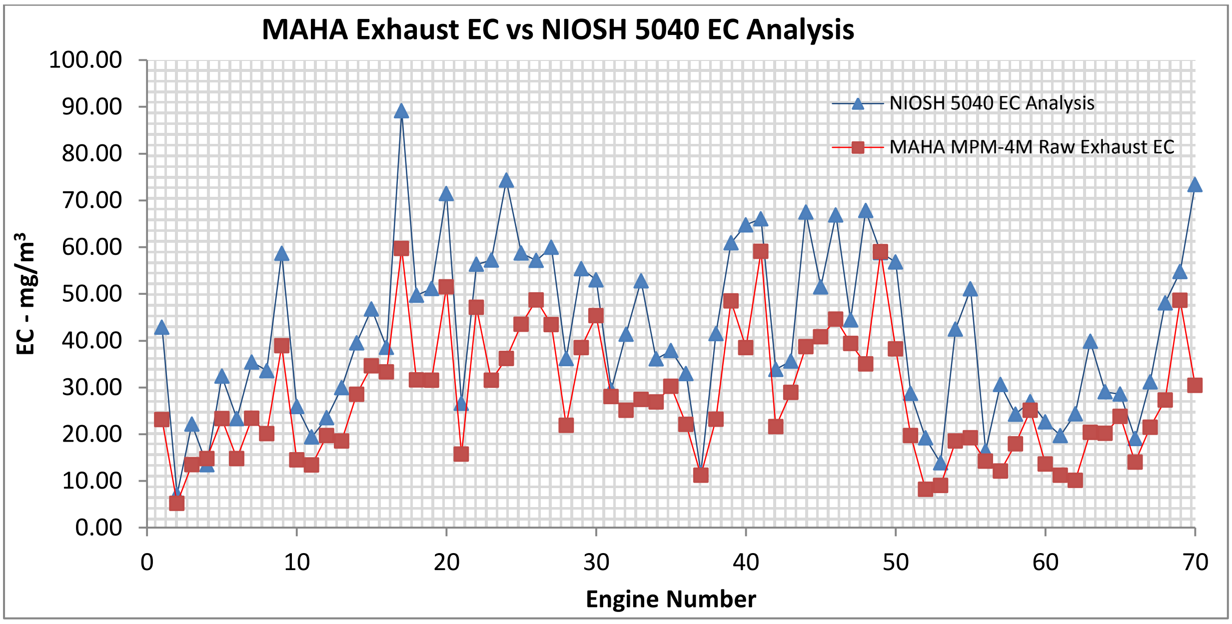
Data source: CMTS

Figure 5.5 – MAHA Exhaust EC vs NIOSH 5040 EC – Residuals



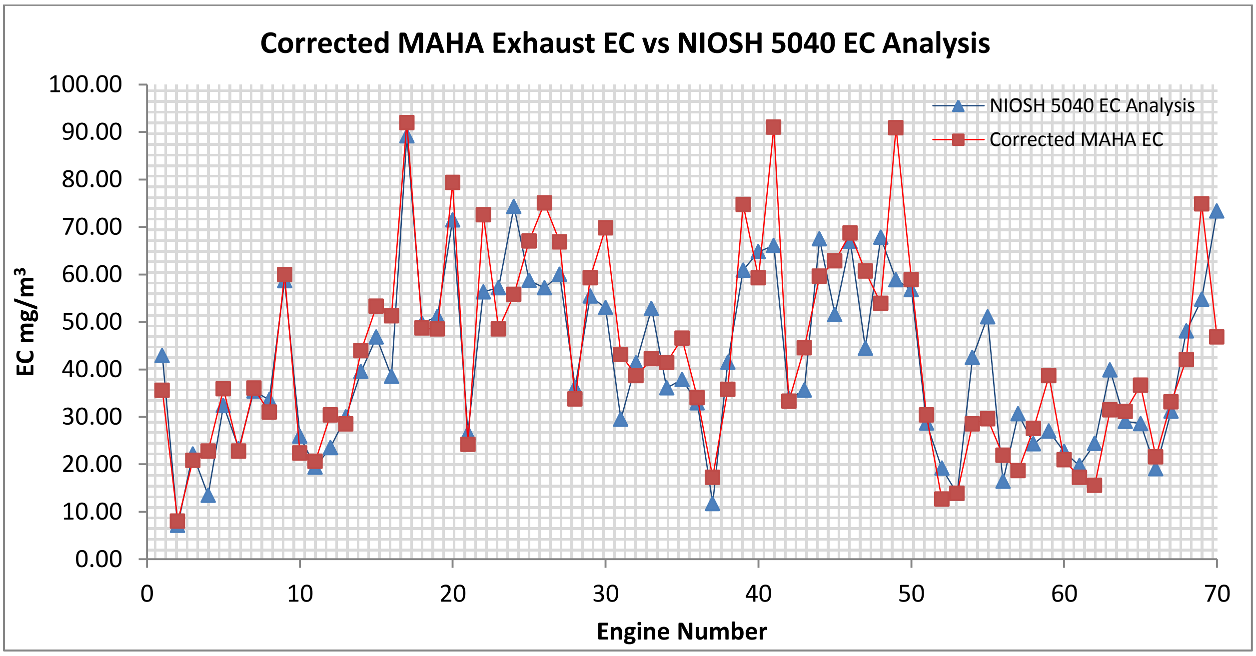
Data source: CMTS

Figure 5.6 – MAHA Exhaust EC vs NIOSH 5040 EC Analysis



Data source: CMTS

Figure 5.7 – Corrected MAHA Exhaust EC vs NIOSH 5040 EC Analysis



Data source: CMTS

5.3 Correlation of EC data between the MAHA MPM-4M manifold exhaust EC and NIOSH 5040 filter analysis and also with a revised correction factor for the MAHA device

Figures 5.8, 5.9 and 5.10 show the correlation between the manifold MAHA exhaust EC analysis and the results from the quartz filter analysis using the NIOSH 5040 method.

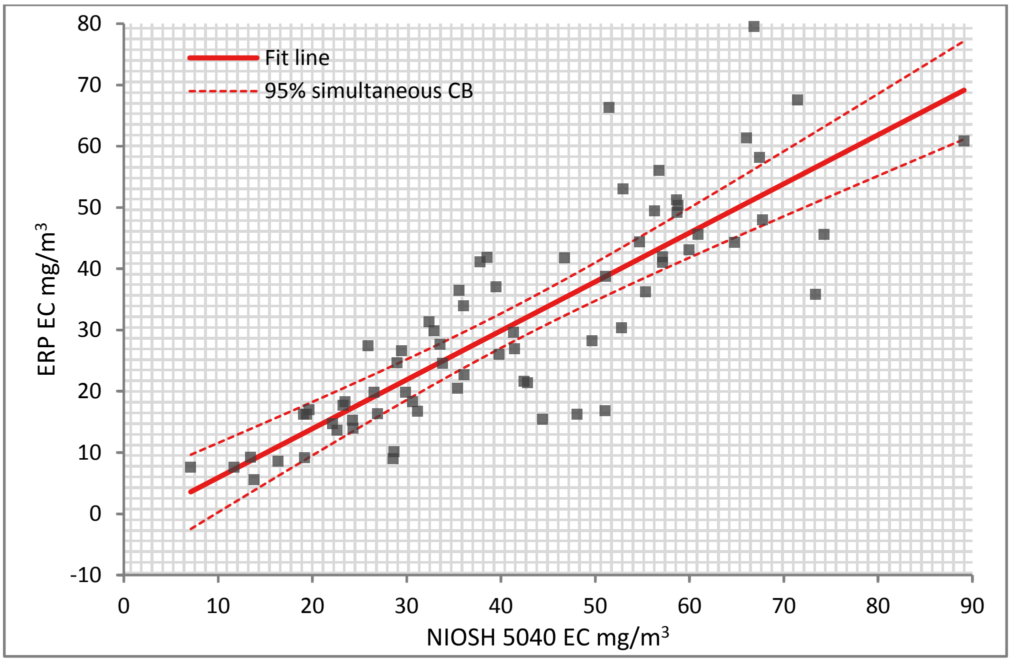
The samples for the MAHA MPM-4M and the quartz filters were collected simultaneously using the ERP collection chamber vessel connected to the exhaust manifold.

An acceptable Pearson correlation of 0.84 was achieved for the data.

The plot of residuals at the manifold showed a similar good random dispersion above and below of the horizontal line to the data from the raw exhaust sampling correlation, indicating a linear regression was appropriate for this data analysis.

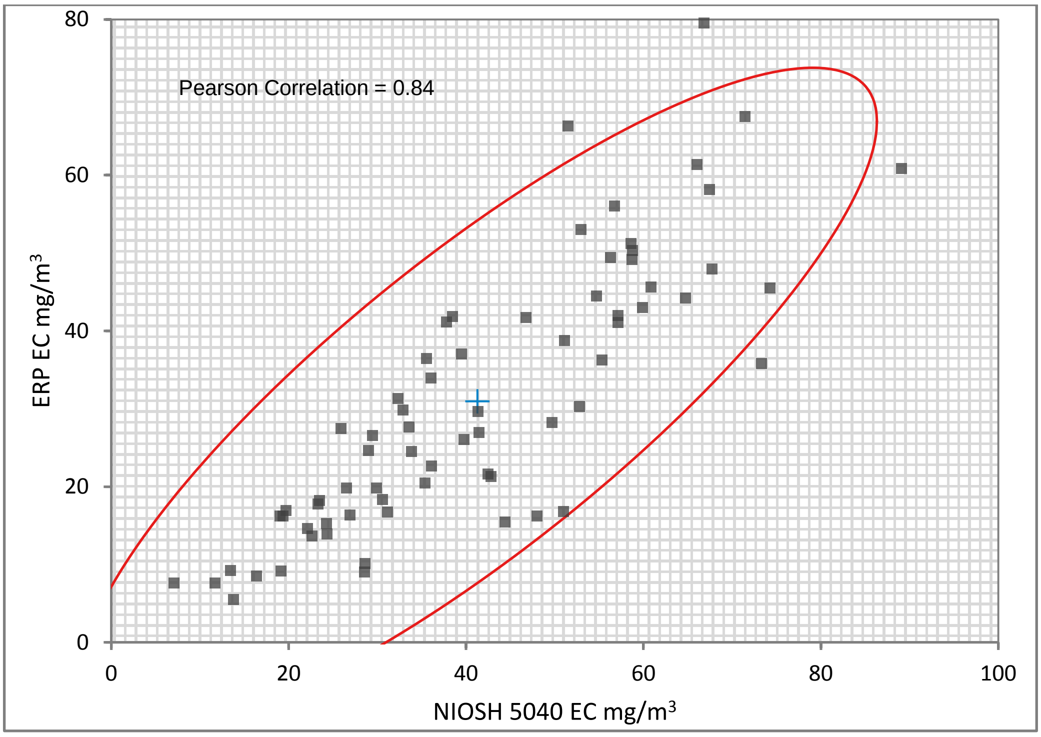
Figures 5.11 and 5.12 graph the EC values for the manifold MAHA exhaust EC analysis and the results from the quartz filter analysis using the NIOSH 5040 method and also the corrected MAHA data using a revised correction factor. The new factor being 0.67 (MAHA MPM-4M internal pre-set factor is 0.46).

Figure 5.8 – Manifold Exhaust MAHA EC vs NIOSH 5040 EC - Linear Regression



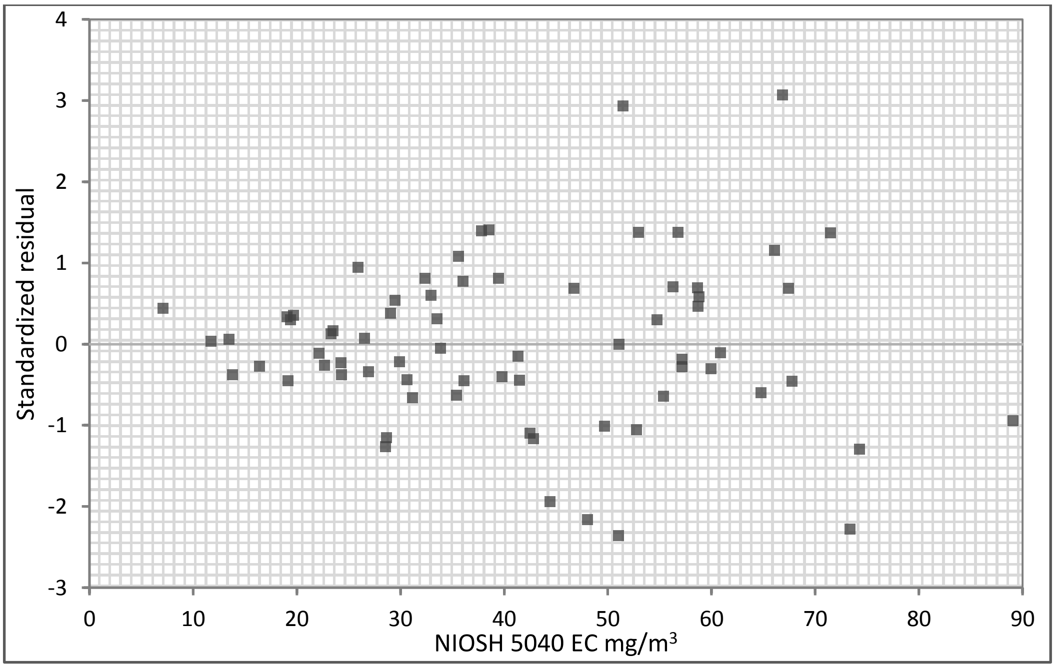
Data source: CMTS

Figure 5.9 – Manifold Exhaust MAHA EC vs NIOSH 5040 EC – Pearson Correlation



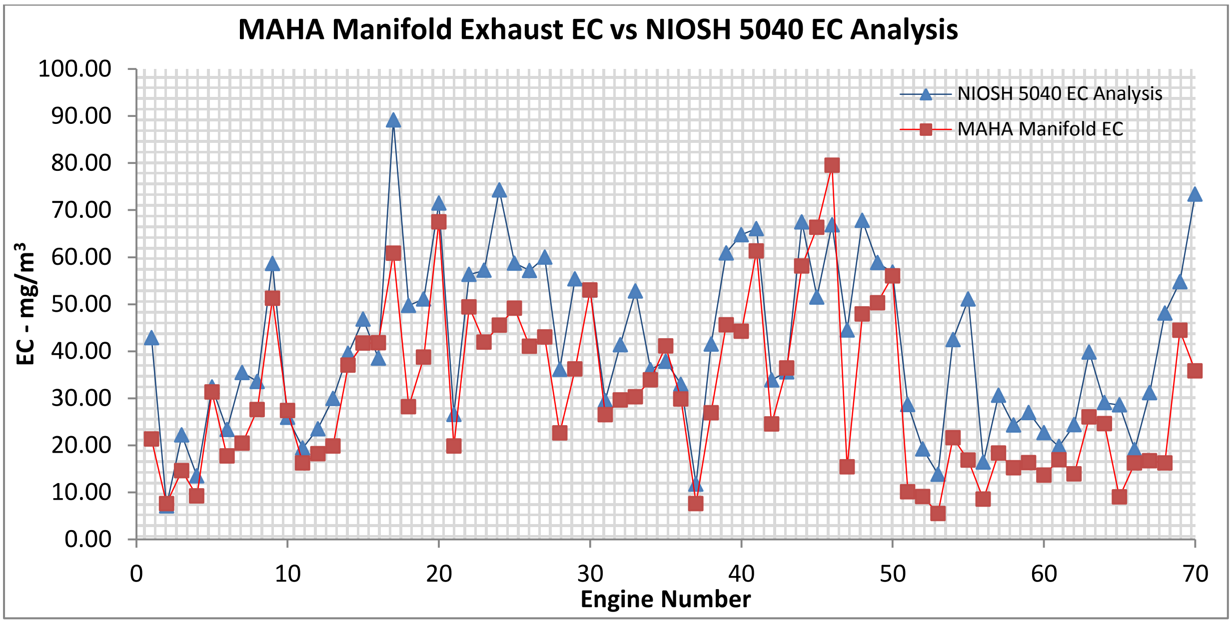
Data source: CMTS

Figure 5.10 – Manifold Exhaust MAHA EC vs NIOSH 5040 EC – Residuals



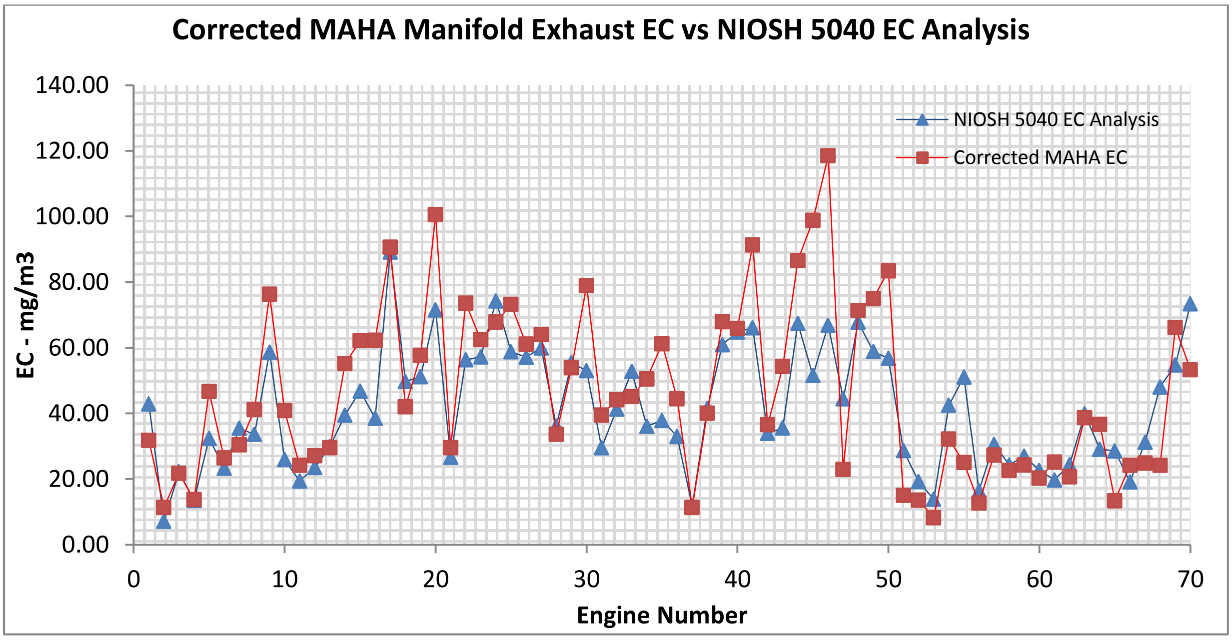
Data source: CMTS

Figure 5.11 – Manifold Exhaust MAHA EC vs NIOSH 5040 EC



Data source: CMTS

Figure 5.12 – Corrected Manifold Exhaust MAHA EC vs NIOSH 5040 EC



Data source: CMTS

6 Concluding comments

1. The study established an acceptable EC correlation between data using the MAHA MPM-4M aerosol DPM analyser for samples collected from the manifold exhaust sample point and samples collected from the vehicle exhaust.
2. The study also showed an acceptable correlation between EC data using the MAHA MPM-4M LLS device and the NIOSH 5040 quartz filter analysis from samples collected at both the manifold and the engine exhaust.
3. Although it was thought that a revised correction factor would be required for different engine types, this was not found to be the case based on the data produced from this study. Despite the fact that the sample size for some engine types was small, these engines exhibited a similar degree of variance in EC between the MAHA MPM-4M LLS device and the NIOSH 5040 quartz filter analysis to that of engine types with a larger sample size.
4. Based on the results of this research, the current correction factor used in LLS devices such as the MAHA MPM-4M requires updating from 0.46 to 0.65 when sampling from the exhaust and 0.67 when sampling from the manifold exhaust.
5. The ability to take samples directly from the manifold exhaust for EC analysis has advantages over taking samples from the vehicle exhaust. These include eliminating issues relating to water vapour in the sample, control over probe insertion and position and more realistic data in relation to engine emissions and condition prior to other devices that may be fitted to the engine.
6. There seems to be an unfounded perception within the coal mining industry that the accuracy of the LLS and other DPM devices that are currently is use is absolute. Given the equipment and testing variables that can occur during the routine EC and TPM engine testing, results will vary between operators. While an acceptable correlation between LLS devices and the NIOSH 5040 quartz filter analysis has been established during this study, the focus should remain with good engine maintenance and perhaps the adoption of EC value ranges as opposed to a specific concentration as an upper limit.
7. While a number of analysis outliers were evident from the results, the number was relatively small and did not impact on the overall findings.
8. The use of the ERP chamber vessel for engine manifold sampling and the Freudenberg sampling system for quartz filter sampling confirmed the observations by Dr Brian Davies in the 2013, Wollongong University, Coal Services Health and Safety Trust research as being suitable devices for this type of testing.

7 References

MDG 29 (2008), Guideline for the management of diesel engine pollutants in underground environments, NSW Department of Primary Industries, April 2008.

Coal Services Health and Safety Trust Research Project, NSW Department of Primary Industries, Mines Safety Technical Services: Methods for measuring diesel particulate matter from underground mining equipment, Report 04/0884, November 2004.

Dr Brian Davies, Coal Services Health and Safety Trust Research Project, University of Wollongong: Calibration of Portable Raw Exhaust Diesel Particulate Analysers, 2 August 2013

8 Acknowledgements

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Emission Reduction Products Engineering Pty Ltd (ERP) for the re-design and modification of their engine manifold sampling chamber vessel that was used for engine manifold sampling.