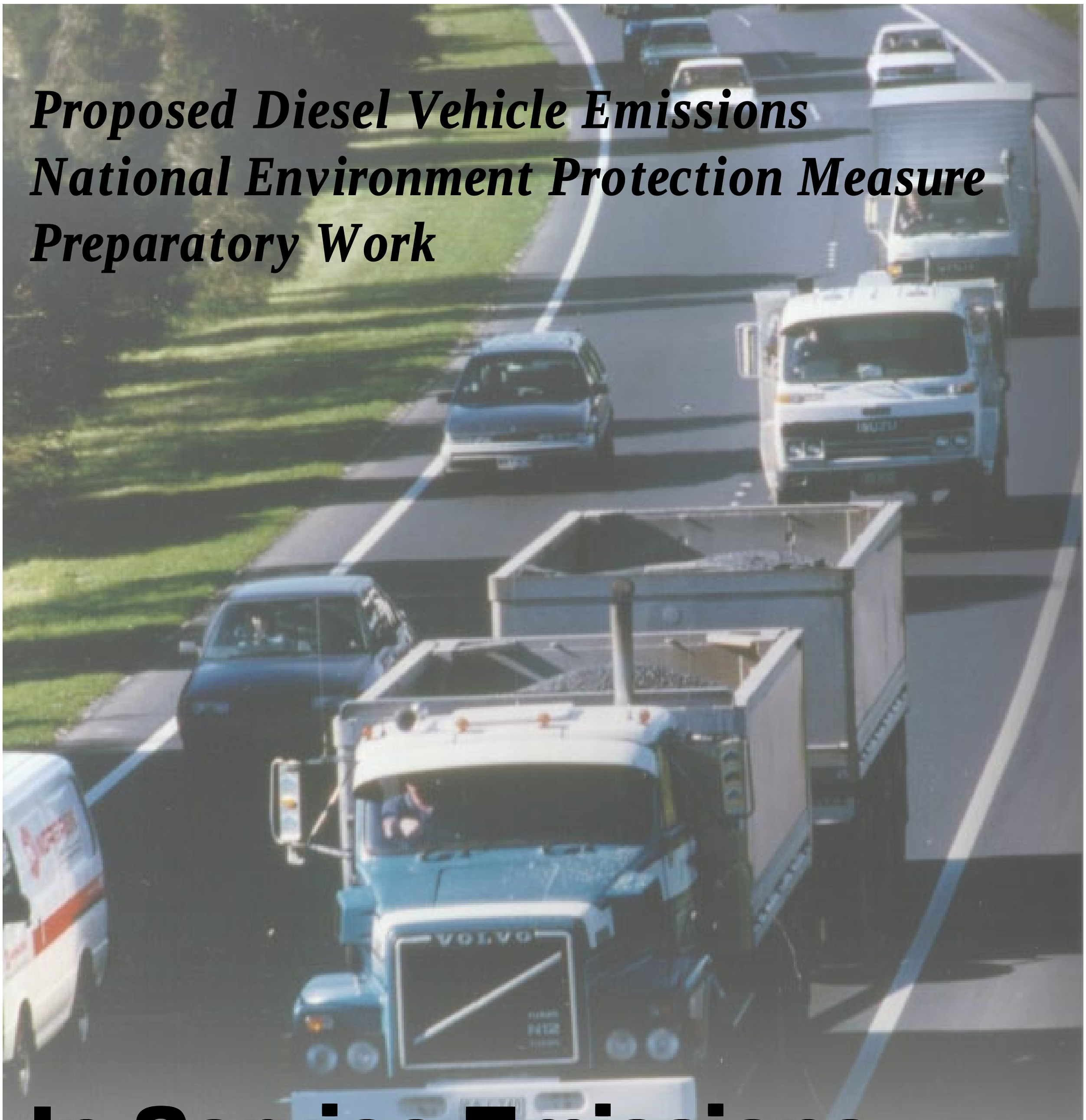

Proposed Diesel Vehicle Emissions
National Environment Protection Measure
Preparatory Work

In-Service Emissions Performance - Phase 2: Vehicle Testing

November 2000

NEPC
NATIONAL ENVIRONMENT PROTECTION COUNCIL

Prepared for the

National Environment Protection Council

by

PARSONS

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ISBN 0 642 323 348

NEPC
NATIONAL ENVIRONMENT PROTECTION COUNCIL

A suite of projects have been developed during the preparatory work for a proposed Diesel Emissions National Environment Protection Measure. These projects are:

The Australian Diesel Fleet Existing Vehicle Characteristics and the Modelling of Transport Demand, Vehicle Populations and Emissions

In-Service Emissions Performance - Phase 1: Urban Drive Cycle Development

In-Service Emissions Performance - Phase 2: Vehicle Testing

In-Service Certification Correlation Studies

A Review of Dynamometer Correlations, In-Service Emissions and Engine Deterioration

In-Service Emissions Testing – Pilot Study, Fault Identification and Effect of Maintenance

Major funding for these projects has been provided by Environment Australia. The other contributing agencies are the Department of Transport and Regional Services, NSW Roads Traffic Authority and the National Road Transport Commission.

Electronic copies of these documents are available from:

National Environment Protection Council Service Corporation
Level 5, 81 Flinders Street
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These documents are also available online: http://www.nepc.gov.au

ACKNOWLEDGMENTS

The authors would like to thank the people and organisations that assisted with the testing either on site or by providing necessary support or vehicles behind the scenes. The project in general was an enormous task to complete within 10 months and at times was arduous and demanding that relied on the dedication and professionalism of individuals to get the job done. It is a credit to our Project Team that we are able to present such an array of data.

This comprehensive data-set has been produced by a small, dedicated team of people supported by some very special people within the local transport industry. It has not been as a result of having a large workforce or extensive budget.

The efforts by all those involved in the many and varied tasks during the project cannot be fully conveyed in a few lines. However, we hope that in reading this report some insight into their commitment may be gained.

We appreciate the tremendous efforts made by all our team members; Dyno Dynamics, Auckland University and the Department of Mineral Resources. Special mention needs to be made of the contribution made by our principal team member CSIRO and all the staff at the Division of Energy and Technology.

We also make special acknowledgment of the support, contribution and advice provided by the Australian Trucking Association, the Bus and Coach Association and in particular their members who contributed in many ways, throughout the course of the project.

To all of you - Thanks!

Peter Anyon	Program Director
Stephen Brown	Project Manager
Darren Pattison	Operations Manager
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EXECUTIVE SUMMARY

PROJECT AIMS

This Project was undertaken to objectively evaluate and report on:

- Pollutant emission levels and trends from diesel vehicles in respect to their age, operating mass and kilometers travelled during their operational life, for a range of typical urban traffic conditions; and
- The feasibility and practicality of introducing a low-cost, short test suitable for use in a program to identify and rectify high-polluting, in-service diesel vehicles.

WHAT DOES THE PROJECT DELIVER?

This report provides a wealth of new and valuable information on the "real-world" emissions performance of diesel vehicles in Australia. The project has also validated some novel and very effective techniques for measuring emissions from diesel vehicles that are suitable for use in an in-service emissions reduction program.

In particular, the project delivers:

- simple test procedures that can reliably detect high-polluting in-service diesel vehicles for emissions of particulates, oxides of nitrogen and exhaust smoke opacity;
- validation of techniques for accurately, reliably and quickly measuring particulate emissions from diesel vehicles using rugged, low-cost equipment;
- comprehensive data on the emissions performance of in-use diesel vehicles in Australia, for all major pollutants, all vehicle age and size categories, operating in a range of "real-world" traffic situations. It will allow the development of updated diesel fleet emission factors for transport planning, airshed modelling and pollutant inventory purposes; and
- reliable data on actual greenhouse emission rates from the full spectrum of diesel fuelled road vehicles operating in Australia.

The main report, appendices and supporting CD-ROM provide comprehensive analysis and discussion of the project's testing and outcomes.

INTRODUCTION

This report summarises a comprehensive diesel emissions research and testing project conducted by Parsons Australia Pty Ltd under contract to the National Environment Protection Council Service Corporation, over the period August 1999 to May 2000.

The Project is one of a series being undertaken by several consultant organisations for the National Environment Protection Council (NEPC), in preparation for the development of a diesel vehicle National Environment Protection Measure (NEPM), which is planned to cover the design and implementation of emission control standards and strategies for in-service diesel vehicles.

Emissions from diesel vehicles

Diesel vehicles are a major source of air pollutants that have a direct impact on human health. The diesel emissions of primary concern are:

Fine Particulate Matter (PM) - Bronchial diseases and cancers are linked to the inhalation of toxic fine particulate matter from diesel engines.

Oxides of nitrogen (NOx) which react in the atmosphere with hydrocarbon (HC) compounds to form photochemical smog

Reactive Organic Compounds comprising mainly hydrocarbons that contribute to the formation of photochemical smog and organic aerosols (which add to atmospheric particle loading).

Sulphur compounds (originating as sulphur in diesel fuel), which add to atmospheric Sulphur Dioxide, and form sulphate aerosols in the atmosphere contributing to atmospheric particle loading.

Carbon Monoxide (CO) which adds directly to atmospheric CO pollution.

Air Toxics. Diesel exhaust contains a range of aromatic compounds (such as benzene, toluene, 1-3 butadiene, PAH), plus various aldehydes, alkanes, alkenes, and ketones. After considerable research into the consequential health risks, in 1999, the California Air Resources Board identified diesel exhaust as a Toxic Air Contaminant.

Carbon Dioxide (CO_2) and much smaller amounts of N_2O and Methane (CH_4), all of which contribute directly to total greenhouse gases.

Visible Smoke while not a direct health threat in itself, is visually offensive and contributes to urban soiling and loss of visual amenity. It is also the public's main perception of vehicle pollution

It is only in recent years that the serious nature of health threats posed by diesel emissions have started to be fully recognised, resulting in world-wide efforts to quickly find ways of reducing atmospheric concentrations of diesel pollutants, with a very strong emphasis on reducing emissions of fine particulate matter.

When dealing with issues involving motor vehicle pollution, measures are developed in conjunction with the Ministerial Council for Road Transport (MCRT) and the National Road Transport Commission (NRTC).

PROJECT SCOPE

The scope of this Project, as defined in the project brief, was to:

(a) **test a representative sample of diesel vehicles in use in urban Australia under the appropriate 'composite urban emission drive cycle' (CUEDC), established in Phase 1 by NSW EPA (report available from NEPC), and determine their emission performance.**
This will subsequently enable the development of emission factors that can be used for local air-shed inventory calculations in Australia, and will improve knowledge of the ambient air quality impacts of the diesel fleet.

(b) **evaluate and compare the suitability of five in-service emissions assessment procedures for the measurement of diesel vehicle emissions.**
These evaluations will assist authorities in developing and specifying programs to reduce emissions from in-service diesel vehicles. The number of procedures evaluated increased to seven during the course of the project, partly in response to the California Air Resources Board's decision to sponsor additional test evaluations in support of their own future diesel emissions reduction programs.

Test Procedures and Equipment

A key element of the project was to measure, under controlled and repeatable laboratory conditions, tailpipe emission levels from a representative sample of 80 vehicles "driven" on a chassis dynamometer over a pre-defined drive cycle designed to replicate "real-world" driving conditions.

This cycle, the "Composite Urban Emissions Drive Cycle" (CUEDC) comprises four segments, each of which represents driving in a different urban traffic condition (congested, minor roads, arterial roads and highway/freeway). CUEDCs were developed for six vehicle categories described in Table1 below. An example of a CUEDC drive cycle (in this case for light commercial vehicles) is shown below.

Table E1: CUEDC Vehicle Categories

ADR Category	Mass Category– tonnes (GVM or GCM)	Vehicle Description
MC		Passenger and off-road passenger ≤ 9 seats
NA	≤ 3.5	Light goods vehicle
NB	> 3.5 ≤ 12	Medium goods vehicle
ME	> 5	Heavy bus
NC	> 12 ≤ 25	Goods vehicle
NCH	> 25	Heavy goods vehicle

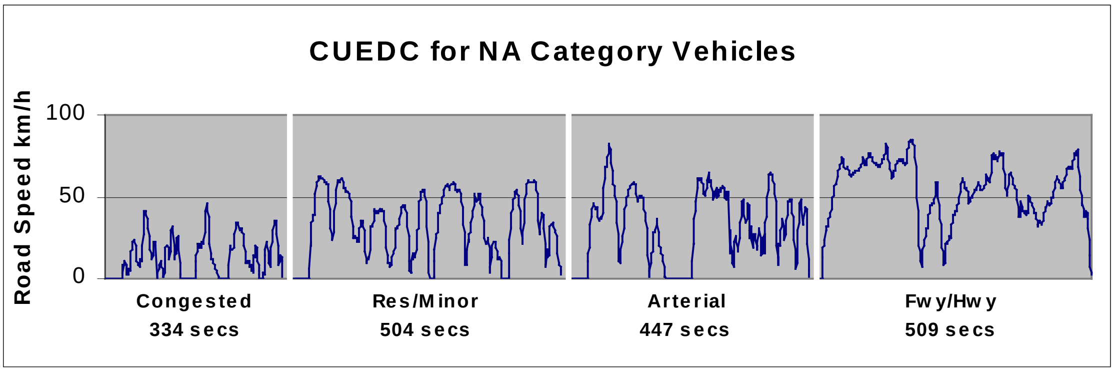


Figure E1: CUEDC Time/Speed Trace for NA Category Vehicles

The CUEDC speed/time traces were developed by instrumenting a number of vehicles during their normal operational driving and synthesising the data into the CUEDC drive cycles, of which there is one for each ADR vehicle category.

To ensure that the sample of vehicles tested in this project reflected the current fleet's overall composition, a closely defined matrix of vehicle age and mass categories was specified. Each age/mass category cell contained a fixed number of vehicles, proportional to that cell's overall representation in the total vehicle population.

How Emissions were Measured

To replicate real-world engine and transmission loads as closely as possible during laboratory testing, the project utilised a heavy-duty "rolling road" chassis dynamometer capable of accurately reproducing the continuously changing driving loads due to acceleration, rolling resistance and aerodynamic drag.

The emissions sampling and analysis system essentially, comprised of:

- full flow, two-stage exhaust dilution with primary and secondary exhaust dilution tunnels and flow controllers complying with US EPA specifications
- the gas analysis system, with laboratory-grade analysers for NOx, CO, CO_2, HC and O_2

- the particle analysis system, with a range of instrumentation to cover particulate sizes from around 0.004microns to over 10 microns.
- the data acquisition system, which collects ,integrates and stores over 40 channels of real-time data.
- dynamic measuring of particles with equipment using “Laser Light Scattering Photometry (LLSP)” principal to measure particles up to 10 microns (PM10) and a diesel TEOM instrument to measure all particles.

Overall Emission Trends

The emissions performance of Australia's vehicle population is of vital importance in setting transport, environmental and urban planning policies. Without detailed knowledge of how the various groups of vehicles perform in typical traffic flow situations, it would be very difficult to plan for population and traffic growth, without adversely impacting on the well being of the population.

While earlier studies have generated good data on the emissions performance of passenger cars and derivatives, until the completion of this project very little was known about the on-road performance of diesel vehicles - an important and increasing segment of the total vehicle population.

If advances in technology and more stringent emission standards are having the desired effect, newer vehicles should exhibit significantly lower emission rates. Also, given that regulated emission levels are linked to engine power, which in turn is a function of vehicle mass, there should also be a trend towards higher emissions from heavier vehicles.

The following chart illustrates the presence of these relationships for emissions of Oxides of Nitrogen (NOx).

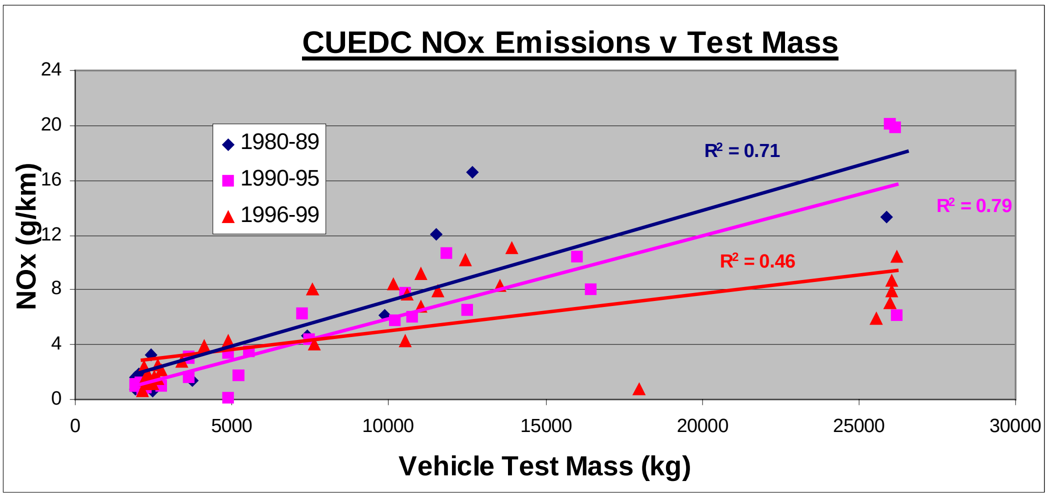


Figure E2 - NOx Emissions vs Vehicle Mass

Although there is considerable scatter in the data, due to variability in emission levels from individual vehicles, overall trends follow the theoretical directions outlined above, ie emissions increase with vehicle mass, and older vehicles tend to be higher emitters than newer age groups, for a given vehicle mass.

The convergence of the trend lines at lower mass limits indicates that NOx emissions for some light vehicle categories have increased in recent years. The greatest reductions in NOx emissions have occurred in larger vehicles that are often built to more stringent emission standards of the countries where they are manufactured.

For particulate matter (PM) Figure E3 illustrates a different story. Although the three trend lines for each age group indicate lower average emissions of PM from newer vehicles, there is great variability in particulate emission levels between individual vehicles.

Some lighter vehicles produce inordinately high levels of particulate matter. For instance, by repairing the worst 20% of the 1990-95 age group light duty vehicles to bring their particulate emissions in line with the average of the remaining vehicles, a 40% reduction in particulate emissions could be achieved in that age group as a whole.

As a result, the overall trend lines for particulate emissions versus vehicle mass actually are either flat or show a downward trend with increasing mass, contrary to what might be expected but highlighting the extremely high emission levels from the lighter vehicles

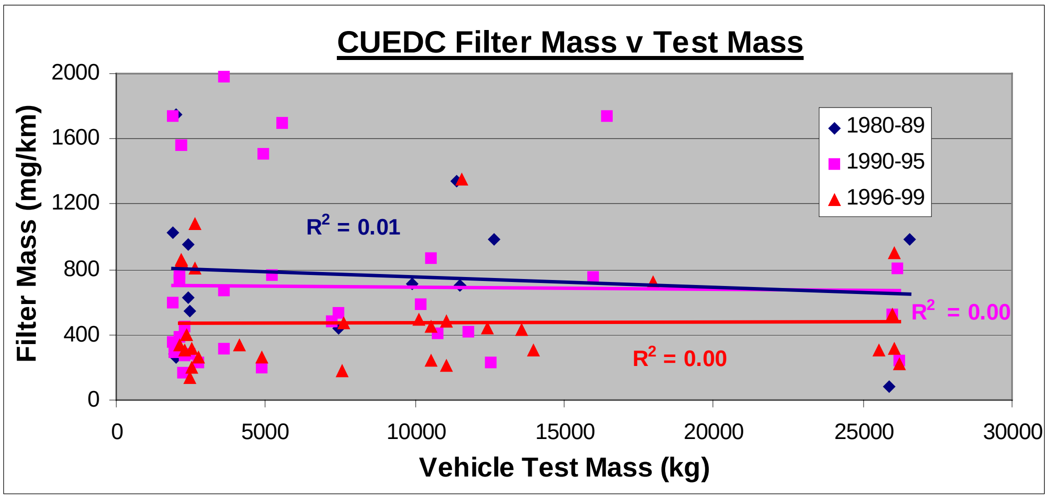


Figure E3 Particulate emissions vs vehicle test mass

This situation is repeated with exhaust opacity (Figure E4) where extremely smoky light duty vehicles dominate the picture.

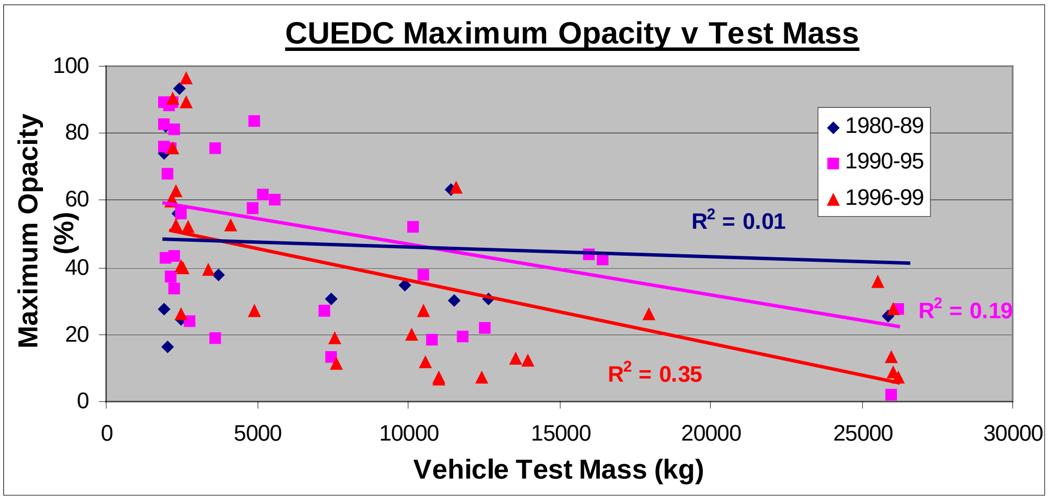


Figure E4 Smoke opacity vs vehicle test mass

A summary of the data collected for each pollutant, vehicle category and age group, is contained in the following table. In this table, the results presented are the average emissions per kilometer travelled over the complete CUEDC cycle.

The table encapsulates the key data describing on-road emission levels from Australia's diesel vehicle population.

(To assist in interpreting the table, Filter, TEOM and LLSP are different methods of measuring particulates. PM10, PM2.5 and PM1 refer to particulates less than 10, 2.5 an 1,0 microns in diameter, respectively)

ADR Category	Age Group	No of Tests	O_2 (g/km)	CO_2 (g/km)	CO (g/km)	NOx (g/km)	HC (g/km)	LLSP (mg/km)	TEOM (mg/km)	Filter (mg/km)	Opacity Ave (%)	Opacity Max (%)	PM1 (mg/km)	PM2.5 (mg/km)	PM10 (mg/km)	Fuel (l/100km)
MC	80 - '89	3	494.36	454.10	3.25	1.72	0.46	360.93	543.52	708.87	11.26	58.15	742.54	745.61	777.31	19.47
	90 - '95	5	475.01	436.88	2.84	1.09	0.11	393.59	606.17	660.28	10.63	60.19	405.48	409.33	424.43	17.89
	96 - '99	5	504.46	464.77	1.18	1.27	0.19	148.10	220.25	266.29	5.76	49.61	255.94	256.66	273.31	20.47
NA	80 - '89	4	481.38	442.48	3.23	1.26	0.08	457.67	459.93	829.87	17.03	50.01	623.07	626.19	637.18	17.14
	90 - '95	9	446.42	410.17	3.28	1.04	0.11	441.72	495.88	538.39	12.53	65.12	354.13	356.93	373.92	16.28
	96 - '99	6	470.64	438.49	3.41	1.84	0.11	362.44	605.93	702.87	14.79	74.12	311.98	313.17	318.74	17.57
NB	80 - '89	2	570.82	523.84	3.47	3.07	1.11	161.60	308.35	440.22	6.91	34.20	682.17	687.72	709.35	22.60
	90 - '95	9	535.32	490.55	3.92	3.02	0.56	425.05	636.67	905.60	12.69	49.74	933.41	939.88	967.43	20.84
	96 - '99	6	541.08	496.30	1.75	4.18	0.47	139.80	243.68	302.05	5.16	33.52	232.26	234.07	244.59	21.28
ME	80 - '89	2	1134.52	1038.59	5.38	16.59	0.93	679.34	910.93	1161.55	8.30	46.92	1065.72	1067.92	1100.78	41.88
	90 - '95	0														
	96 - '99	5	1182.72	1085.26	2.32	9.20	0.47	376.61	494.14	602.33	4.31	23.17	694.01	694.72	698.16	44.11
NC	80 - '89	2	838.02	766.65	2.26	9.10	0.92	311.96	548.91	703.66	4.74	32.59	655.26	672.81	726.17	32.25
	90 - '95	7	871.63	798.40	3.56	7.90	1.01	436.74	557.69	715.85	5.61	33.65	654.07	671.21	719.63	32.93
	96 - '99	5	885.70	813.73	1.72	5.75	0.66	163.10	285.73	422.01	2.15	15.73	396.16	396.62	402.26	33.97
NCH	80 - '89	2	1294.64	1187.28	7.60	13.29	0.85	261.61	513.18	531.81	7.46	47.94				51.07
	90 - '95	3	1286.67	1176.47	5.23	15.36	0.48	209.87	457.32	524.97	3.11	33.81	350.02	355.02	381.71	48.29
	96 - '99	5	1204.36	1107.18	2.03	8.01	0.64	201.65	369.72	453.30	2.38	18.44	662.97	663.99	687.20	45.44

MC	Passenger and off-road passenger ≤ 9 seats
NA	Light goods vehicle
NB	Medium goods vehicle
ME	Heavy bus
NC	Goods vehicle
NCH	Heavy goods vehicle

Table E2: Drive cycle emissions results summary - All Vehicles

While the above table represents a highly summarised snapshot of the data recorded in this project, a large database, only available on CD-ROM because of its size, plus the charts and tables appended to this report, provide several levels of detail in presentation and analysis. Some are briefly discussed below.

Influence of Traffic Flow Conditions

The CUEDC drive cycle comprises four segments, each reflecting a different set of driving conditions for each of six vehicle mass categories, ie:

- Congested
- Minor roads
- Arterial roads
- Highway / Freeway

The speed profile of each of these segments is quite different. They range from frequent stops and starts, with extended idle periods for the congested flow, through to highway / freeway driving with sustained periods of cruise at speeds of up to 80~90 km/h, and only infrequent major changes in speed or periods at rest.

Individual CUEDC segment results reveal some trends worthy of note. Congested driving, because of its highly inefficient stop-go nature, with many idle periods followed by accelerations and decelerations, results in high emission rates for all gaseous pollutants and fuel consumption.

Emissions of NOx, which are linked to combustion temperatures, do not reduce by a significant amount in the more free-flowing segments, reflecting their higher engine loads.

On the other hand emissions of total hydrocarbons (THC), which are very sensitive to transient engine loading, fall sharply in the smooth freeway cycle, despite much higher engine power in this segment.

The variation in particulate emission levels across segments is also of interest. In the heaviest group of vehicles (NC and NCH), particulate emissions are considerably higher in the congested flow than in other modes, while for some of the lightest vehicles, the trend is actually reversed, with the lowest particulate emissions in the congested segment.

Fuel consumption, and hence greenhouse gas emissions of CO_2, is consistently higher in congested flow than for the other three modes.

The data indicates that very significant reductions can be achieved in both pollutant and greenhouse gas emissions from measures to improve and smooth traffic flows in urban areas.

For instance, operating a vehicle in relatively free-flowing instead of congested traffic will deliver a reduction in CO_2 emissions of between 20 and 30 per cent.

Influence of Accumulated Distance Travelled

Conventional wisdom dictates that vehicles deteriorate with age, ie kilometers travelled. While this may be true in an overarching sense, the effects of maintenance play a very significant role in determining emissions from individual vehicles.

Well-maintained vehicles, regardless of kilometers travelled, can perform very well. Conversely, low-kilometer vehicles that have had either poor maintenance, or have been subjected to tampering, can have very high emissions.

The results of this study indicate there is no statistically meaningful linkage between vehicle kilometers travelled and emission levels. In the 80 vehicle sample for this project, there was an almost random distribution of emission levels when plotted against kilometers travelled.

Is Exhaust Smoke a Reliable Surrogate for Particulate Emissions?

Smoke opacity measured under a controlled load on a dynamometer has a poor correlation with particulate emissions. Smoke measured in an unloaded test (such as the snap idle or SAE J1667 free acceleration tests), has essentially no correlation with particulate emissions. The following charts (overleaf) illustrate this.

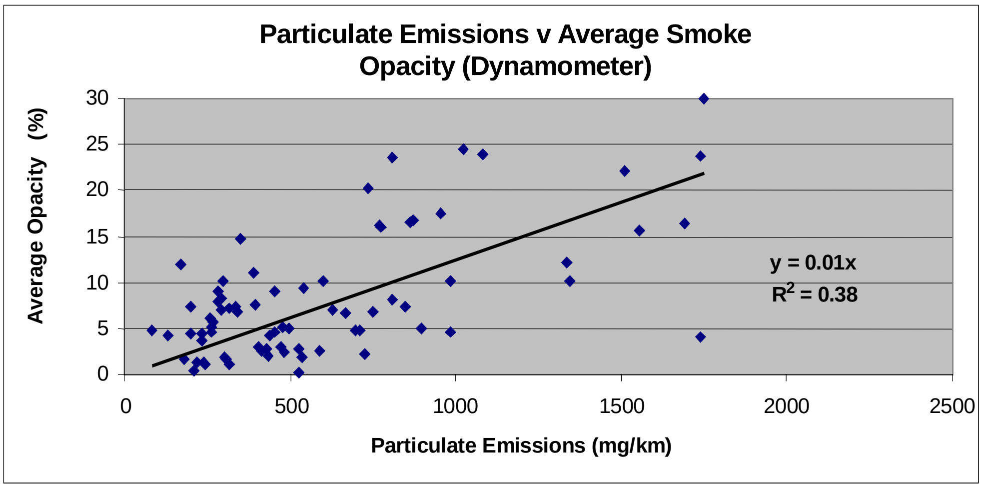


Figure E8: CUEDC Particulates vs CUEDC average opacity

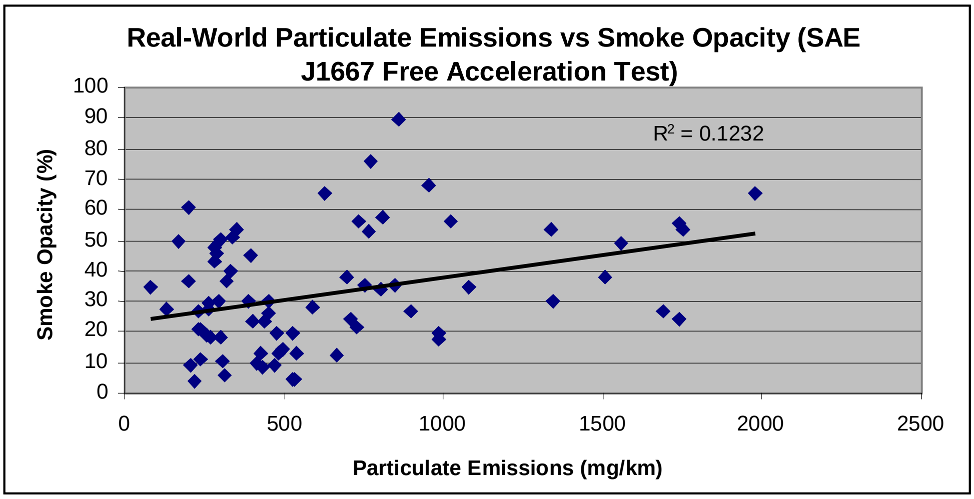


Figure E9: Correlation Particulates vs Average Opacity (Using Dyno Test for Particulates and SAE J1667 Free Acceleration Test for Smoke Opacity)

The conclusion is therefore that smoke opacity is, at best, a very poor surrogate for emissions of fine particulate matter.

MEASURING PARTICULATES: A LOW-COST ALTERNATIVE

The traditional method of measuring particulates has been to divert a known fraction of the total exhaust stream through a very fine, inert filter. By weighing the filter prior to and after this procedure, the mass of particulate matter deposited on the filter can be determined. Since the fraction of total exhaust flow diverted through the filter is known, then the total mass of particulate matter generated in the test can be calculated.

As can be readily appreciated, this is a slow, cumbersome process involving extremely sensitive laboratory scales, very skilled operators and a highly protected environment. All these are exactly the opposite of what is required in a high-volume vehicle test lane.

To make a short, low cost test for particulate emissions a practical reality, a rugged, reliable, real-time device is needed, capable of being operated easily by a semi-skilled person.

Building on earlier Australian work, Parsons investigated the use of laser light scattering photometry (LLSP) as a tool for real-time measurements of particulate matter.

After a great deal of development work on sample handling and preconditioning techniques, this research has been highly successful. The instrument demonstrates accuracy and repeatability close to the best laboratory equipment, but with rugged, simple operation and a price many times lower. The excellent correlation between the LLSP technique and the traditional filter method is shown in the chart below.

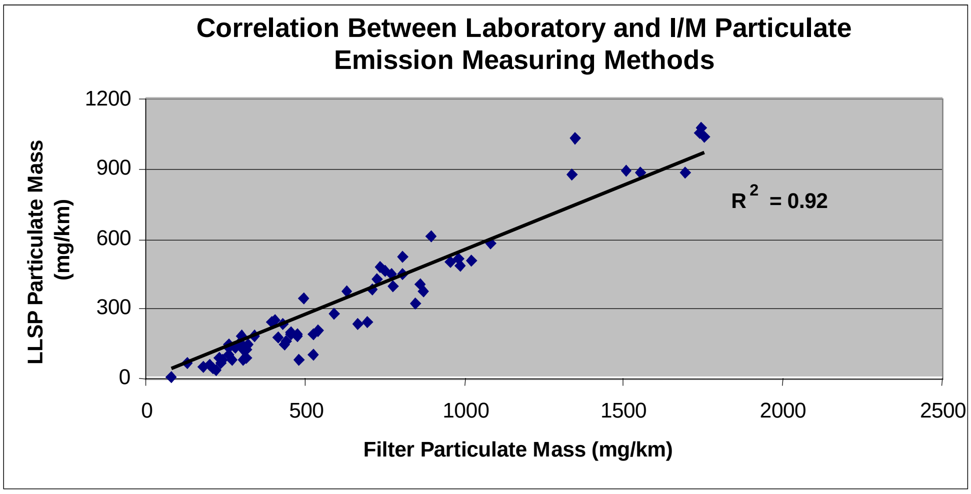


Figure E12: Comparison of Filter Mass vs LLSP Emission Rate

Above all else, the work done to prove the effectiveness and reliability of the LLSP technology has opened the door to low-cost, reliable and fast measurements of particulate emissions from diesel vehicles.

SHORT TEST EVALUATION

The second element of this project was to evaluate a number of short tests for their potential to identify high-polluting vehicles in a program to reduce emissions from in-service vehicles - commonly referred to as an Inspection & Maintenance (I/M) program. Comparison to CUEDC Full details of these tests are provided in Section 3.6.4 of the report.

How Would a Short Test be Used?

The most common approach is to test vehicles periodically, either at a licensed repair establishment or at a dedicated (centralised) test-only facility unecumbered by potential conflicts of interest. Although well established for light-duty petrol vehicles, this approach to testing diesel vehicles is still evolving.

Short Tests Evaluated

Six short tests, plus an on-road visible smoke observation, were included in the tests.

(a) The **D550** is a steady-state test using a constant dynamometer load equivalent to a fully laden vehicle driving up a 5% gradient at 50 km/h.

(b) The **Two-Speed** Test is a steady-state test that measures emissions under full-throttle conditions at two calculated speeds.

(c) The **Lug Down** test is performed at full throttle, with the dynamometer load gradually increased to pull back engine speed so that the engine is labouring, or "lugging".

(d) The **DT80** Test is an aggressive mixed-mode test, with three full-load accelerations to 80km/h, followed by a steady-state 80 km/h cruise. The test requires the use of a dynamometer with inertia simulation.

(e) The **AC50/80** is a new test, developed in Australia for the California Air Resources Board. It is a mixed-mode test having two full-load accelerations and two steady-state cruises. It also requires the use of an inertia-simulating dynamometer.

(f) The **Snap-Idle** (or 'Free Acceleration' SAE J1667) test simply involves fully depressing the accelerator pedal while the transmission is in neutral, and measuring the maximum smoke opacity. The test was developed in the USA as a quick test to evaluate smoke opacity without the need for a dynamometer.

In Australia, the traditional method of assessing whether a diesel vehicle is a "high polluter" has been to observe the intensity and duration of smoke emitted from its exhaust whilst being driven under load on the road. This procedure is both subjective and tedious to carry out and the result achieved is variable depending on the driving method used. Consistent repeatable results are hard to obtain and disagreement between vehicle operators and testing officers often occur because of variations in test conditions

While visible exhaust emissions can be tested using this procedure it is not possible to determine emissions of fine particulates or the gaseous emissions by this method.

On-road testing for visible emissions has its place in the scheme of things, however the knowledge we now have of diesel pollution indicates that more sophisticated methods are needed to identify those vehicles with excessive emissions of particulate matter (PM) and oxides of nitrogen (NOx), as well as smoke opacity.

Correlation with "Real-World" Emissions

Correlations between the "real-world" CUEDC drive cycle and the various short tests ranged from excellent to very poor.

Evaluation of short test correlations can be conveniently split into three groups:

- Non-loaded (Snap Idle)
- Steady state (D550, Lug Down, 2-Speed); and
- Transient loaded (DT80, AC5080)

Snap Idle, the only non-dynamometer test, proved to be an extremely poor indicator of particulate levels, even though it provided a reasonable correlation with maximum CUEDC opacity levels. It's HC and NOx results recorded the lowest correlation with the CUEDC of all the tests evaluated. In addition, this test is unlikely to be an accurate predictor of the emission performance of modern vehicles with computer-controlled engines. Such vehicles perform quite differently when stationary then when moving under load.

The second group **(D550, Lug Down, 2-Speed)** tests did not prove to be good surrogates for the CUEDC. They were generally poor indicators of particulate emissions, although their NOx and HC results provided a fair correlation with the CUEDC.

Only the two transient dynamometer based tests **(DT80 and AC5080)** delivered good correlations on all pollutants studied. The following tables summarise the correlation of each short test with the CUEDC test cycle. The second chart is normalised for mass by dividing the emissions test result (in g/km) by the vehicle test mass (tonnes) so that emission levels are closely linked to the useful payload and power output of the vehicles tested.

TableE3 – Correlation Coefficients of CUEDC emissions vs Short Test emissions

Short Tests	Correlation Coefficient (R^2) for all test results Average NOx (g/s)	Average HC (g/s)	Average LLSP (mg/s)	Filter mass (mg)	Average Opacity (%)	Maximum Opacity (%)	Rating 1 - best 8 - worst
AC5080	0.95	0.92	0.70	0.71	0.87	0.80	**1**
DT80	0.90	0.85	0.63	0.58	0.68	0.81	**2**
2 speed torque	0.62	0.72	0.30	-	0.40	0.68	3
DT80 last 10s	0.80	0.74	-0.35	-	0.15	-0.21	4
Lug Down	0.60	0.68	0.22	-	0.26	0.68	5
2 speed power	0.55	0.36	0.12	-	0.15	0.17	6
D550	0.64	0.53	-0.18	-0.23	0.03	-0.23	7
Snap idle	0.47	0.23	-0.02	-	0.29	0.59	8

Table E4 – Correlation Coefficients of Short Test Emissions vs CUEDC - (Mass Normalised)

Short Tests	***Correlation Coefficient (R^2) – Mass Normalised*** *Average NOx (g/s)*	*Average HC (g/s)*	*Average LLSP (mg/s)*	*Pm by Filter (mg)*	*Pm (LLSP vs Filter) *****	*Rating 1-best 2-worst*
DT80	*0.84*	*0.76*	*0.84*	*0.86*	*0.85*	*1*
AC5080	*0.68*	*0.68*	*0.88*	*0.84*	*0.84*	*2*
Lug Down	*0.33*	*0.54*	*0.61*	*-*	*0.70*	*3*
2 speed	*0.27*	*0.21*	*0.63*	*-*	*0.59*	*4*
Snap Idle	*0.23*	*0.46*	*0.39*	*-*	*0.36*	*5*
D550	*0.24*	*0.26*	*0.23*	*0.49*	*0.34*	*6*

**LLSP for short tests and Filter for CUEDC tests

After normalising for vehicle mass (refer Table E4 above), the DT80 performed better than the AC5080, with correlations (R^2) 0.84 for NOx and 0.86 for particulates (filter mass).

From a statistical correlations standpoint, the DT80 appears to be marginally better than the AC5080 test procedure.
Two example charts (E13 and E14), showing the correlation between the DT80 test and the CUEDC, for emissions of Particulates and NOx follow (charts are normalised for mass).

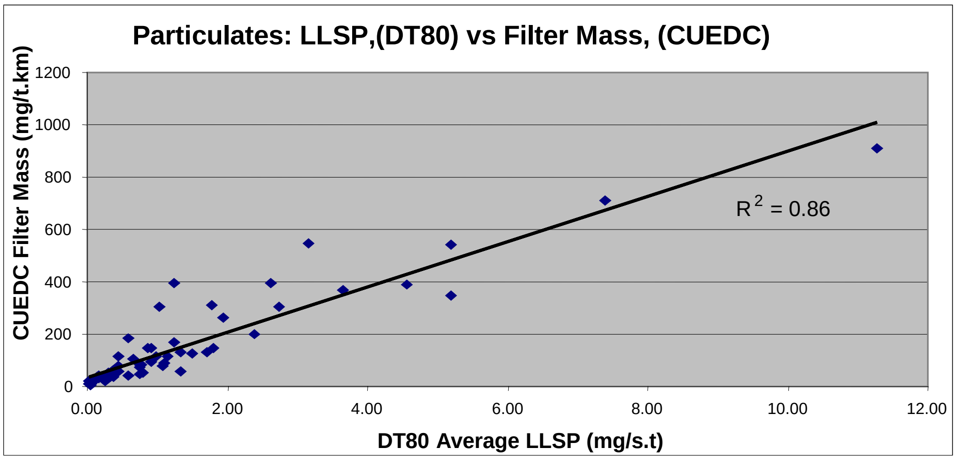


Figure E13: Mass-Normalised Particulate Correlation, DT80 vs CUEDC

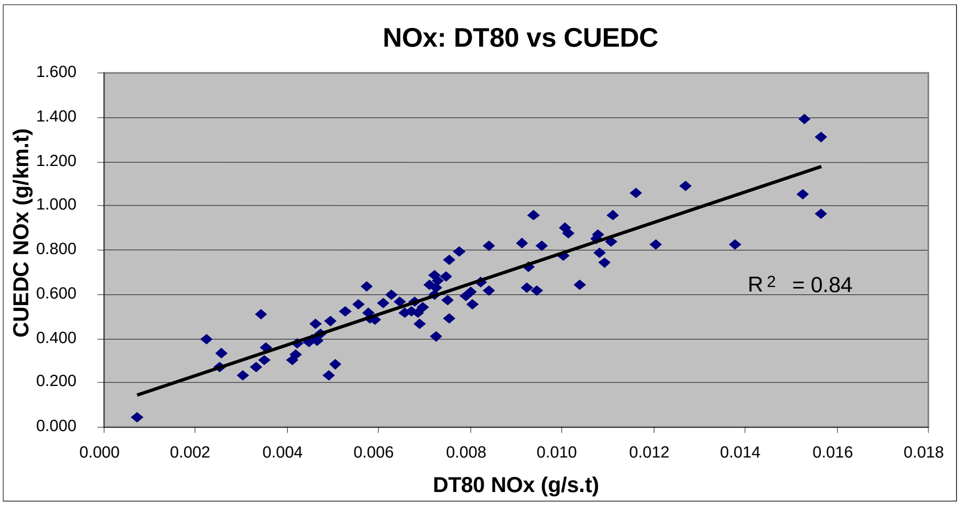


Figure E14: Mass-Normalised NOx Correlation, DT80 vs CUEDC

Can a Short Test Reliably Pick the High Polluters?

As noted above, only two short tests (the DT80 and the AC5080) appear to have sufficient statistical correlation with the CUEDC results to warrant serious consideration for use in an I/M program.

To test their practical effectiveness, a very basic but nevertheless extremely important measure of the potential value of a short test is to determine whether it identifies the same high-polluting vehicles as the CUEDC.

If we arbitrarily assume that 20% of the diesel population may be classed as "high emitters", a perfect short test would select the same 16 vehicles (from the project's sample of 80) that are selected by the CUEDC. To pick up any "near misses", a second category can be included that contains those vehicles classified by the CUEDC as lying between the highest 20% and the highest 30% emitters.

The outcomes of this empirical analysis, based on mass normalised emission results, are as follows:

Table E5: Table of ability of DT80 test to pick highest CUEDC Emitters

Pollutant	No of highest 20% CUEDC emitters (16) selected in top 20% (16) DT80 emitters		No of highest 30% CUEDC emitters (25) selected in top 20% (16) DT80 emitters	
	Selected by DT80	Not selected	Selected by DT80	Not selected
PM	11	5	14	2
NOx	13	3	15	1
Smoke	11	5	14	2

Table E6: Table of ability of AC5080 test to select highest CUEDC Emitters

Pollutant	No of highest 20% CUEDC emitters (16) selected in top 20% (16) AC5080 emitters		No of highest 30% CUEDC emitters (25) selected in top 20% (16) AC5080 emitters	
	Selected by AC5080	Not selected	Selected by AC5080	Not selected
PM	11	5	14	2
NOx	9	7	12	4
Smoke	13	3	15	1

As can be seen in the tables, both tests performed extremely well, except for the AC5080 in respect of NOx emissions.

Is a Low-Cost Diesel Test a Practical Reality?

From the results of this project, loaded transient tests demonstrate a very strong potential and warrant further evaluation. The data presented in this report clearly indicates that a low-cost, reliable test to identify high-polluting diesel vehicles is a practical reality.

At least two candidate tests have proved to have correlations with real-world emissions at least as good as the best of the widely used tests for petrol-fuelled vehicles.

The project has also shown that a low-cost, reliable and simple technique exists for measuring diesel exhaust particulate matter that can be readily applied to a high-volume emission testing program.

The remainder of the equipment required (dynamometer, gas analysers and data acquisition hardware) are already commercially available as commodity items. For light-duty diesel emissions testing where there is already an IM240 (or equivalent) gasoline vehicle testing program in operation, the same dynamometer equipment can be used for both diesel and gasoline vehicles.

CONCLUSIONS

As mentioned earlier readers should note that, from this sample size (80 vehicles), relationships that are based on data from all the vehicles tested, should be fairly robust. On the other hand, some of the age/category groups contain only a very small number of vehicles and so it may not be appropriate do draw any firm inferences, at this stage.

Based on the results obtained the following conclusions are made under the two main headings: ***Inventory*** and ***Inspection & Maintenance:***

Inventory

The diesel vehicle fleet displays a highly variable emission profile, unlike the petrol fleet where a more consistent profile is evident.

In the main areas of concern (NOx and Particulates), new engine technologies are delivering lower Particulate emissions. However, there has been little overall reduction in average NOx emissions over the last two decades.

No single road flow condition of the 6 CUEDC's is dominant in terms of grams emitted per kilometer traveled. The proportion of emissions generated in each road flow category can vary, depending on the mass of the vehicle tested.

Approximately 90% (by mass) of all diesel Particulate emissions have a size of less than 1 micron.

Smoke opacity is not a surrogate for particulate emission levels. It should only be referred as a measure of visual amenity. As such, smoke density cannot be used in isolation to determine the emission performance of a vehicle. Particulate emission levels can only be reliably determined by directly measuring the particles

Vehicle age and distance traveled are not reliable predictors of the emission performance of diesel vehicles. Vehicle emissions can vary according to condition of the engine and its state of tune.

Inspection & Maintenance

The short test evaluation has shown that:

- Dynamometer-based short tests with transient acceleration segments perform much better than unloaded or steady state tests in estimating "real world" emissions of all regulated pollutants.
- There is a very poor correlation between smoke opacity and particulate emissions. Smoke opacity is a measure of visual amenity only.
- Of all the short tests evaluated in this project, the DT80 and AC5080 are by far the most suitable tests for determining if a vehicle is a high emitter. These tests have excellent correlation with CUEDC emission levels, for all pollutants and have significant potential for use in IM program applications.
- The 6-point inspection did not provide a clear indication of a vehicle's state of tune or its emissions performance.
- The On-Road smoke test also did not correlate well with the CUEDC and was onerous and impractical as an IM test. On-road smoke observations may, nevertheless, have some use as a supplementary tool to support a loaded test IM program.
- Light-scattering photometry, in conjunction with effective sample pre-conditioning techniques, can be an accurate, robust and reliable method of measuring particulate mass and has strong potential as an effective, low cost IM tool.

1. BACKGROUND

1.1 PROJECT CONTEXT

This project is one of a series of projects encompassing the preparatory work to be carried out prior to developing a Diesel Emissions National Environment Protection Measure (NEPM) for consideration by the National Environment Protection Council (NEPC).

Agencies charged with managing air quality within urban air-sheds are considering an array of strategies for managing emissions from diesel vehicles. A series of diesel emission studies has been developed to improve the understanding of the extent and dynamics of emissions by diesel vehicles and to assist in the assessment of emission management options.

This Project builds on the work carried out previously in Project 2, Phase 1. That work established Composite Urban Emission Drive Cycles (CUEDCs), that replicate on road driving patterns of diesel vehicles under each of the four typical road flow conditions, 'highway / freeway', 'arterial', 'residential / minor' and 'congested'. Also, that work identified five 'short tests' for further assessment as potential in-service 'inspection / maintenance ' (I / M) procedures.

This Final Report completes work on *Project 2 - Phase 2: Vehicle Testing,* undertaken by Parsons Australia Pty Ltd in association with others, under contract to the National Environment Protection Council (NEPC).

This Report outlines the facilities, equipment, vehicles and test procedures used in carrying out the project, and summarises the results achieved. The results are analysed and discussed in the context of the Project Objectives and the various issues raised in the Project Specification.

The data will subsequently enable the development of emission factors that can be used for local air-shed inventory calculations in Australia, and will improve knowledge of the ambient air quality impacts of the diesel fleet.

The information obtained will assist NEPC in developing a sound technical basis for the NEPM and provide a sound basis for an IM guideline.

1.2 EMISSIONS FROM DIESEL ROAD VEHICLES

Diesel vehicles are a major source of air pollutants that are widely acknowledged to have a direct impact on human health. Diesel vehicles also emit a significant and growing proportion of Australia's total greenhouse gases. Diesel road transport contributes 4% of the total emissions of greenhouse gases.

In Australia, diesel vehicles are an increasingly significant source of criteria air pollutants (i.e. those included in the National Environment Protection Measure (NEPM) on Ambient Air Quality, issued by the National Environment Protection Council (NEPC) in 1997. These include:

- ozone (O3), nitrogen dioxide (NO2), and suspended particulate matter (PM10), and
- to a lesser extent, carbon monoxide (CO) and sulphur dioxide (SO2).

Diesel vehicles are also of increasing concern as a source of non-criteria air pollutants (those not included in the NEPM) –

- fine, and ultra-fine particulate matter (PM2.5 and PM1).
- reactive organic compounds (ROCs), and
- a range of toxic compounds.

Diesel vehicles also emit a significant and growing proportion of Australia's total greenhouse gases (mainly carbon dioxide (CO_2)). These emissions would be subject to control worldwide through the Kyoto Protocol to the UN Framework Convention on Climate Change, signed by Australia in 1998 (Commonwealth of Australia 1998). When ratified, the Protocol would impose legally binding limits for greenhouse gases on a nation by nation basis.

The absolute contribution of diesel vehicles to total pollutant and greenhouse emissions has been growing due to their increasing numbers in the fleet and distances traveled. Their relative emission contribution to pollutant emissions has also been growing because (until quite recently) diesel emissions have been largely unregulated, unlike pollutant emissions from petrol vehicles and industrial sources, where control programs have led to progressive reductions.

The diesel emissions of concern are –

- **Particulate matter** which adds directly to atmospheric fine particle loading (PM_{10}). According to the California Air Resources Board (CARB 1998) 98% of diesel particles are less than 10 um diameter, 94% less than 2.5 um diameter, and 92% less than 1 um diameter. The large fractions of diesel particulate in the fine and ultra-fine ranges are of particular (and growing) concern to health professionals. Particulate matter generally in the range of ½ to 2 μm, causes the light absorption and scattering associated with visible smoke and atmospheric haze.
- **Oxides of nitrogen (NOx)** which react in the atmosphere with ROCs to form a number of secondary air pollutants. These include Ozone (O_3 - a principle constituent of photochemical air pollution, or smog), NO_2, and nitrate aerosols (which add to atmospheric particle loading).
- **ROCs** comprising mainly hydrocarbons (HC) but including many other reactive species contributing to formation of photochemical air pollutants (including O_3) and organic aerosols (which add to atmospheric particle loading).
- **Sulphur compounds** (originating as sulphur in diesel fuel), which add to atmospheric SO_2, and form sulphate aerosols in the atmosphere contributing to atmospheric particle loading.
- **CO** which adds directly to atmospheric CO pollution.
- **Air toxics**. These include aromatic compounds (such as benzene, toluene, 1-3 butadiene, PAH), various aldehydes, alkanes, alkenes, and ketones. They also include a number of metals and their inorganic and/or organic compounds. These and other contaminants are listed as *Hazardous Air Pollutants* by the US EPA, and as *Toxic Air Contaminants* by the State of California. Some of these contaminants are emitted as gas or as particles. Others are emitted as liquids, which may be adsorbed by particulate matter. Mostly, these air toxics are emitted in very low concentrations, but contribute significantly to the toxicity of ambient air. In 1999, the California Air Resources Board identified diesel exhaust as a Toxic Air Contaminant.
- **CO_2**, and much smaller amounts of **N_2O** and **Methane** (CH_4), which contribute directly to total greenhouse gases.

Particle Size

Emissions of particulate material from industrial sources have received considerable attention for many years. In the past, the interest was related to a number of effects, including visibility reduction. In recent years this interest has increased as a consequence of concerns about the health impacts of fine particles. As a result, the issue of fine particulate material is of great current research and community interest, and the sources, formation, and transformations of fine particles in the atmosphere are likely to be the most important issues in air pollutant research in the next 10 years.

Studies of urban air pollution in the United States, Europe and Australia have revealed a strong correlation between fine particle concentrations and mortality (Schwartz *et al*, 1996). While it is possible to question whether this correlation is a result of a causal effect, there is a need to deal with the immediate response to these findings. The USEPA, for example, has recently drafted a major downward revision of the Air Quality Standard for $PM_{2.5}$ (to 15 $\mu g/m^3$, annual mean, and 50 $\mu g/m^3$, 24-hour average). Hence, emissions of fine particles will come under increasing scrutiny.

Diesel vehicles are a major source of fine particle emissions in urban locations, and an accurate characterisation of the particle size distribution of particulate emissions from diesel vehicles is a high priority. Diesel emission control strategies, both engine design and after-treatment related, are being examined and re-evaluated for their effectiveness in the control of the finest particulate. However, a fair assessment of the fine particulate performance of various technologies can be possible only if the research community reaches a consensus on the definition of the fine particles and their measurement techniques. In particular, sampling methods, particularly dilution rates, are key variables that must be taken into consideration to ensure accurate and repeatable results.

Ambient particulate matter can be divided into the following categories:

- PM_{10} - particulates of an aerodynamic diameter of less than 10 µm
- Fine particles, $PM_{2.5}$ of diameters below 2.5 µm
- Ultrafine particles of diameters below 0.1µm or 100 nm
- Nanoparticles, characterized by diameters of less than 50 nm.

A typical size distribution of diesel exhaust particulates is shown in Figure 1-1 (from www.dieselnet.com) in terms of number and mass distribution. Clearly, the number distribution is dominated by very fine particles, mostly less than about 50 nm in size, while most of the particulate mass falls in the 0.1-1 µm size range. The coarse mode diesel particles with aerodynamic diameters above 1µm constitute only a small fraction of the total PM emissions, consistent with what was found elsewhere in this project using the APS instrument to partition diesel particulate mass. The coarse particles are unlikely to be generated in the diesel combustion process. Rather, they are formed through deposition of large particles and subsequent re-entrainment of particulate material from walls of the exhaust system or the particulate sampling system.

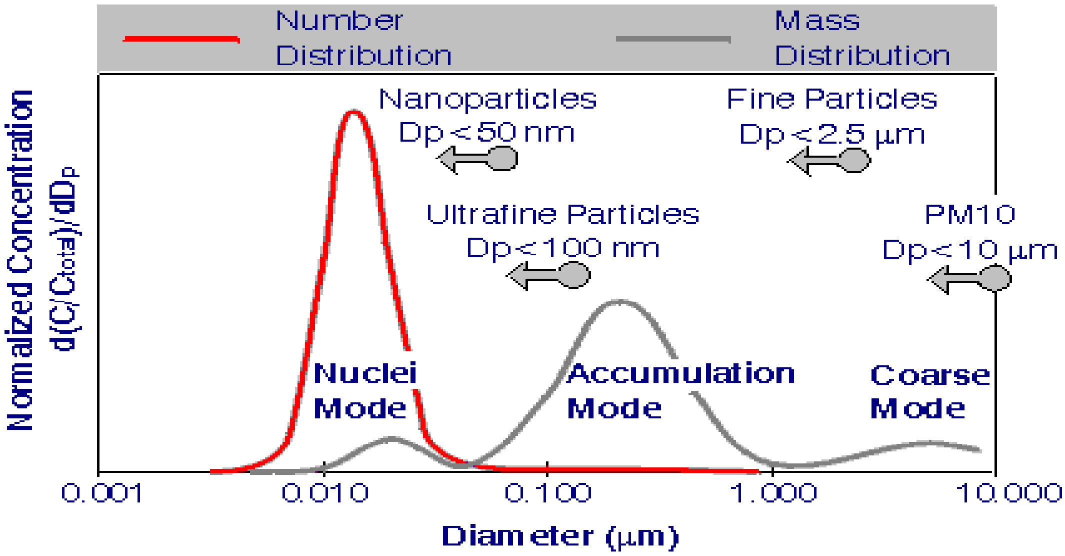


Figure 1-1: Diesel Particulate Size Distribution (from www.dieselnet.com)

The formation of very fine particles is believed to proceed by a nucleation process, but particles less than 100 nm are also unstable, and rapidly grow to larger sizes by a process of agglomeration of the nuclei particles. The nucleation occurs both in the combustion chamber of the diesel engine (for particles rich in carbon) and in the dilution tunnel (where hydrocarbons, sulfuric acid, and water may be involved). Both homogeneous and heterogeneous nucleation mechanisms can contribute.

Interactions with the ambient urban aerosol will also be important, and it is likely that the ultimate particle size distribution of emissions originating from diesel exhaust, will be determined by agglomeration of the particles with the ambient aerosol.

From these considerations it is clear that measured diesel particle size distributions will be a function of the initial particle size, determined by the combustion process, and other factors which influence the gas to particle conversions, including nucleation and adsorption/condensation, as well as coagulation, including:

- Dilution ratio,
- Cooling,
- Residence time,
- Temperature,
- Humidity,
- Ambient aerosols

The effects of some of these parameters have been investigated (Abdul-Khalek and Kittelson, 1999; Ahlvick *et al*, 1998; Kittleson, 1998).

1.3 Regulatory Environment

In the major world markets over the last decade, particularly in Europe, North America and Japan, heightened awareness and concern for air pollution has led to considerable tightening of regulated design standards for emissions from new diesel vehicles.

These standards apply to emissions of NOx, HC, CO, total particulate, and smoke opacity. Future European, US and Japanese standards are tending to converge in response to growing globalisation of the automotive industry.

In Europe, new standards are being introduced in five progressively more stringent steps, Euro1 from 1992, Euro2 from 1995, Euro3 from 2000, Euro4 from 2005 and Euro5 from 2008. The technical requirements of these standards are being progressively adopted as United Nations ECE standards, which are the bases for standards set in many non-European nations.

In Australia prior to 1995, diesel-vehicle engines were required only to be certified to Australian Design Rule (ADR) 30, which sets limits for smoke opacity. All diesel engines (and most diesel vehicles) marketed in Australia are imported. At this time, there is little published information to indicate the gaseous and particulate emission standards these vehicles/engines were actually designed to meet.

ADR 70, phased in between 1995 and 1997, set emission limits for NOx, HC, CO, particulate and smoke opacity by reference to European, USA and Japanese standards current in 1994.

Recently, the Australian Government adopted new ADRs 30.01(smoke), 79.01 and 79.02 (emissions from light vehicles), 80.01 and 80.02 (emissions from heavy vehicles). For diesel vehicles, these new ADRs adopt the technical requirements of Euro2/3 for implementation in 2002/3, and the technical requirements of Euro4 for implementation in 2006/7. (For heavy vehicles, US 1998 is specified as alternate to Euro2/3, and US 2004 is specified as alternate to Euro4.)

These new ADRs are anticipated to be introduced as Trans Tasman Vehicle Standards, and will substantially reduce new vehicle emission levels. The US 1998 and Euro3 standards adopt new requirements for emissions durability and for on-board diagnostics, which are expected to significantly improve in-service compliance.

1.4 THE NEED FOR ‘REAL WORLD’ EMISSIONS DATA

Design certification testing for heavy-duty diesel vehicles/engines supplied in Australia, has in all cases been carried out overseas. These emissions type-certification tests have been based upon engine bench test procedures, which are difficult to relate to actual vehicle performance under ‘real world’ driving conditions. Currently, there are no applicable standard procedures for emissions testing of completed diesel vehicles (as opposed to engines) anywhere in the world.

Estimates of diesel vehicle emissions have hitherto been based upon overseas derived ‘emission factors’, developed mainly from desk analyses of emission results from type-certification engine bench tests. For the Australian fleet, emissions estimates for inventory purposes have been derived mainly from US EPA ‘emission factors’. While these may be representative of vehicles in the US, they have doubtful application for vehicles in Australia. As a result, local inventories of diesel vehicle emissions are at best crude, providing doubtful guidance for emission control policy.

Over the last several years a number of researchers, particularly in North America and Europe, have studied in-service vehicle emissions performance, reflecting growing concern for the health and environmental impacts of diesel vehicle emissions. However, there remains almost a complete lack of representative data that can be extrapolated to the Australian context, and that would provide reliable information on the performance of the Australian heavy-duty diesel fleet.

This Project, in combination with others comprising the preparatory work for the scoping of a diesel emissions National Environment Protection Measure (NEPM), aims to provide information on the emissions performance of Australian diesel vehicles. This will assist NEPC in developing credible inventories of fleet emission performance, and thus assist in developing optimum strategies for diesel vehicle emission control.

1.5 IN-SERVICE VEHICLE EMISSION TESTING

The introduction of progressively more stringent diesel-engine certification standards, will certainly lead to significant reductions in new-vehicle emissions. However, it will take many years before this will result in significant reductions in fleet emission performance due to the slow rate of fleet replacement. Also, reductions achieved will be eroded as vehicles age, and as emissions increase from their design levels. This will be especially so for vehicles subject to less than adequate levels of service and maintenance.

Proper maintenance of the diesel fleet is therefore important in reducing overall fleet emissions.

Many US States, together with an increasing number of jurisdictions around the world, have recognised that the need for ensuring that vehicles are maintained to deliver acceptable emissions performance throughout their service lives.

The most effective mechanism for minimising emissions from in-service vehicles is now almost universally accepted to be through periodic testing to identify and ensure the rectification of high-polluting vehicles. These are most commonly termed ***'Inspection and Maintenance'***, or **I/M** programs

Until very recently, I/M programs have focused primarily on petrol (gasoline) fuelled motor cars. These programs have been developed over the past two decades, primarily to deal with photochemical smog problems, and have been proven to deliver very significant reductions in emissions from these vehicles.

In addition to the well-established existing programs in the USA and Mexico, many Asian, South American and European countries are now planning or implementing programs of this type. The NSW RTA, is also planning to introduce light-duty I/M testing, based on the US EPA I/M240 chassis dynamometer test procedure.

However, given the relatively recent public awareness of the health and environmental threats posed by diesel vehicles, there is now world-wide interest in 'catching up' with equivalent programs and test protocols to reliably and economically identify high-polluting diesel vehicles. Australia, through a number of government decisions and cooperative State-Commonwealth activities, is at the forefront of this work.

This report describes a key element of Australia's research into "real world" pollution levels from diesel vehicles and the rigorous assessment of a number of candidate short tests for possible application in future diesel vehicle Inspection and Maintenance programs.

The work is being keenly followed by regulatory authorities around the world in the pursuit of a practical, low cost yet effective test for diesel vehicles.

2. SCOPE OF WORK

2.1 OBJECTIVES

The objectives for the Project were set out in the Project Specification. These objectives, together with the scope of activities carried out to achieve them, are shown below.

2.1.1 Establishment of Fleet Emission Performance

Objective: ***To test a representative sample of diesel vehicles in use in urban Australia under the appropriate 'composite urban emission drive cycle' (CUEDC), established in Phase 1, and determine their emission performance.***

This will subsequently enable the development of emission factors that can be used for local air-shed inventory calculations in Australia, and will improve knowledge of the ambient air quality impacts of the diesel fleet.

For each of 80 vehicles, separate measurements of each nominated emission and fuel consumption were made over each of the four road-flow conditions of the CUEDC, and for the overall CUEDC.

The nominated measurements were –

- Oxides of nitrogen (NOx),
- Particles (mass and size),
- Carbon monoxide (CO),
- Carbon dioxide CO_2),
- Oxygen (O_2),
- Total hydrocarbons (THC),
- Visible smoke (opacity),
- Fuel consumption.

During emission testing, each vehicle was subjected to an inertia load equal to its tare mass plus half its cargo capacity, i.e. ½ (tare mass + GVM).

2.1.2 Evaluation of In-Service Emission Assessment Procedures

Objective: ***To evaluate and compare the suitability of five in-service emissions assessment procedures for the measurement of diesel vehicle emissions.***

The 80 vehicles were each tested over the five assessment procedures identified in Phase 1 as candidate short Inspection & Maintenance tests for evaluation. -

- The stationary 'snap idle' test as detailed in SAE J1667. This test has been used for "smoke" testing of in-service vehicles in USA and Europe
- A two-speed, full load (maximum rated power and torque), steady-state chassis dynamometer test. This test was suggested in the Phase 1 Report. It measures emissions at two steady state conditions with the engine under full load.
- A 4-point 'lug-down' chassis dynamometer test. This test was suggested in the Phase 1 Report. It is based on a similar test specified in the State of Colorado Regulation 12 for measuring smoke emissions.
- The 'D550' (5% incline at 50 km/hr) steady-state chassis dynamometer test. This is a short test first proposed by in Anyon P, 1995, "Diesel Inspection and Maintenance".

- A new ‘DT80’ mixed-mode chassis dynamometer test. A new test proposed in the Phase 1 Project by Brown S and Mowle M, 1999,”In-service Emission Performance – Drive Cycles”. It is an aggressive driving test with 3 full-load accelerations and an 80km/h cruise carried out on a chassis dynamometer.

Part way through the Project, a new short test called the AC50/80 (proposed by Parsons Australia to meet the requirements of the California Air Resources Board) was agreed to and included in the evaluation.

Details of these test procedures are included in Section 3.6.4 and Appendix 3.

The emissions measured during each of the six procedures are shown in Table 2-1.

Table 2-1: Emission Measurements during each of the short tests

I&M Test	NOx	THC	PM (Filter) Mass)	PM (LLSP)	Opacity	Opacity
	Average	Average	Total	Average	Average	Maximum
SAE J1667	X	X		X	X	X
D550	X	X	X	X	X	X
2-Speed	X	X		X	X	X
Lug-down	X	X		X	X	X
DT80	X	X	X	X	X	X
AC5080	X	X	X	X	X	X

In addition, each vehicle underwent a 6-point static inspection as identified in Phase 1, and an on-road visible smoke evaluation procedure based on the ‘10-second smoke rule’ used for on-road surveillance by State environment agencies. Details of these procedures are included in Appendix 3.

2.2 PRESENTATION OF RESULTS

2.2.1 Fleet Performance

For each nominated emission, results are provided detailing vehicle emission performance under each road flow condition for the appropriate CUEDC test cycle for each test vehicle. This report includes a critical analysis of the results by ADR vehicle categories, odometer reading, vehicle/engine age and other relevant variables.

2.2.2 Particulate Measurement Comparisons

Emissions of particles were measured by a range of measuring devices. A comparative assessment of results is presented in Section 6.

2.2.3 Comparison of In-service Tests

Evaluations of each in-service emissions test included evaluation of –

- Test correlation with the CUEDC emission results for each ADR category, traffic flow condition, and the overall CUEDC cycle.
- Sensitivity of the test to reflect CUEDC emission performance.
- Suitability for use across the range of vehicles tested.
- Ease of use.
- Time and resource requirements for testing by ADR category.
- Suitability for use in a large-scale in-service vehicle-testing program (cost, equipment, training, etc).
- Correlation with vehicle 6-point inspection and the '10-second smoke rule'.

3. METHODOLOGY

3.1 PREPARATORY WORK

Recognising that no suitable test facilities existed in Australia to undertake the NEPC diesel vehicle testing projects, Parsons Australia researched, designed and commissioned a heavy-duty emissions laboratory in Auburn, NSW during mid-1999. This work included:

- Investigation of the supply of a suitable dynamometer to perform heavy-duty transient testing. Dyno Dynamics, a leading Australian dynamometer manufacturing company, was engaged by Parsons to develop and manufacture a suitable dynamometer system. Working closely with Parsons staff, Dyno Dynamics constructed and tested a 450kW, heavy-duty dynamometer capable of testing single and dual drive axle vehicles. Customised dynamometer control hardware, software and transient loading algorithms were developed to calculate and control, in real-time, the effects of each vehicles' test mass (inertia), rolling resistance, frontal area and drag coefficient under continuously changing speed conditions. A "drivers aid" system comprising real-time graphical speed/time traces, error bands and error-tracking software was also designed and integrated into the dynamometer system.
- A full-flow, double dilution tunnel with Critical Flow Venturi (CFV) system supplied from Auckland Universtity was adapted and calibrated to meet the US EPA standards for gaseous and particulate emissions measurements for all vehicle categories. This work involved the fabrication of two separate exhaust ducting systems, for light and heavy-duty vehicles, the fabrication of three new critical flow venturies and the installation of a high pressure, 5000cfm centrifugal air blower and 100kW electric drive motor.
- Construction of an instrument laboratory to house gas analysers, sampling equipment, computers, data acquisition systems and operations staff. The room included air conditioning, a soundproof window for viewing the test cell and communications equipment to liase with the test driver and other key personnel.
- Design and commissioning of a real time (second-by-second) data acquisition system to record the numerous instruments, probes, data loggers and sensors installed to control and monitor the emissions measuring system.
- Meeting with and securing the support of transport fleet managers from approximately 30 companies. It was considered essential that prior to the commencement of the project the advice and support of the industry regarding test protocols and how best to obtain a representative sample of the fleet was obtained. The industry's enthusiastic participation and generous contributions, both in advice and the supply of vehicles, proved to be instrumental in the overall success of the project.

3.2 Facilities and Equipment

A description of the Parsons Australia "Vehicle Emissions Test Facility", and the equipment and instrumentation used to carry out this Project, are provided in Appendix 1.

The operational centerpiece of the facility is the heavy-duty vehicle test cell and instrument laboratory, which were equipped and commissioned during July and August 1999, specifically to carry out preparatory work for the NEPC Diesel NEPM. They provide capability to conduct a full range of tests and analyses of heavy-duty diesel vehicle exhaust emissions. A schematic plan view of the test cell and laboratory is shown below in Figure 3-1. A picture taken from within the test cell is shown in Figure 3-2.

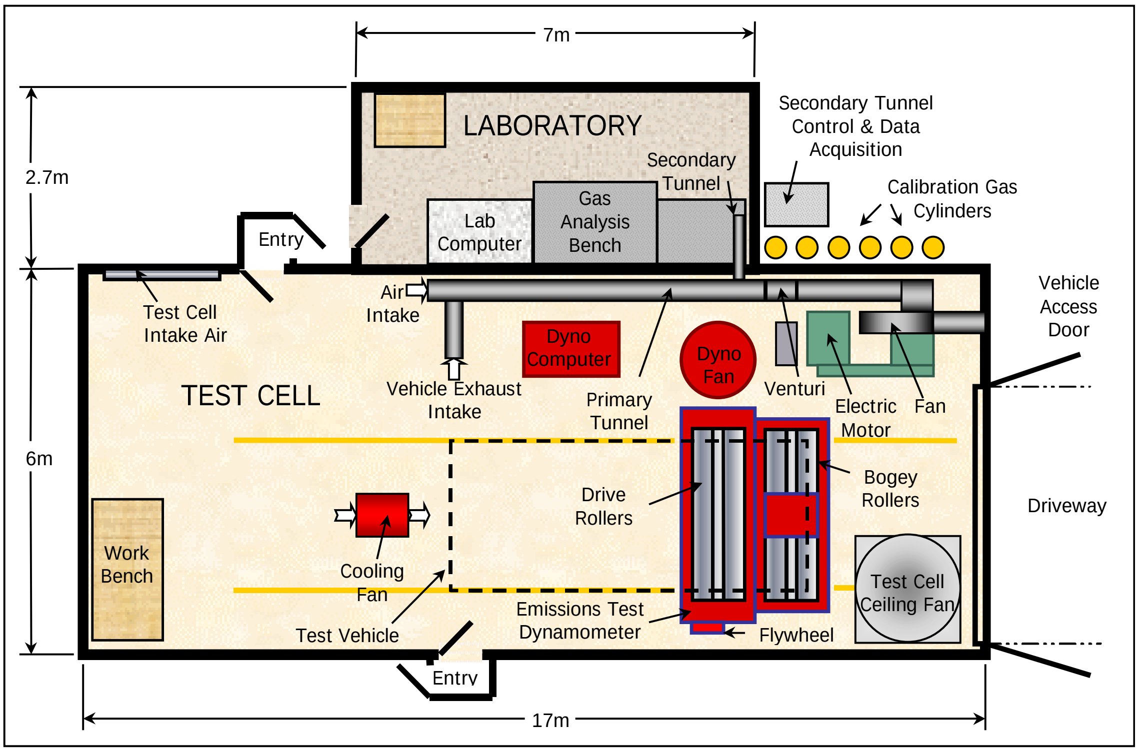


Figure 3-1: Schematic Plan View of Test Cell and Laboratory.

3.2.1 Dynamometer

The custom-built Dyno Dynamics heavy-duty chassis dynamometer is shown in Figure 3.2. The dynamometer incorporates sophisticated control software and electronics that support complex, transient drive cycle testing of vehicles, with inertia simulation for vehicles to 45 tonnes GVM and beyond. It uses large diameter rollers to reduce the potential for tyres to overheat, a 'drivers aid' to display the appropriate drive cycle trace and a single flywheel to provide a base inertia of 1360kg (this falls within the IM240 equipment specification). Acceleration inertia above 1360kg is simulated electrically via the eddy current brake and controlled by the drive cycle software.

The custom-developed open-access dynamometer software allows any drive cycle to be quickly loaded as a time-speed Excel spreadsheet file into the control computer.

The chassis dynamometer was capable of testing the full range of vehicles listed in the project brief. Four wheel drive vehicles were tested by disengaging the front wheel hubs and allowing only the rear wheels to drive. Bogie-axle vehicles were tested by locating the rear wheels on the dynamometer idler rollers, and engaging the power divider so that only the front wheel set drove the rollers. Permanent all-wheel drive vehicles were not tested.

Figure 3-2: Dyno Dynamics Chassis Dynamometer inside the test cell

3.3 SAMPLING AND ANALYTICAL SYSTEMS

The overall sampling system and layout of the instruments, as used in this project, is shown schematically in Figure 3-3. Essentially, the system comprised the following main components –

- the primary and secondary exhaust dilution system
- the gas analysis system
- the particle analysis system
- the data acquisition system.

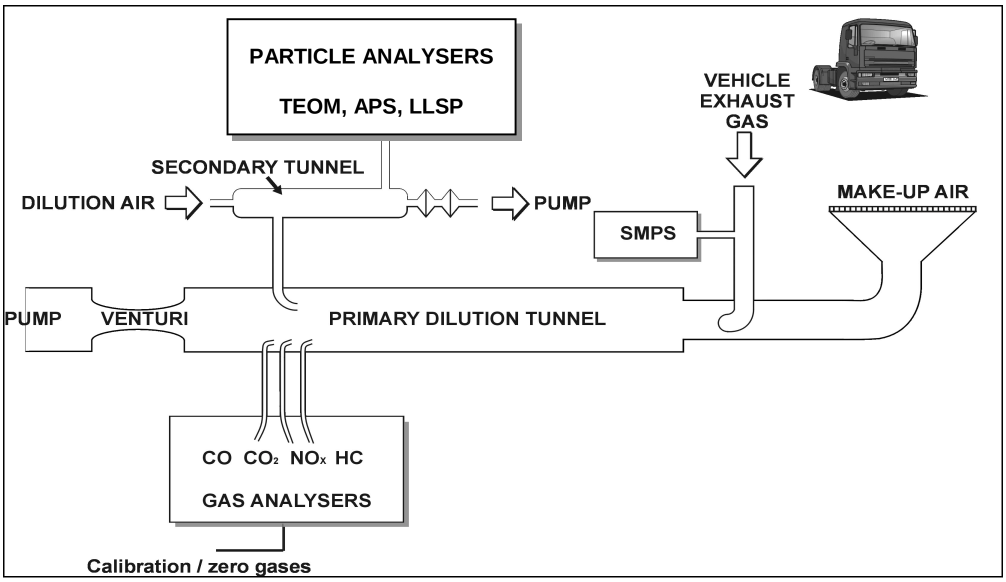


Figure 3-3: General Layout of Sampling and Analytical Systems.

3.3.1 Primary and Secondary Exhaust Dilution System

The system utilises the *constant volume flow* (CVS) concept with *electronic flow compensation* (EFC), and was designed –

- To meet the requirements of the US Code of Federal Regulations, Title 40, Subpart B, §86.110-94, applicable to (*inter alia*) 'light duty diesel vehicles' and 'light duty diesel trucks'.
- To enable these technical requirements to be met while testing heavy-duty diesel vehicles, for which the CFR has no chassis dynamometer test requirements.

The CO, CO_2, NO_x and hydrocarbon analysers sampled the diluted exhaust stream from the primary tunnel. All of the particle analysers except the scanning mobility particle sizer (SMPS) sampled from the secondary tunnel.

3.3.2 Gas Analysis System

The diluted exhaust gas in the primary tunnel was analysed with a range of on-line, continuous analysers for CO_2, CO, NO_x and total hydrocarbons. The analogue output from each instrument was continuously logged by the data acquisition system. A summary of emission analysis techniques are provided in Table 3-1 below. The various instruments and their manner of use was generally in conformance with US CFR Title 40, Subpart B, §86.111-90/91.

Table 3-1: Emission Analysis Techniques

Gas	Technique
NOx	Chemiluminescence
HC	Flame Ionisation Detector (FID)
Co, CO_2	Non-dispersive infra-red (NDIR)
O_2	Paramagnetic analyser

3.3.3 Particle Analysis System

Particulate sampling during the CUEDCs was conducted using the following instrumentation –

- Total particulate mass by filter collection.
- Real time particulate mass by Laser-light Scattering Photometry (LLSP).
- Real time particle mass measurement by Tapered Element Oscillating Microbalance (TEOM), summarised over periods of acceleration, deceleration, cruise and idle, for each road flow condition and each CUEDC.
- Particles PM1, PM2.5, and PM10 by Aerodynamic Particle Sizer (APS).
- Particulate PM<0.5 by Scanning Mobility Particle Sizer (SMPS) during a steady state test only
- During the D550 tests, measurements of size distribution of ultra-fine particles less than 0.5 µm diameter were made using a Scanning Mobility Particle Sizer (SMPS).

A series of on-line particle analyses instruments were used to provide continuous measurement of the total mass and size distribution of particles within the exhaust.

These included –

- A TSI Model 8520 DustTrak Laser Light-Scattering Photometer (**LLSP**) specially calibrated for diesel exhaust particulate size distributions was used for on-line measurement of particle mass during all vehicle tests. The LLSP was set up to measure particles up to 10 microns (PM10).

This is a relatively inexpensive (less than $10,000) rugged, general-purpose instrument. Once calibrated it does not require further adjustment, close monitoring or even regular servicing. The LLSP has a dynamic range of 0.1 µm to 10 µm.

For this project, the LLSP was calibrated specifically for the measurement of particles emitted from diesel exhaust at the Queensland University of Technology. The standard manufacturer (TSI) calibration is based on particles of a mass and size range referred to as Arizona Dust.

- A Rupprecht & Patashnick Co Inc Model 1105 Diesel Tapered Element Oscillating Microbalance (**TEOM**) instrument was run routinely during drive cycle testing for each vehicle. The TEOM was run without the cut-off sampler so that it measured all particles in the sample gas stream (TSP).

  The TEOM is a relatively expensive (~AUS$75,000) high quality laboratory grade instrument that provides particulate mass measurement in real time. For this project, it was set up to measure total particulate during the CUEDC. As with many scientific instruments, it is complex; requires careful handling, setup and sample preparation; constant monitoring of operation; and frequent change of microbalance filter in order to maintain its high accuracy and reliability.

  During this project the TEOM provided a means to judge the real time performance of the other instruments, a cross-check on the reference filter paper method and to gather data during the CUEDC for dissection into various vehicle operating modes (idle, acceleration, cruise and deceleration).
- A TSI Model 3310 Aerodynamic Particle Sizer (**APS**) was used for continuous measurement of particle size distribution during all drive cycle testing. The APS measures particles in the size range of ~0.5 to 50 µm.

  The APS is a very expensive (~AUS$100,000), sophisticated laboratory measurement system which relies on time of flight measurement of particles in the size range between ~0.3µm to ~30µm.

  Precautions were taken concerning the dynamic range of the APS. At high levels of ultra-fine particle loading, the APS has difficulty separating the individual particles and the potential to view them as a series of large ones. To minimise this effect, the average particle distribution recorded at lower particle concentrations during a given test was used to correct for any artifact or 'phantom' particles in the higher mass ranges that might result from overloading. Also, to account for particles less than ~0.3µm the data analysis subtracted the total mass recorded by the APS from the filter mass, which was then added to the PM_1 fraction. Thus the particle size estimates were based on both APS results and the filter paper weights. The APS was set up to record PM_1, $PM_{2.5}$ and PM_{10}.
- A Scanning Mobility Particle Sizer (**SMPS**) measured particle size distribution within the range 0.04 to 0.5 µm, of 'grab-samples' taken from the raw exhaust inlet during the D550 short test.

  Particle size characteristics were determined on a comparative basis, and under steady state engine conditions. Samples of raw exhaust were diluted with ambient air in a ratio of ~50:1 (similar to dilution ratios under driving conditions) into a tedlar sampling bag. Particle size distributions were determined using a scanning mobility analyser, SMPS (TSI) immediately after collection, and then for about 30-60 minutes afterwards. At longer times, particle numbers decreased and particle size increased due to agglomeration. The following information obtained included:
  - the size of the particle when first measured; and
  - the size and count of particles as they agglomerate over a period of 60 minutes.

- A smoke opacimeter was connected into the exhaust sampling system, upstream of the dilution air inlet to the primary tunnel.
  Opacimeters are low cost (~AUS$15,000) simple to operate instruments that are used in certification testing and I/M programs in many overseas countries.
  They measure opacity as a surrogate for visible smoke, based on light obscuration techniques. Due to fundamental physics of light interactions, these techniques have difficulty distinguishing between combinations of particle numbers and sizes. As a result, opacity is well known to be a poor surrogate for particle mass emissions.
  For this project a top of the line relatively expensive (~AUS$30,000), accurate and high quality AVL opacimeter was used. The meter drew a sample of raw exhaust just upstream of the dilution tunnel on a continual basis during all tests.

Consistent with standard certification testing procedures for particulates, primary and backup filters collected total suspended particulate (TSP) samples from the secondary tunnel. Computerised mass flow controllers were used to measure and regulate sample and dilution-air flow through the filters. Standard gravimetric methods were used for weighing the primary and backup filters. All particle instruments (apart from the SMPS) were connected to the secondary tunnel through isokinetic sampling nozzles for each instrument. The secondary tunnel sampling arrangement is shown in Figure 3-4.

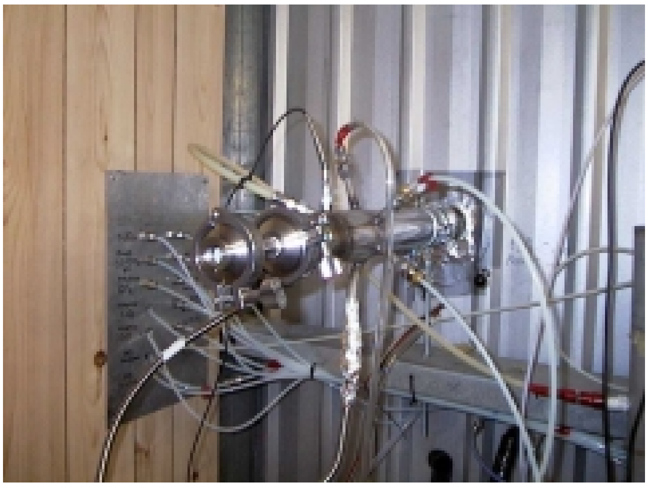


Figure 3-4: Secondary Tunnel Particle Sampling Arrangement

3.3.4 Data Acquisition System

The following data outputs were all continuously logged on a second-by-second basis:
- all instruments (except for the APS, SMPS and LLSP).
- dynamometer speed, tractive effort, drive cycle tracking errors.
- secondary dilution tunnel controller (temperatures, mass flows).
- the transducers for atmospheric pressure, temperature and relative humidity inside the dynamometer cell, and temperatures of the heated gas sample lines and NOx analyser.

Custom designed software was used to control the logging hardware, display the data in real time and record data to disc. Over 40 data channels were logged at one-second intervals over the entire test sequence.

At the completion of testing, data from all of the instruments were transferred to an automated spreadsheet program for processing and plotting.

As the APS and SMPS do not generate real-time outputs, they each required dedicated control and data management software, the output of which was appended to the main data file for each vehicle.

3.4 TEST VEHICLES

3.4.1 Test Vehicle Selection

The Project Brief specified the number of vehicles in each ADR Category, including particular makes and vintages, that were required to be selected for testing based on a total sample size of 80 vehicles.

Vehicles were selected generally in accordance with these criteria, while at the same time covering as wide a variety of manufacture, model and engine capacities as practical. Where difficulties were encountered in meeting these criteria, alternative selections were made in discussion with the NEPC Project Manager. The selection criteria, together with the number of vehicles within each category actually tested, are shown in Table 3-2.

ADR Categories

Vehicle selection included vehicles of the following ADR categories:

MA, MB, MC Passenger & off road passenger vehicles ≤ 9 seats.
MD Light Bus ≤ 5 tonnes GVM
ME Heavy Bus >5 tonnes GVM
NA Light goods vehicle ≤3.5 tonnes GVM
NB Medium goods vehicle >3.5 tonnes, ≤12 tonnes GVM
NC Heavy goods vehicle >12 tonnes GVM

For the purposes of this Project, the NC category is broken into two sub-groups:

NC goods vehicle >12 tonnes ≤25 tonnes GVM or GCM
NCH goods vehicle >25 tonnes GVM or GCM

(Note: GVM = Gross Vehicle Mass; GCM = Gross Combination Mass)

A complete list of test vehicle and engine specifications is provided in Appendix 2.

Table 3-2: Test Vehicle Matrix

ADR Category	**No of Vehicles Required (Tested)**			
	1980-89	***1990-95***	***1996-99***	***Total***
MA, MB, MC	**3 (3)**	**5 (5)**	**5 (5)**	**13 (13)**
Makes acceptable for testing and number tested ➨	Toyota 2 Ford Nissan / Datsun 1 Mitsubishi Holden Mazda	Toyota 2 Ford Nissan 2 Mitsubishi 1 Holden Mazda	Toyota 1 Ford Nissan 1 Mitsubishi 2 Holden Mazda 1	
NA	**5 (4)**	**8 (9)**	**6 (6)**	**19 (19)**
Makes acceptable for testing and number tested ➨	Holden 1 Ford Mazda 1 Toyota 2 Nissan 1 Mitsubishi	Isuzu Ford 3 Toyota 3 Mitsubishi 3	Isuzu Toyota 3 Mitsubishi 1 Ford 2	

ADR Category	No of Vehicles Required (Tested)			
	1980-89	***1990-95***	***1996-99***	***Total***
NB	**3 (2)**	**8 (9)**	**6 (6)**	**17 (17)**
Makes acceptable for testing and number tested ➨	International 1 Isuzu 1 Mitsubishi Toyota / Hino Ford 1 Mercedes-Benz Volvo	International 1 Isuzu 2 Mitsubishi 2 Toyota / Hino 2 Ford 1 Mercedes-Benz Nissan-UD 1 Volvo	International 1 Isuzu 2 Mitsubishi 2 Toyota / Hino 1 Mercedes-Benz Nissan-UD Volvo	
NC	**2 (2)**	**7 (7)**	**5 (5)**	**14 (14)**
Makes acceptable for testing and number tested ➨	International 1 Isuzu 1 Mitsubishi Toyota / Hino Ford Mercedes-Benz Volvo	International Isuzu 3 Mitsubishi Toyota / Hino 1 Ford Mercedes-Benz 1 Nissan-UD 1 Volvo 1	International Isuzu Mitsubishi 1 Toyota / Hino 3 Mercedes-Benz Nissan-UD 1 Volvo	
NCH	**2 (2)**	**3 (3)**	**5 (5)**	**10 (10)**
Makes acceptable for testing and number tested ➨	International 1 Kenworth Mack 1 Volvo Ford	International 1 Kenworth 1 Mack 1 Volvo Ford	International 1 Kenworth 1 Hino 1 Volvo 1 Ford 1 Scania	
ME	**3 (2)**		**4 (5)**	**7 (7)**
Makes acceptable for testing and number tested ➨	MAN 1 Mercedes-Benz Isuzu 1 Volvo		MAN 1 Hino 2 Scania 1 Volvo 1	
Totals	**18 (15)**	**31 (33)**	**31 (32)**	**80 (80)**

3.4.2 Vehicle Sourcing

Two approaches were used to source the vehicles in the range required -

- Those major transport operators who are members of the Road Transport Forum (RTF) and who participated in Phase 1 of the project, were contacted and asked to supply their vehicle for a half-day of testing. Also these operators, and members of the Bus and Coach Association (BCA) who attended the focus group meetings held as part of Phase 1, were also contacted to support the testing work.
- Most smaller vehicles (which could not generally be sourced from major transport operators) were sourced from:
  - Commercial hire companies such as Hertz, Sargents and Ranger.
  - Used vehicle lots specialising in diesel vehicles.
  - Tradesmen and owner-driver vehicle operators.

The following private and government organisations provided vehicles, thus ensuring a range of vehicles having quite different maintenance regimes and usage patterns:

Australia Post	State Transit
RTA	1st Fleet
Boral	AGL
CSIRO	Hertz
Thrifty	Kennards Hire
DTM Transport	Stillwell Trucks
International Trucks	Ranger Rental

Lintott Automotive Group	Sargent Truck Rental
Gilbert & Roach	Budget
McPhee Transport	Auburn Automobiles
Metro Truck Center	Carlins
Beaut Utes	Robert Roel Pty Ltd
Scania Australia	TNT

3.4.3 Vehicle Suitability for Testing

Following delivery to the Test Facility, each vehicle underwent a pre-test inspection. Vehicle and engine specifications were recorded and assessments were made of the vehicle's safety and suitability for test. A copy of the Inspection Form is included in Appendix 2.

Eleven vehicles (around 10% of the total number of vehicles sourced for the project) proved unsuitable for testing due to mechanical problems and were rejected prior to commencement of testing. Reasons for rejection were:

- 1 x engine noise – injector timing out and uncertain engine condition,
- 1 x overheating and excessive breather leakage,
- 1 x broken differential lock,
- 1 x uneven tyre sizes,
- 1 x threw a tyre tread (capped tyre),
- 1 x exhaust leaks,
- 1 x poor fuel filter not enough fuel delivery under load,
- 2 x unable to be tied down (airbags, not enough room on differential),
- 1 x no differential oil plug - oil topped up & new plug installed,
- 1 x air line to differential lock broken.

Other vehicles were selected but could not be tested for non-mechanical reasons such as:

- late arrival to the test site due to traffic,
- had to be returned at a specified time, leaving insufficient time to complete the test sequence,
- were not ready for collection,
- had been sold prior to testing.

3.5 SIX-POINT INSPECTION

A six-point inspection of each vehicle was carried out prior to testing. This comprised the items shown in Table 3-3.

Table 3-3: 6-Point Inspection Items

Item to be Checked	Record Response
Air filter condition?	Clean; moderate; needs replacing
Fuel pump condition Seal intact? Tampering suspected?	 Yes; no Yes; no
Any missing engine parts?	Yes; no
Any blue smoke from engine breather & exhaust pipe at idle?	Yes; no
Turbocharger oil leaks?	Yes; no
Intercooler and compressed air inlet pump hoses condition?	Intact; leaking

3.6 EMISSION TESTING

3.6.1 Test Fuel

Forty 200-litre drums from a single batch of commercial diesel fuel (sulfur content of 0.17% and cetane number 45.5) were supplied by Shell, together with a certificate of analysis for the batch. A copy of the certificate is included in Appendix 3.

The fuel was drummed at the Melbourne refinery and transported to Parramatta, close to the Auburn test facility, for distribution to the test site on an as-required basis.

Prior to testing, each test vehicle was parked in the dedicated refueling area where its fuel tank(s) was emptied and refilled with sufficient test fuel to complete the testing sequence. The vehicle was then driven to the dynamometer in readiness for testing.

On completion of testing, the 'waste fuel' was used to top up the tank prior to returning the vehicle to its owner.

3.6.2 Preparations for Test

3.6.2.1 Instrument Room Preparation

Daily maintenance, service, calibration and quality control checks were carried out on the sampling and analytical equipment at the start of each test day. All calibrations were logged on the central data acquisition computer.

A copy of the start-up work sheet is included in appendix 3.

3.6.2.2 Test facility preparation

Each vehicle was driven onto the dynamometer, properly secured, and the exhaust sampling system connected.

Vehicle details (registration number, make, category and test weight) were entered into the dynamometer control computer for identification and calculation of the inertia loading applicable for the vehicle. The information was then saved to a dedicated file from which the CUEDC and short test cycles were referenced to set the correct speed and loads during testing. Selection of dynamometer configuration, single or dual axle (1,2,3 or 4 rollers in use) was also made to adjust for parasitic losses.

All safety items, connections and data inputs and dynamometer settings were independently verified.

The vehicle was then driven to warm the engine to normal operating temperatures and pressures. During this period the exhaust concentrations were measured and venturi size(s) selected to provide optimum dilution to meet the calibration ranges of the instruments. The primary dilution tunnel mass flow controller was set for the venturi size selected. Background checks of the dilution air were carried out to establish the baseline for gaseous emissions measurement.

3.6.3 Sequence of Tests

A consistent sequence of tests was applied to each of the 80 vehicles reported on in this document. The test sequence comprised:

(a) Measurements of power and tractive effort,

(b) Emissions performance on each of the short tests.
(c) Emissions performance on the complex "real-world" CUEDC test cycle.

A listing of the testing sequence is provided in appendix 3. Each test (except following the SAEJ1667) was pre-ceded by two free accelerations to maximum governed speed and back to idle (snap idle) to clear any residue soot from the exhaust system. As the SAE J1667 is a snap idle test there was no requirement to repeat this prior to the next test. A schematic diagram is presented in Figure 3-5.

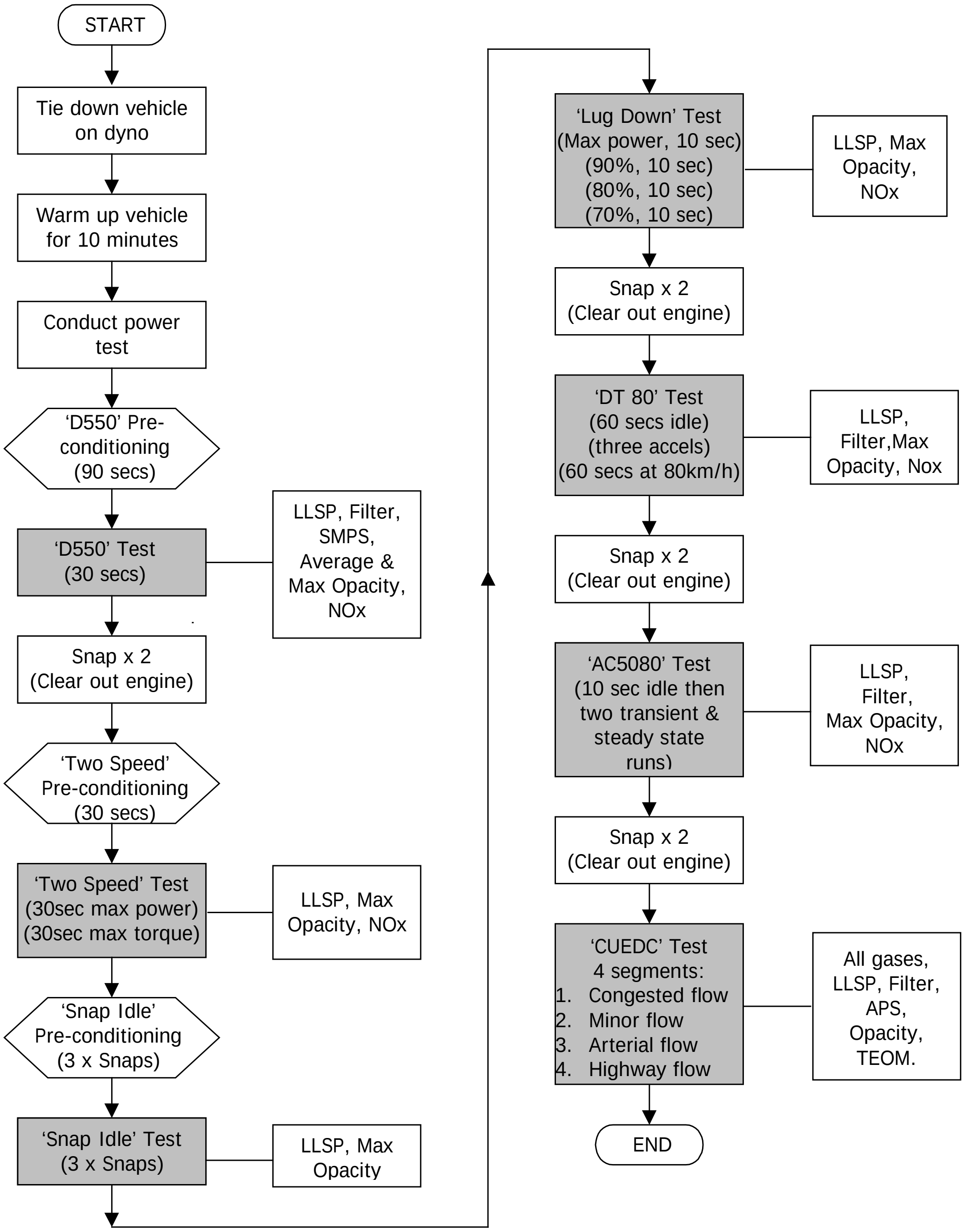


Figure 3-5: Test Sequence

3.6.4 In-service Emissions Short Tests.

Test vehicles were run at idle while final test preparations were completed. A power and tractive effort test was carried out to establish each vehicle's rated and intermediate speeds for use during the two-speed and lug-down short tests.

The first of the seven short tests was selected from the dynamometer control software menu, and the vehicle was driven sequentially through each test following the trace displayed on the driver's aid. Particulate filters were changed and any required adjustments to the sampling and analytical systems were made in between the short tests.

3.6.4.1 D550 Short Test

The D550 test is detailed in Anyon P, 1995, *Diesel Inspection and Maintenance. The D550 Short Test*. This paper is included as attachment 3 in the Phase 1 Project Report. Emissions sampling occurs during the last 30 seconds of the test cycle as illustrated in Figure 3-6 below.

This Steady-state test is carried out at a dynamometer load equivalent to a fully laden vehicle driving up a 5% gradient at 50 km/h. This represents a near full-load condition for most vehicles. As it is a constant load, constant-speed test, it requires only a simple power dynamometer. The test is designed so that there is no need to establish maximum power or torque outputs, unlike the lug-down and 2-speed tests described later.

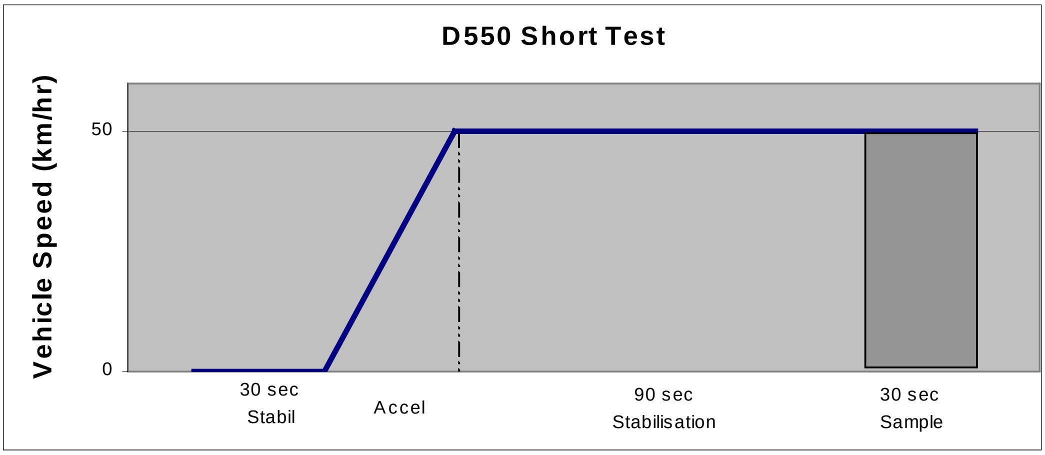


Figure 3-6: D550 Short Test

3.6.4.2 Two-Speed Short Test

The Two-Speed Test (Figure 3-7) was suggested in the NEPC Project 2.1 Report. It is designed for measurement of emissions under steady-state conditions replicating two of the four test points in the engine dynamometer tests carried out for ADR 30 (Diesel Engine Smoke Emissions). Emissions are sampled at two points (rated speed and intermediate speed) for 30 seconds each. The test is carried out under full-load conditions using a simple power dynamometer.

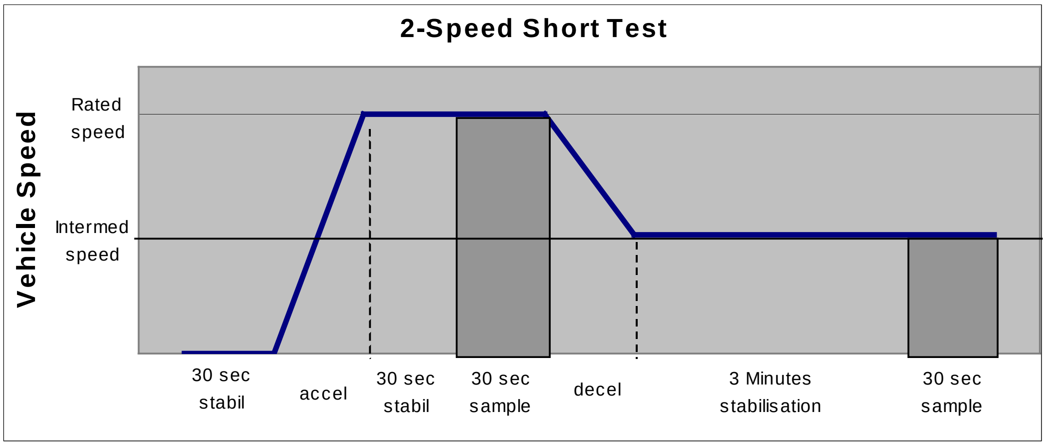


Figure 3-7: 2-Speed Short Test

3.6.4.3 Snap Idle Short Test

The Snap-Idle (or 'Snap Acceleration' or 'Free Acceleration') test (Figure 3-8) is variously described in Regulations and standards in USA, Europe, Japan and a number of other countries. The most detailed specification for the test is given in Society of Automotive Engineers, 1996, *Surface Vehicle Recommended Practice J1667 Snap Acceleration Smoke Test for Heavy-Duty Diesel Powered Vehicles*. The test is very simple to perform, and requires no dynamometer. Emissions are sampled during the period from 0 to 100 % full throttle.

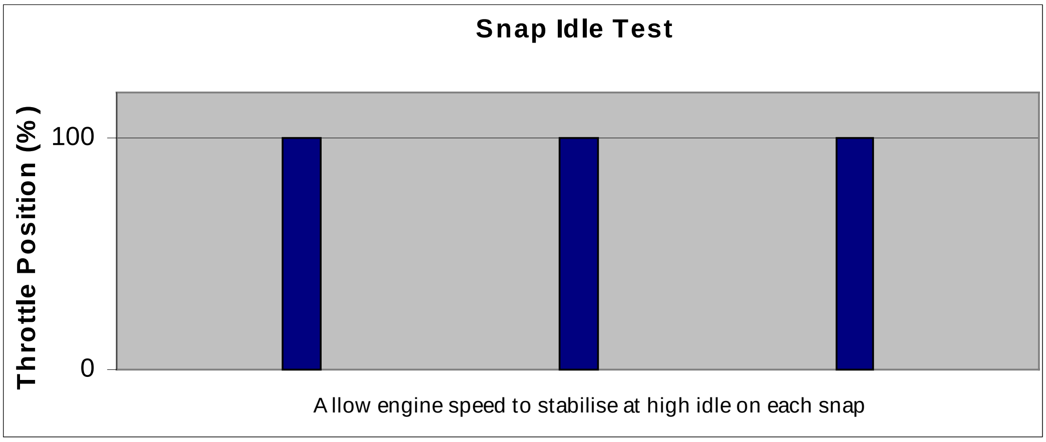


Figure 3-8: Snap Idle Short Test

3.6.4.4 Lug-Down Short Test

The lug down test (Figure 3-9) is based upon similar tests carried out for smoke emissions specified in the *State of Colorado – Regulation 12 'the Reduction of Diesel Vehicle Emissions'*. (A copy of this Regulation is included in the DNEPM Project 2.1 Report). The test is carried out at full load, requiring a relatively simple power dynamometer and control system at four steady state points during which time emissions are sampled for 30 seconds.

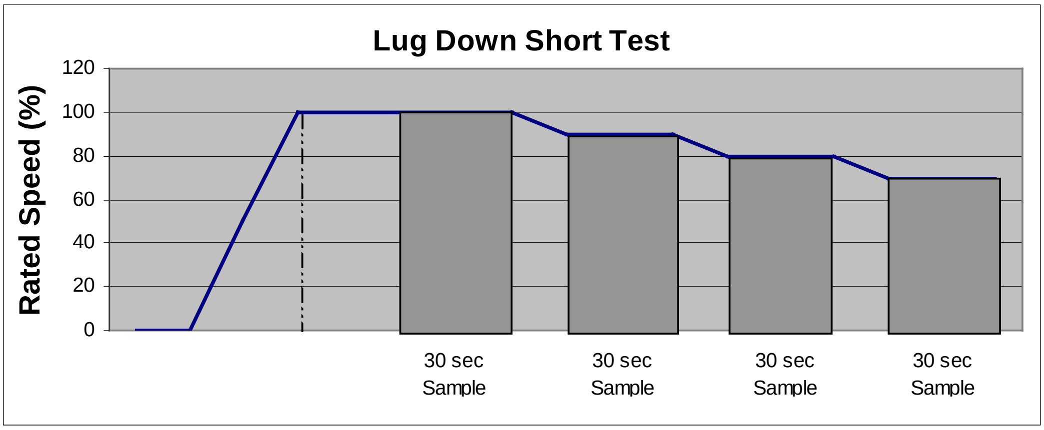


Figure 3-9: Lug Down Short Test

3.6.4.5 DT80 Short Test

The DT80 Test (Figure 3-10) is a newly proposed test developed by Brown S. and Mowle M. during Phase 1 of this Project. A description is provided in Attachment 6 to that Report by the NSW Environment Protection Authority titled "In-Service Emission Performance – Drive Cycles". It is a relatively aggressive mixed-mode test, having three full-load accelerations, as well as a steady-state 80 km/h cruise. The test requires the use of a dynamometer with inertia simulation. Emissions are sampled during the entire cycle.

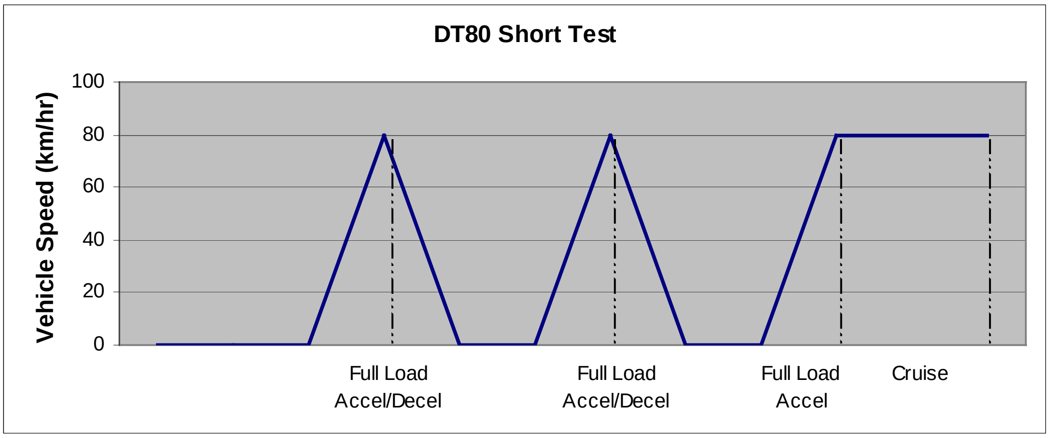


Figure 3-10: DT80 Short Test

3.6.4.6 AC50/80 Short Test

The AC50/80 (Figure 3-11) is a newly proposed short test, suggested by Parsons for the California Air Resources Board and included as a first trial in this Project after discussion with the NEPC Project Manager.

It is a mixed-mode test having two full-load accelerations and two steady-state cruises. It is less aggressive than the DT80, but emissions are sampled during the full period of the cycle like the DT80. It requires the use of an inertia-simulating dynamometer.

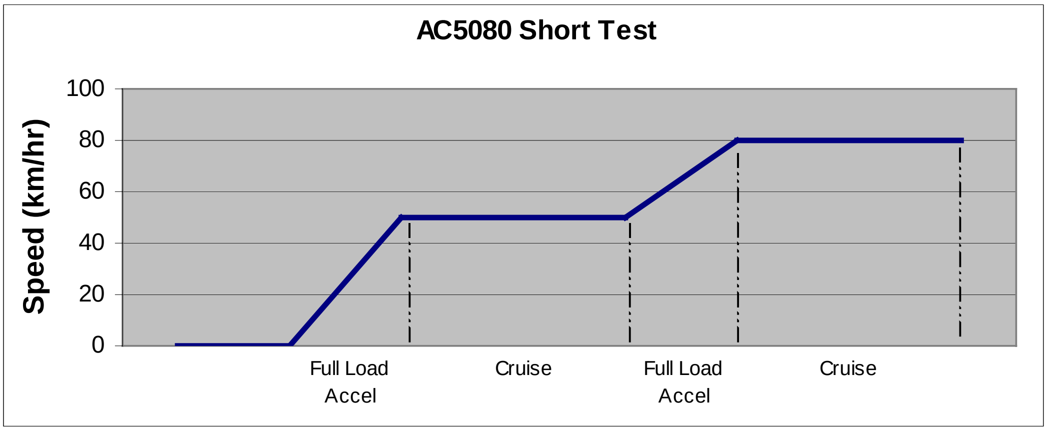


Figure 3-11: AC50/80 Short Test

3.6.5 Composite Urban Emissions Drive Cycle (CUEDC)

To provide a method of testing vehicles that closely replicates actual on-road driving conditions, NEPC commissioned a study in 1998 (DNEPM Project 2.1) to instrument a range of vehicles and record their actual speed/acceleration profiles in congested, minor roads, arterial and highway driving conditions.

The recorded data was then statistically analysed and synthesised into drive cycle segments that most accurately reflected the speed-time patterns for each of these four driving conditions, and subsequently combined into a Composite Urban Emissions Drive Cycle (CUEDC).

Because vehicles of different types have varying driving patterns, a different CUEDC was developed for each of the six major vehicle categories used for emission certification in Australia. The CUEDC drive cycle for each category is shown graphically below.

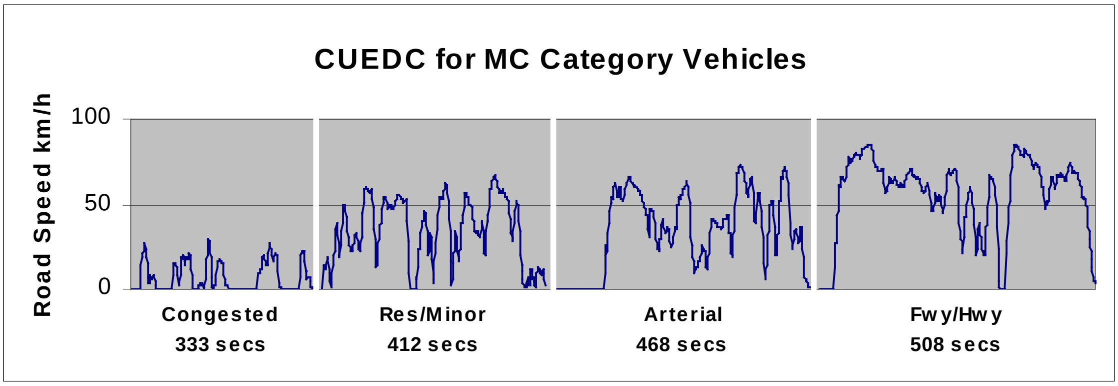


Figure 3-12

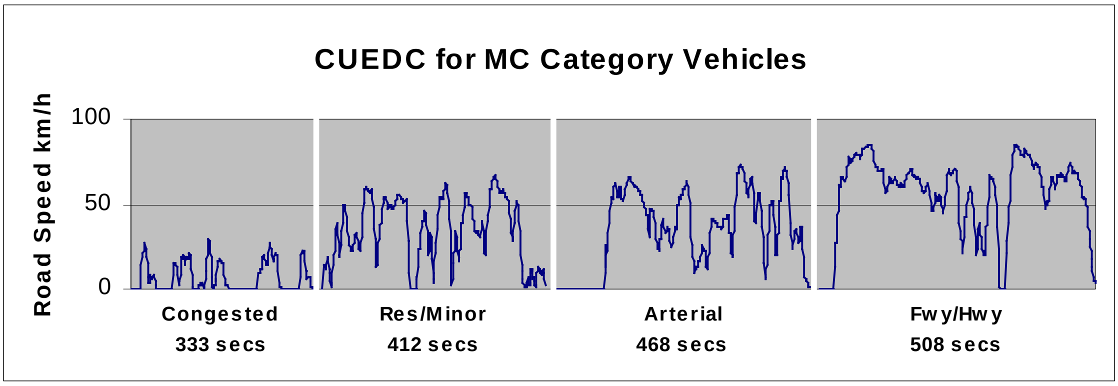


Table 3-4: CUEDC Details for MC Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	333	19.3%	7.1	0.7	3.9%
Minor	412	23.9%	34.5	3.9	23.4%
Arterial	468	27.2%	33.9	4.4	26.1%
Highway	509	29.6%	55.7	7.9	46.7%
Total	1722	100.0%	32.8	16.9	100.0%

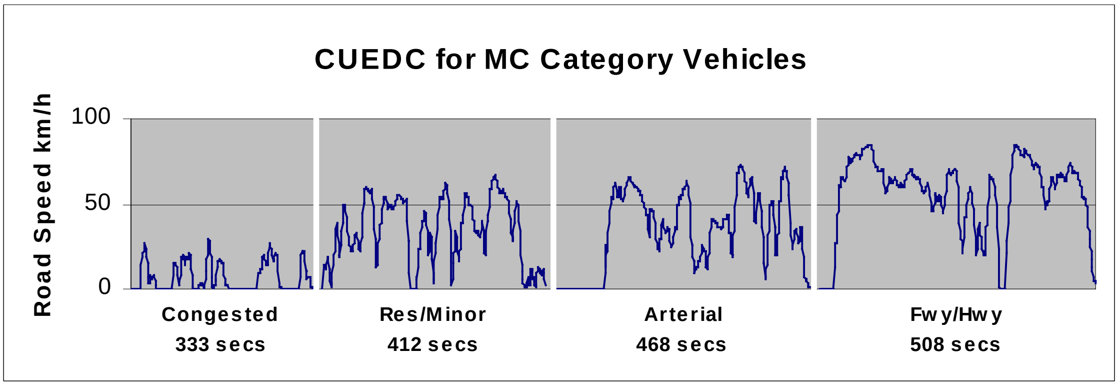


Figure 3-12: CUEDC for MC Category vehicles – Passenger and offroad passenger vehicles ≤ 9seats

Table 3-5: CUEDC Details for NA Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	334	18.6%	12.9	1.2	6.9%
Minor	504	28.1%	32.8	4.6	26.3%
Arterial	447	24.9%	32.0	4.0	22.8%
Highway	508	28.3%	54.4	7.7	44.0%
Total	1793	100.0%	33.0	17.4	100.0%

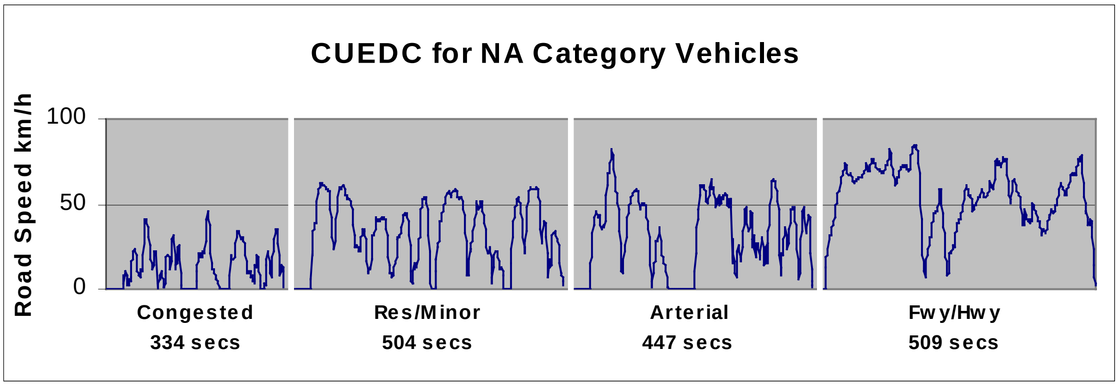


Figure 3-13: CUEDC for NA Category vehicles – Light goods vehicle ≤ 3.5 tonnes gvm

Table 3-6: CUEDC Details for NB Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	319	18.7%	10.9	1.0	4.7%
Minor	405	23.8%	35.7	4.0	19.6%
Arterial	390	22.9%	29.8	3.2	15.7%
Highway	591	34.7%	75.1	12.3	60.0%
Total	1705	100.0%	37.9	20.5	100.0%

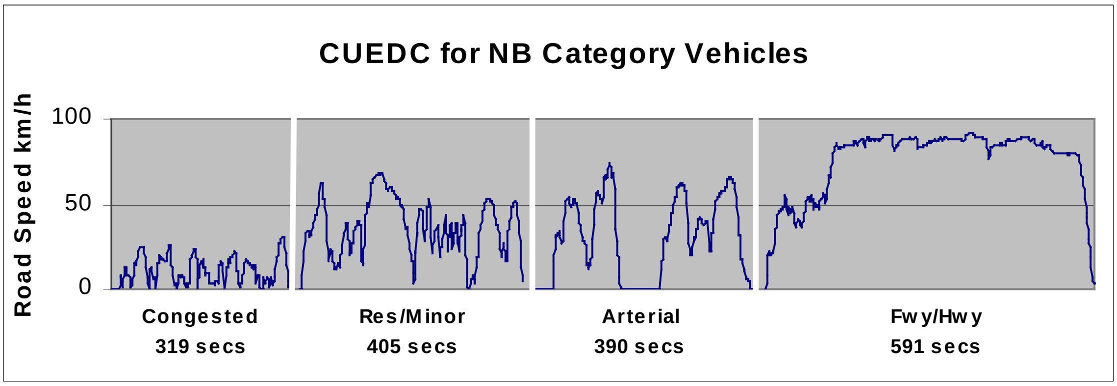


Figure 3-14: CUEDC for NB Category vehicles - Medium goods vehicle > 3.5 ≤ 12 tonnes gvm

Table 3-7: CUEDC Details for ME Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	322	19.2%	11.1	1.0	6.9%
Minor	506	30.2%	33.3	4.7	32.6%
Arterial	435	25.9%	23.7	2.9	19.9%
Highway	414	24.7%	50.8	5.8	40.6%
Total	1677	100.0%	29.7	14.4	100.0%

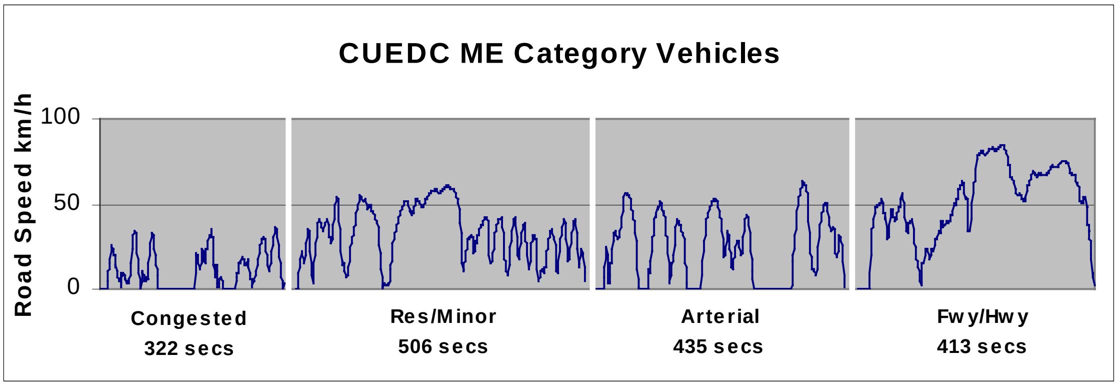


Figure 3-15: CUEDC for ME Category vehicles – Heavy buses > 5 tonnes gvm

Table 3-8: CUEDC Details for NC Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	328	18.3%	7.9	0.7	4.2%
Minor	509	28.3%	32.4	4.6	26.8%
Arterial	431	24.0%	31.5	3.8	22.2%
Highway	528	29.4%	54.3	8.0	46.8%
Total	1796	100.0%	31.6	17.0	100.0%

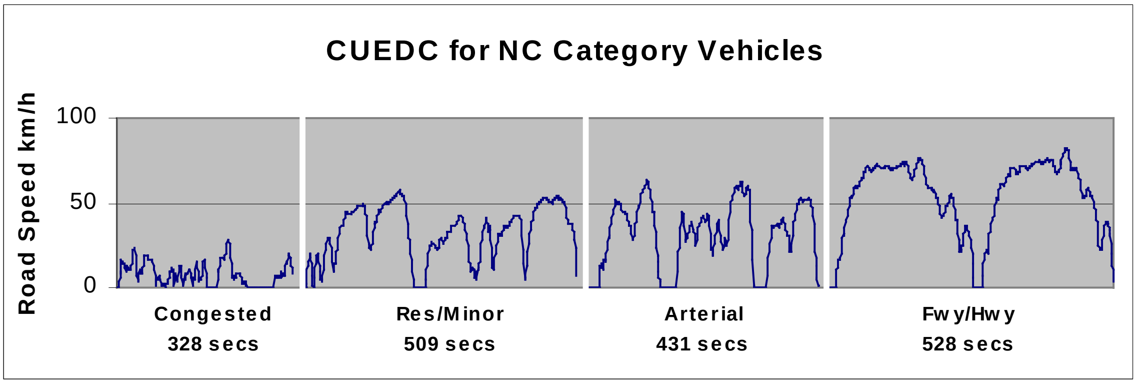


Figure 3-16: CUEDC for NC Category vehicles – Heavy goods vehicles > 12 ≤ 25 tonnes gvm or gcm

Table 3-9: CUEDC Details for NCH Category Vehicles

Mode	Duration (seconds)	Percentage (Time)	Av Speed (km/h)	Distance (km)	Percentage (km)
Congested	364	21.7%	6.7	0.7	4.4%
Minor	477	28.5%	32.6	4.3	27.8%
Arterial	444	26.5%	28.1	3.5	22.4%
Highway	390	23.3%	65.2	7.1	45.5%
Total	1675	100.0%	33.1	15.5	100.0%

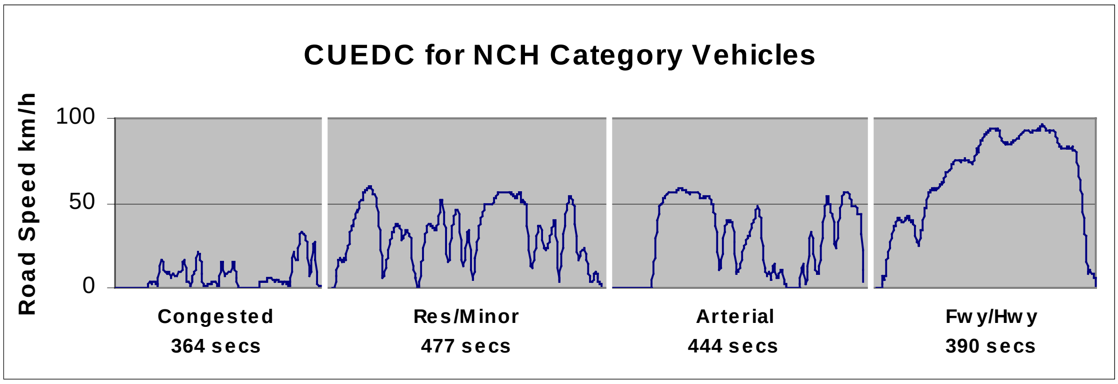


Figure 3-17: CUEDC for NCH Category vehicles – Heavy goods vehicles > 25 tonnes gvm or gcm

It is well known that traffic flow conditions can have an effect on the emission performance of vehicles. To gain a better understanding of how diesel vehicles are driven under Australian conditions the CUEDC drive cycle comprises four segments, each reflecting a different set of driving conditions, i.e.:

- Congested
- Minor / Residential roads
- Arterial roads
- Highway / Freeway

As might be expected, the speed profile of each of these segments is quite different. The congested segment is characterised by frequent stops and starts, followed by periods at idle, with low maximum speeds (rarely exceeding 30km/h) and only moderate accelerations.

Minor road driving has higher overall speeds (up to 50km/h) and with fewer decelerations to rest. This driving pattern simulates relatively free-moving vehicles and roundabouts / intersections where there are few passing vehicles to bring traffic to a complete halt.

The arterial segment replicates the familiar dash between two sets of traffic signals - a fairly rapid acceleration to 60~70km/h, which is sustained for a short period before braking to a halt and waiting for the lights to change.

Highway / freeway driving has sustained periods of cruise at speeds of up to 80~90 km/h, with only infrequent major changes in speed or periods at rest.

Just prior to the start of each CUEDC drive cycle test, the vehicle was accelerated twice under full throttle to clean any excess soot built up during the idle period. The applicable CUEDC for the vehicle weight category was then selected from the dynamometer control menu, and the driver's load/speed command switch placed in the load position. The test drive and exhaust sampling was then commenced.

The vehicle was then driven according to the 'driver's aid' speed trace displayed on the monitor. Between each of the four 'traffic flow' sequences, the vehicle was kept stationary and gas sampling was interrupted while particulate filters were changed.

Following completion of the four road modes (approximately 40 minutes), the vehicle's engine was stopped, a background air analysis was made, and the analytical instruments were re-calibrated in readiness for the next vehicle. Graphs were printed from the dynamometer control computer showing the speed and power absorbed during the test, and the driver's error count.

The vehicle's exhaust was disconnected from the sampling system and the vehicle dismounted from the dynamometer.

3.6.6 Test Data Acquisition

During the test sequence, all instrument readings, sampling system controls, dynamometer parameters, and test cell environmental conditions were continuously monitored and logged on a second-by-second basis and recorded to disk. At the completion of each test sequence, all data were backed up and copies taken for subsequent data validation, processing and analyses.

Particulate samples were collected during all CUEDC tests, and analysed for total mass using the reference filter method. All particulate filters were stored in petri dishes for transport to the CSIRO laboratories for conditioning and weighing.

Parallel sample streams from the secondary dilution tunnel were also measured continuously by Tapered Element Oscillating Microbalance (TEOM), Laser Light Scattering Photometer (LLSP), and Aerodynamic Particle Sampler (APS). In addition, an opacimeter, connected at the vehicle exhaust outlet, gave continuous readings of opacity.

The Laser Light Scattering Photometer (LLSP) and Opacimeter were used during all short tests. The filter method was used during the D550, DT80 and AC50/80 tests. The TEOM was not used during any of the short tests.

3.7 ON-ROAD SMOKE ASSESSMENT

On-road visible smoke testing was performed on each vehicle either prior to or after the dynamometer testing, depending on laboratory test cell utilisation on the day.

The vehicle was first loaded to approximately half its cargo capacity, then driven on public roads in the Auburn area. The test route included a ½-km stretch of road having a 3~5% incline, and a 3-km stretch of substantially level expressway. Observations of the colour, intensity and duration of any visible smoke emission were made and recorded from a following vehicle.

The specified procedure is reproduced in Appendix 3.

3.8 DATA MANAGEMENT AND ANALYSIS

3.8.1 Composite urban emission drive cycles

Results for each CUEDC traffic flow segment together with a weighted total for the CUEDC, for each of the 80 vehicles tested are included in the Project Companion CD-ROM.

For analysis purposes, these data have been aggregated for each ADR/year category, showing results over the four traffic flow segments and weighted CUEDC results. They are presented in Appendix 4, as tables A4-1 to A4-17.

It should be noted that the 'weighted total' mass/km emission results for each CUEDC have been derived by adding the results of each of the 4 component traffic flow segments and dividing by the *total kilometers driven over the entire CUEDC. These 'weighted total' CUEDC results are illustrative of fleet trends. They are not intended to represent emissions in any specific city or region where a particular mix of traffic-flow or (road-flow) conditions apply. Sydney or Melbourne for example, would likely have a greater proportion of total VKT in congested flow conditions than say the ACT, which would likely have a greater proportion of free-flow highway driving.*

The 'weighted' CUEDC results for each vehicle age and weight category are presented by "bar graphs" on a grams/km bass and "scatterplots" on a grams/km/tonne basis. The scatterplots are provided to highlight any trends that existed in the relationship between g/km emission levels and the vehicles' corresponding test mass (which for the purposes of this project is the mass of the vehicle when carrying half its maximum payload). That is emission results were normalised as g/km/tonne vehicle test mass. A much more coherent picture emerges from this approach given the wide spread of vehicle sizes/weights in the diesel fleet. The trend lines are derived using least-squares regression analysis.

The range and variance of emissions across the diesel vehicle fleet is illustrated by way of "boxplots". These are only presented for all vehicles on a road flow mode basis and also for each road flow mode by vehicle category Pre and Post ADR70.

The box plots give another view of the degree of scatter in the data and highlight the number of excessive emitters in relation to the fleet mean. Figure 3-18 illustrates the format of the boxplots used in this report with accompanying text to provide a brief explanation of the terms used to describe a particular data set.

a) Median - 50% of the data falls above the median and 50% below.
b) Lower Quartile (Q1) - 25% of the data set has a value equal to or less than the lower (or first) quartile.
c) Upper Quartile (Q3) - 25% of the data set has a value equal to or greater than the upper (or third) quartile.
d) Possible Outlier - an extreme value that lies outside the upper and lower whiskers, as indicated below.

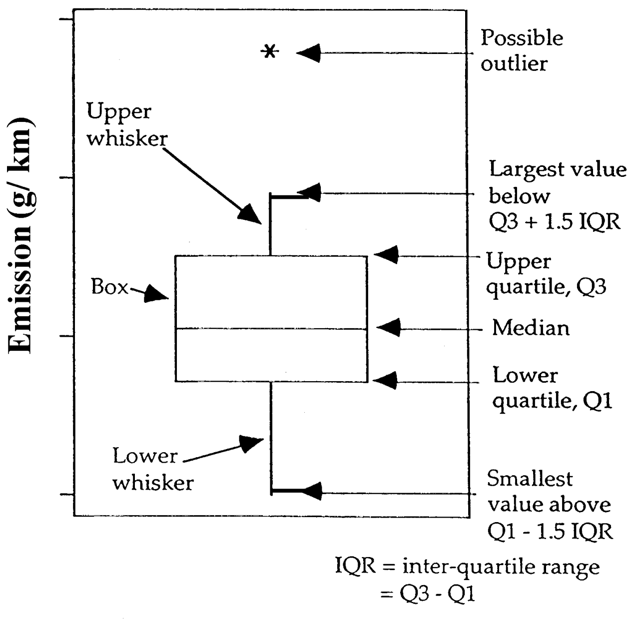


Figure 3-18: Format of Boxplots

3.8.2 Effect of Year of Manufacture and Accumulated Distance Travelled

The impact of vehicle age has been explored by examining the relationship of vehicle CUEDC emissions and odometer reading. The weighted CUEDC emission results for NOx, particulate mass, average opacity and CO_2 for each vehicle were plotted against its odometer reading.

Cautionary Note:
When interpreting results for each ADR vehicle category by Vehicle Age breakdown the reader should be aware of the small numbers of vehicles involved.

When sample sizes are as low as 5 or less the statistical tests have a reduced power to detect a significant difference. Where possible, we have attempted to maintain sample sizes above five by reporting results for either all vehicles (80) or by total ADR category. Any further breakdown into specific vehicle age groups should be treated with caution and the numbers within the groups referenced. For exploration of the scatter within the samples using "boxplots" we have combined Year of Manufacture into two categories corresponding to compliance and non-compliance with ADR70 to provide a more robust assessment of the data.

Also when comparing the short test results it should be noted that as the AC5080 test was introduced later in the project only 45 of the 80 vehicles were tested using this test.

3.8.3 Data Management

The 50 megabytes of data generated during a vehicle test included all emissions measurements, dynamometer settings, tunnel flows, atmospheric conditions and sensor data across each of the short tests and individual road modes of the CUEDC.

CSIRO Energy Technology staff corrected the data for the specific test conditions, calculated the dilution ratios, cleaned it for erroneous spikes, and formatted it to a manageable database. Data from the LLSP, APS, TEOM and SMPS were collected separately at the end of each test from their dedicated computers and labelled accordingly to match the central data system Zip disk. These data were also processed off site by CSIRO Energy Technology.

Results were then generated for both the CUEDC road modes and the various short tests in various units, grams/km, grams/test mass and grams/sec.

Once test results were assigned to a test number and vehicle registration number the data, including the supporting information (vehicle mass, type, dilution ratio, kilometers travelled etc), were then transferred electronically back to Parsons Australia for inclusion in the "flat database" developed specifically for the project. From this database, various combinations of results were tabulated and graphed for analysis.

The database structure enabled plotting of any combination of the data and allowed drilling down into low levels of detail such as whether the air filter was declared dirty during the 6-point inspection or if the vehicle was fitted with a turbo charger.

3.8.4 Quality control of data analysis

At each reporting stage the data were tabulated and plotted to highlight potential problems, show emission trends, correlations and general information to refine the overall direction of the project. Various exploratory drilling exercises were also undertaken during the course of the project to resolve specific issues of concern to NEPC, to address a technical query within the project team or just as a matter of interest in managing the progress of the project.

Both the scientists within the CSIRO Energy Technology group and engineers at Parsons Australia conducted various analysis and data validation checks during the project. On completion of all testing further analysis was carried out, but in more detail, to enable a better understanding of relationships and to assist with general interpretation of the results. In addition, an independent accredited statistician was engaged to peer review and audit the results and to provide advice on analysis and presentation of the data.

John B Donnelly and Associates Pty Limited, specialising in data cleaning and statistical analysis, undertook the peer review of the data and statistical work. The consultant was provided with a complete copy of the database, the interim reports and initial Project Brief. The following steps were undertaken by the consultant in assessing the data and the results presented in this report:

- The CUEDC and Short test results were copied and imported for statistical analysis.
- A random audit check of calculations was carried out. This included recalculation of weighted total emissions across all CUEDC segments.
- Exploratory data summaries were performed to permit familiarisation with the large dataset and frequency counts were obtained to confirm numbers of vehicles and sample sizes of groups. This work confirmed sample sizes within vehicle ADR and Age categories.
- Checks were performed on representative samples of data for the special case of regression through the origin against the standard model.
- Data points removed, as indicated in the report were re-installed and an assessment made as to whether it is reasonable to exclude the point when calculating correlation values.
- Boxplots were generated to show the scatter of the dataset for Pre and Post ADR70 categories for the principle emissions (NOx, CO_2, Pm and Smoke Opacity) of interest over the CUEDC and the two candidature short tests (DT80 and AC5080).
- Cautionary notes were compiled and inserted in the report to warn readers about the effects of small sample sizes.

The database has been copied onto the accompanying CD for further analysis work to be undertaken.

3.8.5 Taking Account of Anomalous Data Points

In checking the data for consistency, a few particulate filter data points are extremely suspect and have been viewed as outliers. All points in question are abnormally high and could be as a result of discrete flakes of particulate residue build-up in the vehicle's exhaust pipe dislodging and being deposited on the sample filter, thereby distorting the result by giving a falsely high mass reading. This is a common occurrence in measuring particulates using the traditional filter paper method, particularly on in-service (old, high polluting, poorly maintained) vehicles.

The data points considered statistically invalid for each of the two primary short tests have been identified (asterisks *) in Figure 3-19 and Figure 3-20. They are:

DT80 - Test No’s 90, 84 and 29
AC5080 - Test No’s 90 and 46

Removing these points dramatically improves particulate correlations for the two short tests versus the CUEDC. The correlations for DT80 and AC5080 particulates are shown on the following charts.

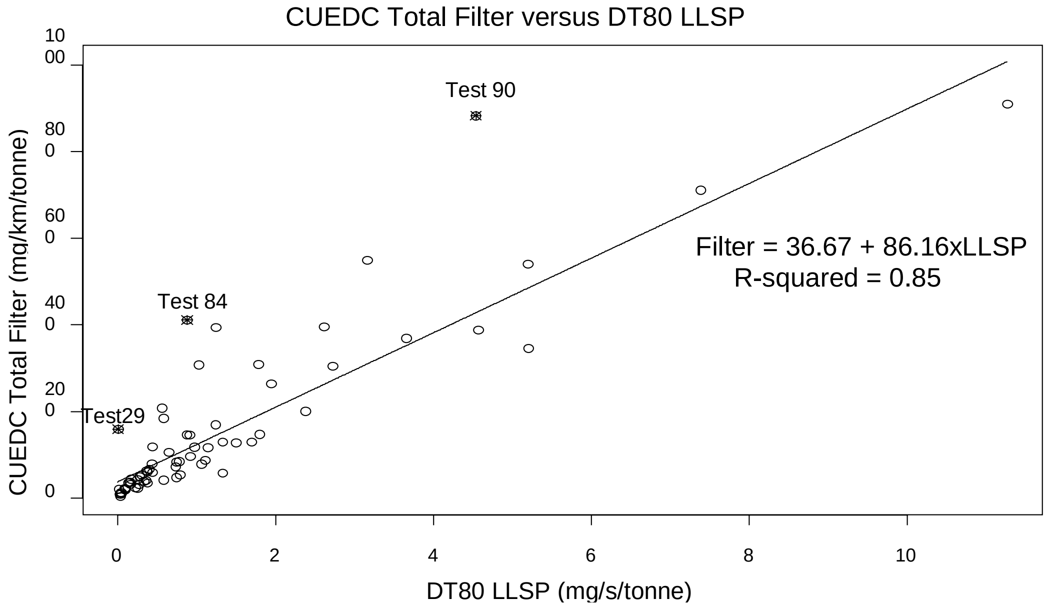


Figure 3-19: DT80 LLSP vs CUEDC Particulate filter – mass normalised, (invalid points omitted)

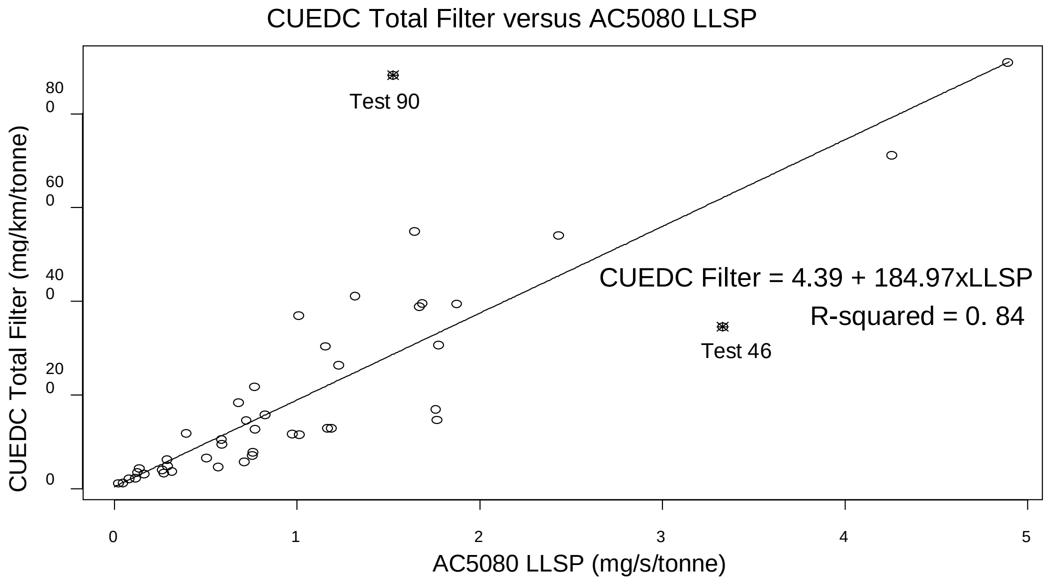


Figure 3-20: AC5080 LLSP vs CUEDC Particulate filter mass – mass normalised (invalid data points omitted)

The DT80 test was most affected by the invalid data points, and its R^2 correlation coefficient improved from around 0.74 to 0.85. The AC5080 changed from R^2 0.79 to 0.84.

4. ANALYSIS OF RESULTS – FLEET PERFORMANCE

This section discusses how data generated during the project may be used to explore relationships between tailpipe emissions and known vehicle attributes, such as age, mass, vehicle type, etc. Most importantly, these relationships may be used to:

(a) predict emission rates from sub-populations of vehicles operating in defined geographic areas, for the purposes of developing emissions inventories and airshed models, and

(b) develop pass/fail criteria that may be used to identify high-polluting vehicles in an in-service emissions test program.

Until this project was completed, no "real-world" emission performance data were available for diesel fuelled vehicles in Australia. Predictions of in-service fleet performance have, in the past, mainly relied on estimated values, or on data from overseas research based on vehicles that were often built to different standards and used different fuel formulations to those available in Australia.
A summary of the data collected for each pollutant, vehicle category and age group, over the CUEDC complex transient drive cycles is contained in Table 4-6.

These data can be studied in a number of ways to explore the presence (or otherwise) of logically valid relationships between vehicle characteristics and emission rates of the pollutants studied in this project.

At the simplest level, trends in emissions performance can be presented using bar charts that illustrate average pollutant emissions, over the complete CUEDC drive cycle, for each vehicle age group and ADR vehicle category tested.

As will be seen in the following sub-sections, aggregating the data in this way results in a somewhat confused picture with some apparently inconsistent emission trends across vehicle groups. However, some more meaningful indications of trends are produced by using vehicle test mass rather than ADR category to explore the data.

4.1 NO_X EMISSIONS

4.1.1 Effect of Year of Manufacture and Vehicle Mass

Figure 4-1 summarises NOx emissions from the project's three age groupings across each of the ADR categories.

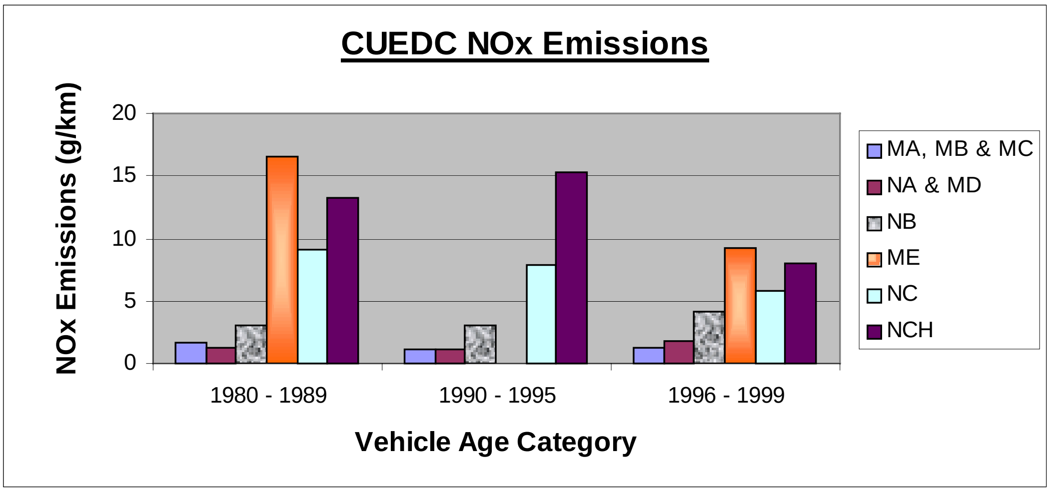


Figure 4-1: CUEDC NOx Emissions

On the basis of this chart, some newer vehicle groups appear to be generating lower NOx emissions (as one might expect), but in other groups the reverse is apparent. Because the data are so highly aggregated, the chart does not provide any clues as to why this paradoxical situation appears to exist.

Another perspective of the fleet is presented below in Figure 4-2 where vehicles are presented by their year of manufacture rather than by ADR weight grouping. However there still is no significant trend in the data.

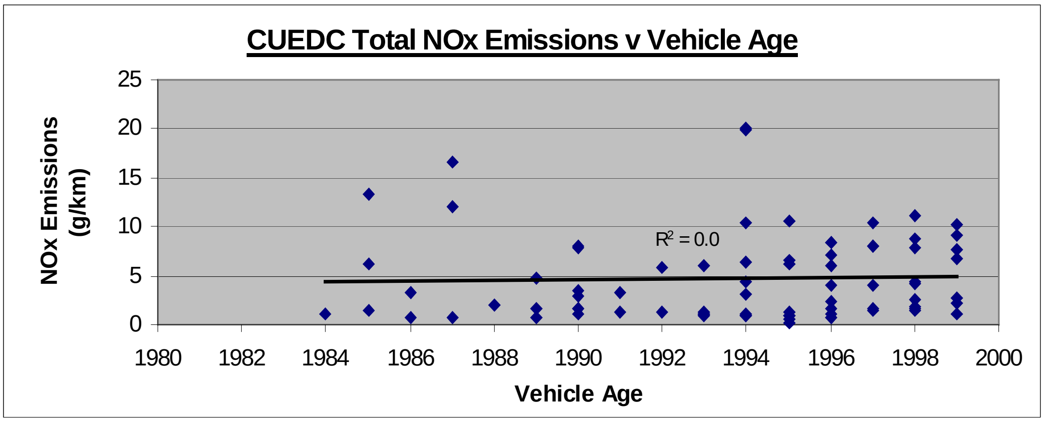


Figure 4-2: CUEDC NOx emissions by year of manufacture

One possible reason, explored in some of the following charts, is that the ADR mass categories are very wide. For instance, the NB vehicle category spans vehicles with a mass ratio of almost 4:1 (from 3.5 to 12 tonnes).

Given that engine power levels over the CUEDC cycle are strongly influenced by vehicle mass, it is likely that significant differences in g/km emissions will be measured from vehicles at the light and heavy extremes of each ADR category, even if the engines employ similar emission control technologies. Hence, a more meaningful relationship between emission levels and vehicle characteristics may be apparent if vehicle mass, rather than broad ADR category, is used to explore emission trends.

To illustrate this point, the following charts plot NOx emission trends that exist in the relationship between g/km emission levels and the vehicles' corresponding test mass (which for the purposes of this project is the mass of the vehicle when carrying half its maximum payload). A much more coherent picture emerges from this approach. The trend lines are derived using least-squares regression analysis.

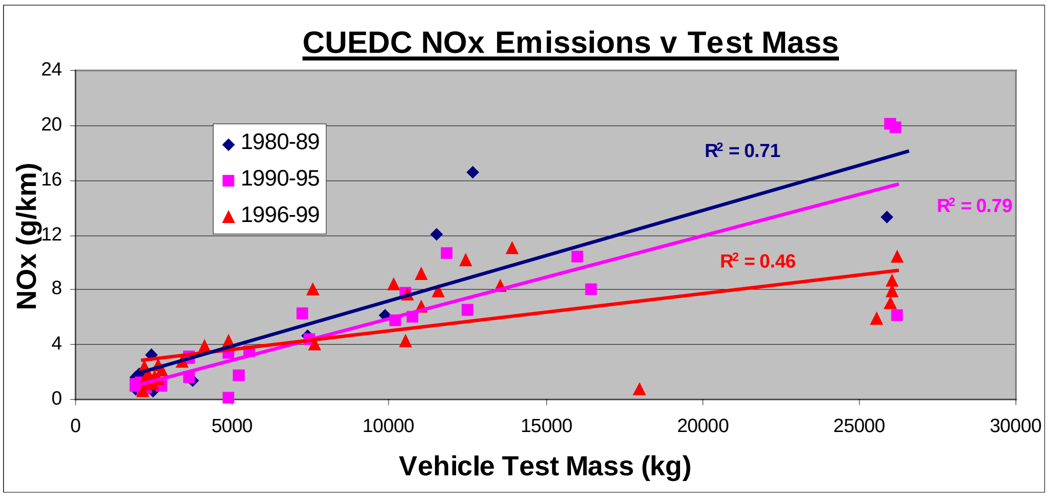


Figure 4-3: CUEDC NOx Emissions v Test Mass

By substituting actual vehicle test mass for the broad vehicle size categories used in the previous bar charts, a clear trend emerges where, as might be expected, the amount of NOx emitted each kilometer increases with vehicle mass.

The trend becomes a little confused in the 1996-99 age group, probably because this bracket includes a large part of the ADR 70/00 phase-in period. At this time there was a significant technology shift in vehicles supplied to the Australian market in order to meet the more stringent ADR 70/00 emission limits.

For inventory estimation purposes, the data collected in this study will allow the generation of much more accurate emission factors than those previously available, truly reflecting the performance of current and older technology vehicles operating in "real world" conditions.

Further analysis of the data is made on a segment-by segment basis. These data are summarised in Appendix 4, tables A4-1 to A4-18, and are further discussed in Section 4.1.2.

4.1.2 Effect of Road Flow Conditions

The variation in NOx emissions across the fleet is illustrated in Figure 4-4 below. The boxplot shows a wide spread in emissions across all road flow modes with a few points classified outliers or potentially “high emitting vehicles”.

Emissions of NOx, which are linked to combustion temperatures, do not reduce by a significant amount in the more free-flowing segments, reflecting higher engine loads.

NOx emissions for all vehicles on a mass normalised (grams/tonne) basis across each of the four road flow segments of the CUEDC are presented in Figure 4.3.

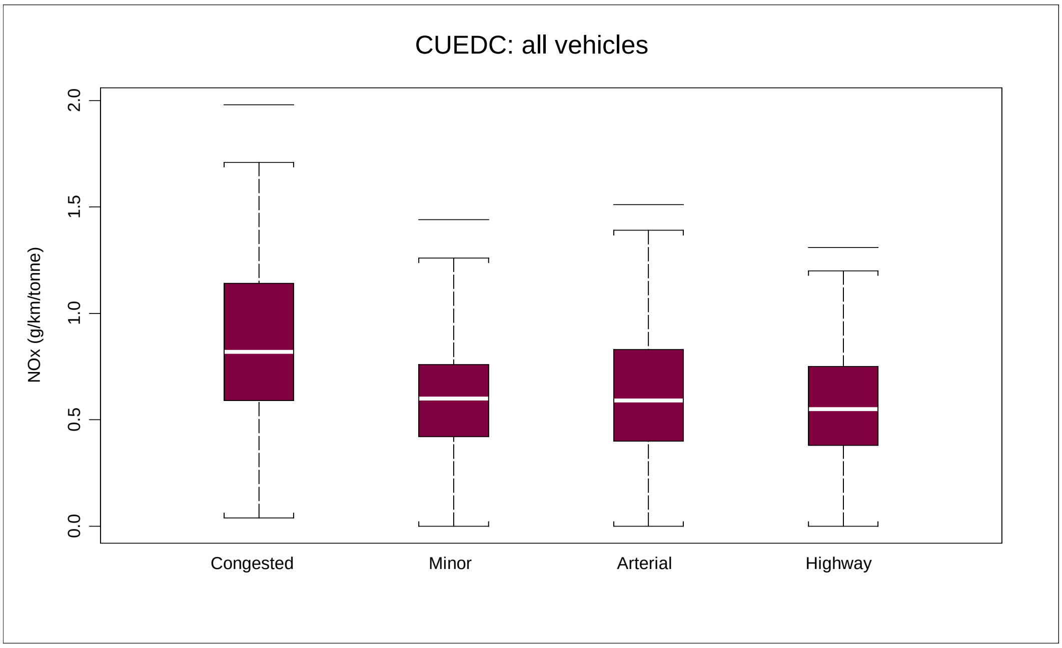


Figure 4-4: NOx emission variance by road flow segment for all vehicles on a mass normalised basis.

The plot shows a large spread of data in all road flow modes across the vehicle mix tested. The sample is diverse with vehicles ranging from less than 3.5 tonne to over 25 tonne with varying levels of engine technology.

4.1.3 Effect of Emission Standards

In assessing the data on a Pre and Post ADR basis the Post ADR 70 vehicles (Figure 4-5 in most categories show lower variability than the older Pre ADR 70 vehicles (Figure 4-6). This could equate to improvements in technology brought about by the introduction of ADR70 or that the newer vehicles are better maintained, reducing the variance between vehicles. This is most noticeable for vehicle category NCH (Rigid Trucks >25tonne).

It appears that there are fewer data outside the upper quartile (25% of values) in the light duty vehicle categories MC and NA across both Pre and Post ADR70. The other vehicle categories all have a greater scatter of data within each of the road modes. This is reasonable given the range in vehicle weight, engine power, make and model within these groups.

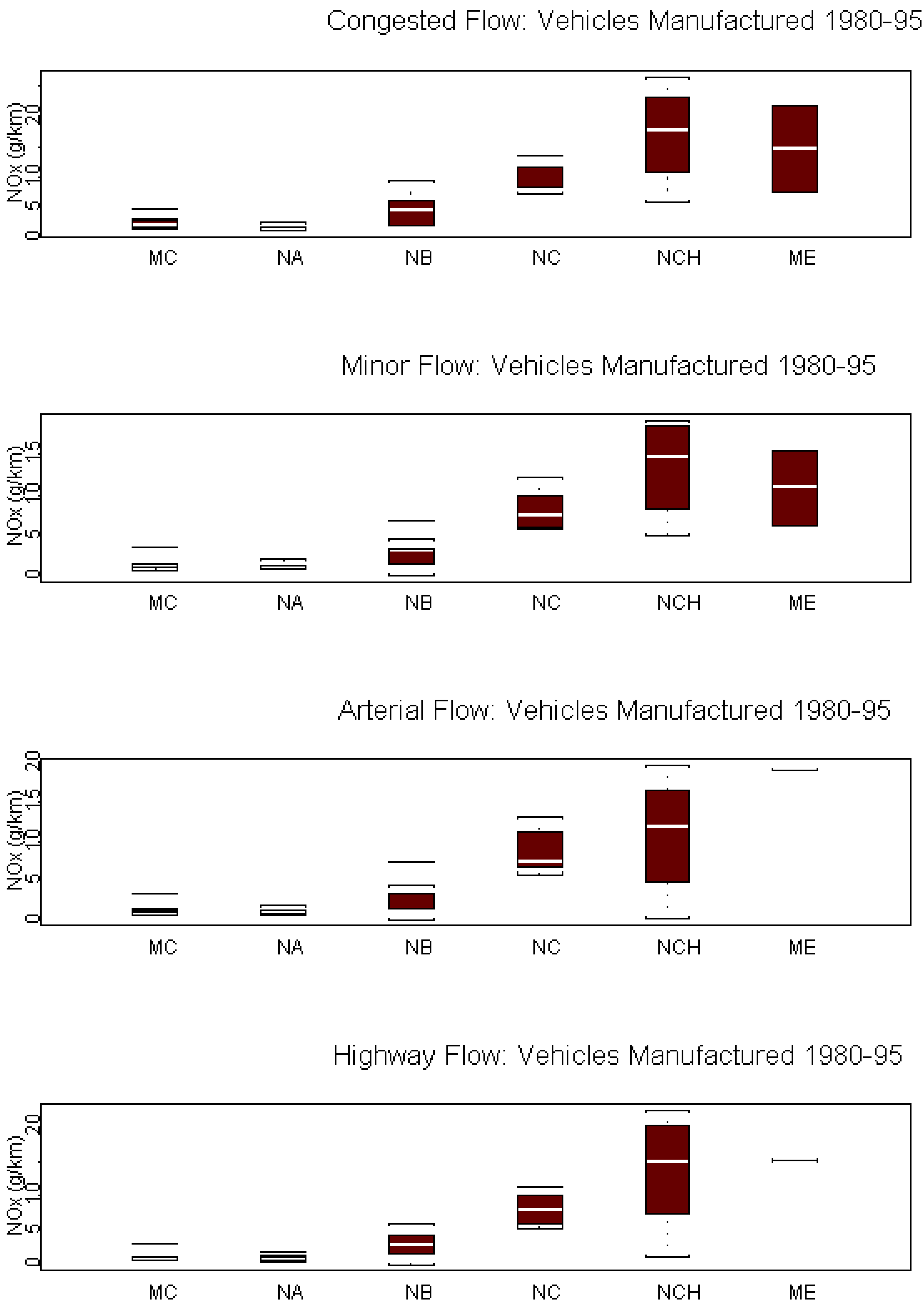


Figure 4-5: NOx emissions by CUEDC road flow mode – Pre ADR70 (1980-95)

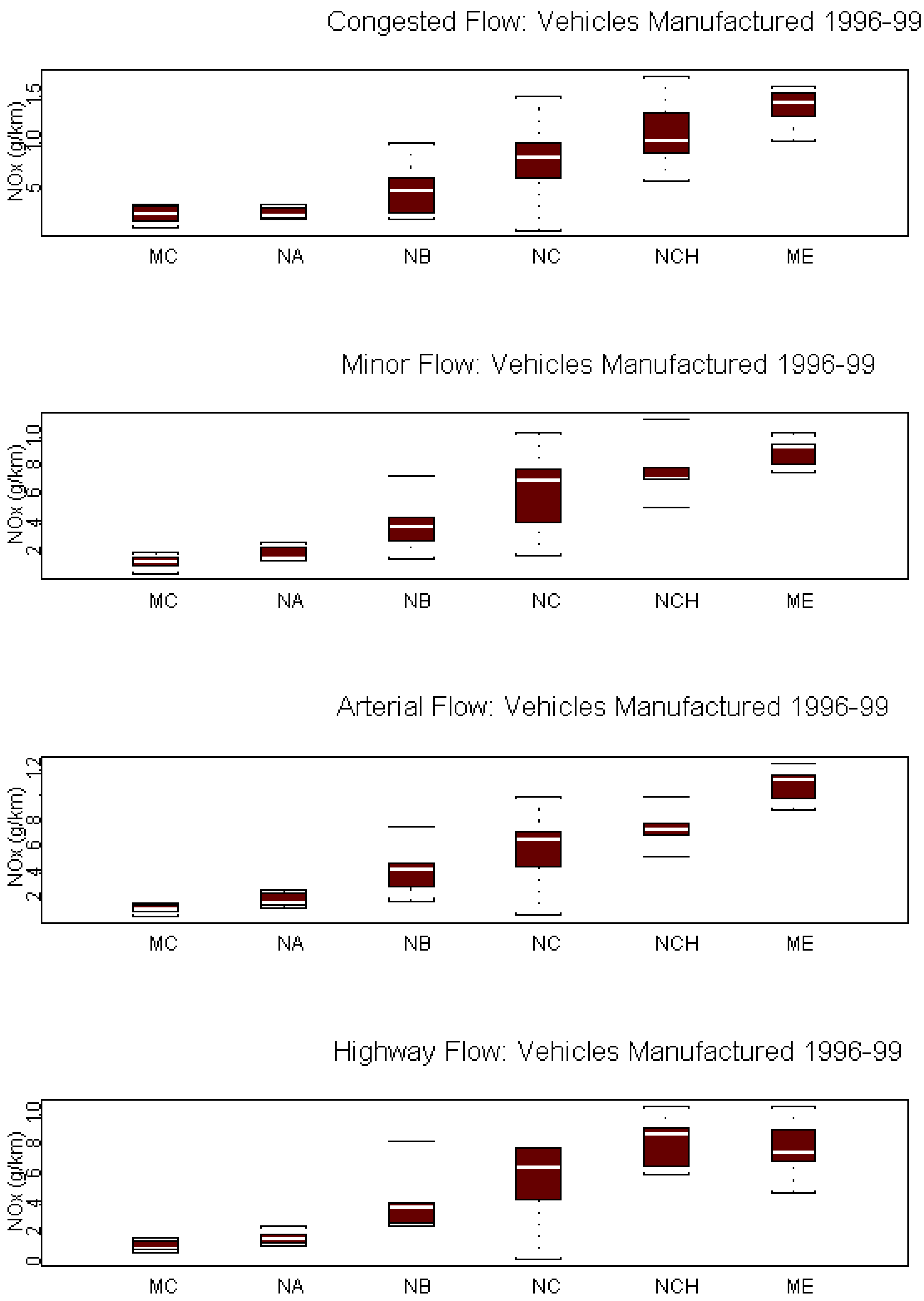


Figure 4-6: NOx emissions by CUEDC road flow mode –Post ADR70 (1996-99)

4.1.4 Effect of Accumulated Distance Travelled

It is very clear from the data in Figure 4-7 that there is no relationship between NOx, and accumulated distance travelled.

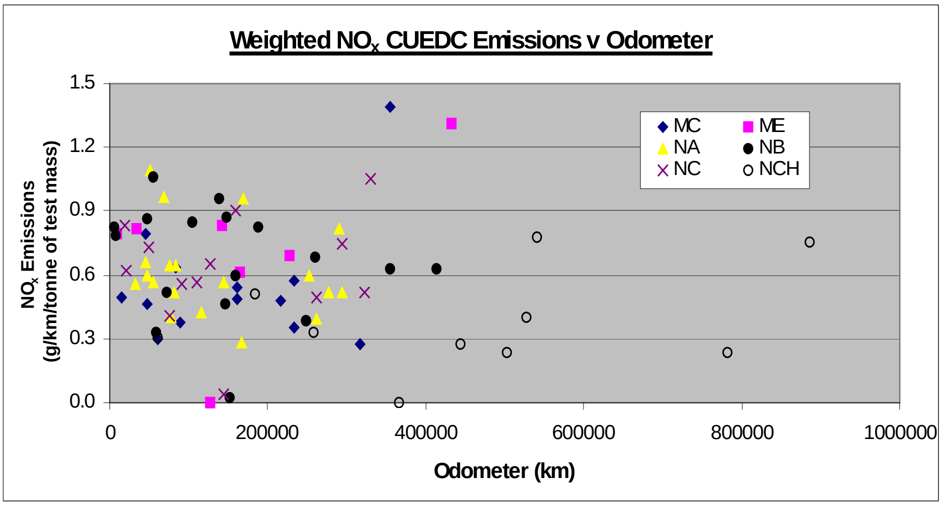


Figure 4-7: CUEDC NOx Emissions v Odometer – by ADR category

The large scatter in the data and the weak correlation suggest that factors other than distance accumulation have a much greater influence on NOx levels.

4.2 PARTICULATE MASS EMISSIONS

4.2.1 Effect of Year of Manufacture and Vehicle Mass

The picture for particulate matter is very different to that seen for NOx.

Figure 4-8 and Figure 4-9 shows the emission data for particulate mass measured by the reference filter method.

There is a high degree of scatter in the data but generally the newer vehicles tend to be lower emitters than the older pre ADR70 vehicles. However, within all ages there are vehicles much higher than the average within the group as illustrated in Figure 4-47 where the year of manufacture for vehicles is plotted.

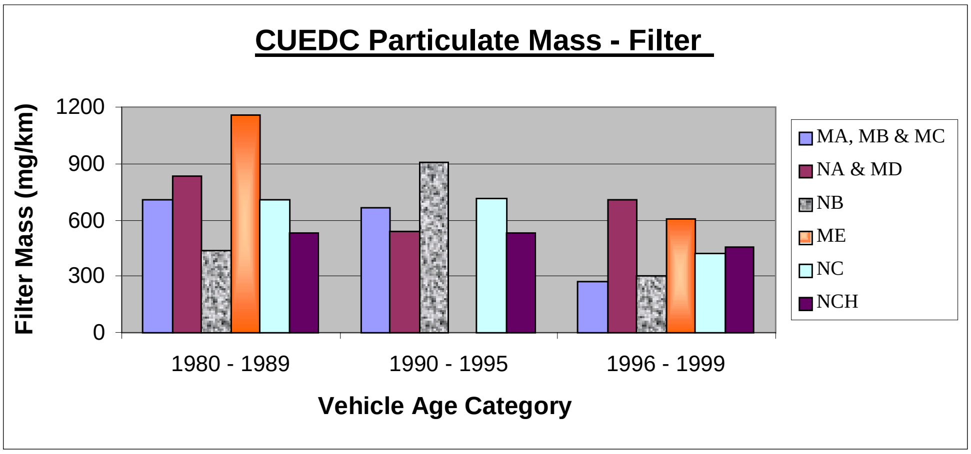


Figure 4-8: CUEDC Particulate emissions by age category

Figure 4-9 below illustrates the lowering trend in emissions with newer vehicles but also highlights that high emitting vehicles occur across all ages.

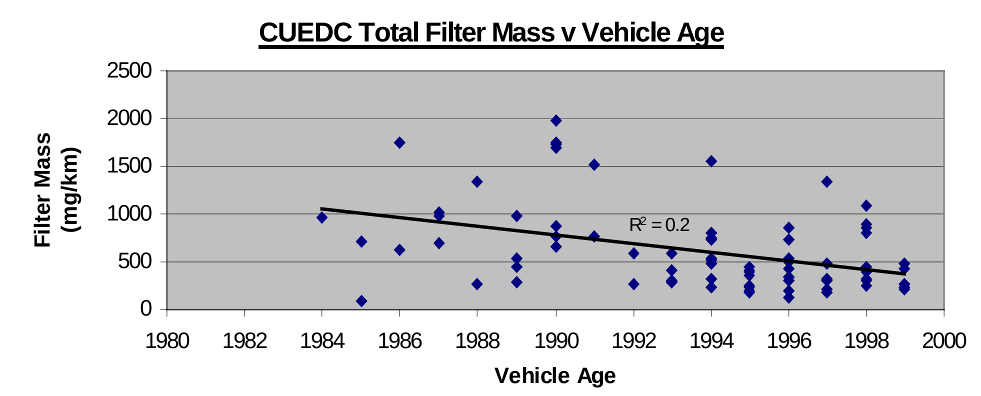


Figure 4-9 Particulate emissions by vehicle age

Unlike the NOx test results, particulate emissions do not appear to correlate well with vehicle mass. Indeed, the gram/km particulate emissions from many of the 4-wheel drive and light commercial vehicles exceeded the levels recorded for large trucks weighing ten times as much. This can be attributed to a number of factors.

Most 4WDs and many light commercial vehicles are owner-operated, and maintenance of emission-related features may not be a priority. Overseas research has concluded that failure to maintain injectors and pumps accounts for the majority of all particulate emission defects in diesel vehicles. On the other hand, reliability and fuel economy is all-important to the operators of heavy truck fleets, so maintenance of fuel system components is likely to be more regular and thorough.

Also, until the phased implementation of ADR70/00 in 1995-97, there were no regulatory controls over diesel particulates - only visible smoke. Accordingly, one might expect to see a significant reduction in particulate emissions in the newest (1996-99) vehicle groups. While such a trend is apparent for the 4WDs (the MC category), it is of some concern that emission levels from the light commercials (NA category) appear to be rising. This may be attributed to the fact that these vehicles were excluded from having to comply with ADR70.

Figure 4-10 shows the data plotted against vehicle Test Mass.

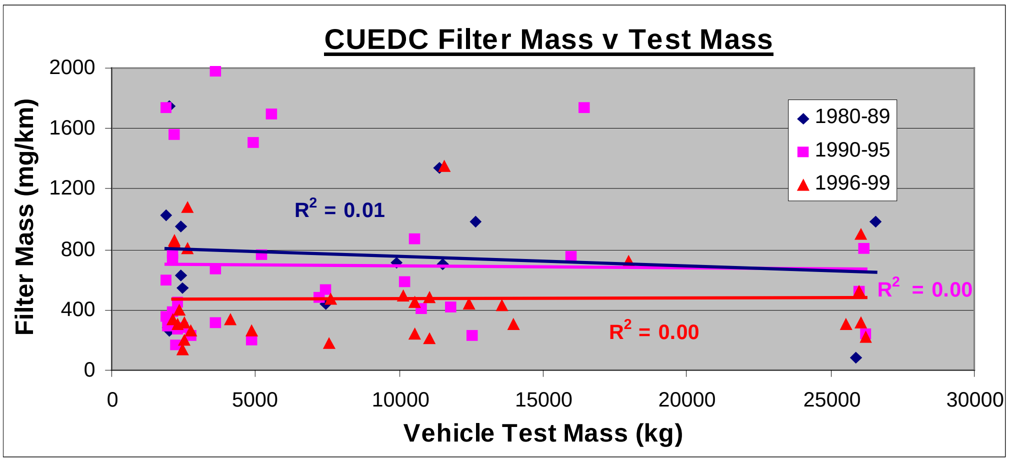


Figure 4-10: CUEDC Particulate emissions vs vehicle test mass

This chart shows there is little if any relationship between particulate mass and vehicle test mass. The data are though, very interesting as it is immediately apparent that a small number of very high polluting vehicles are exercising a great deal of 'leverage' on the average emission levels. This is further illustrated in the boxplot below where it can be seen that there are many vehicles outside the fleet average.

If these 20% or so high emitters were to be rectified so they had emission levels comparable to the average of the other 80% of vehicles in the group, overall particulate emission levels for some age groups could be reduced by up to 40%.

Also, given that many of these high emitters are at the lighter end of the spectrum, it appears that the trend lines would also then show particulate emissions increasing with vehicle mass, though still a long way from an a direct, linear emission / mass ratio.

4.2.2 Effect of Road Flow Conditions

4.2.2.1 Variation of data over the CUEDCs

As shown by Figure 4-11 below the data set is very scattered with many outliers above the 25% upper quartile bar (highlighted by the highway road mode) compared to only a few for NOx. This is similar for smoke opacity as illustrated in Figure 4-43.

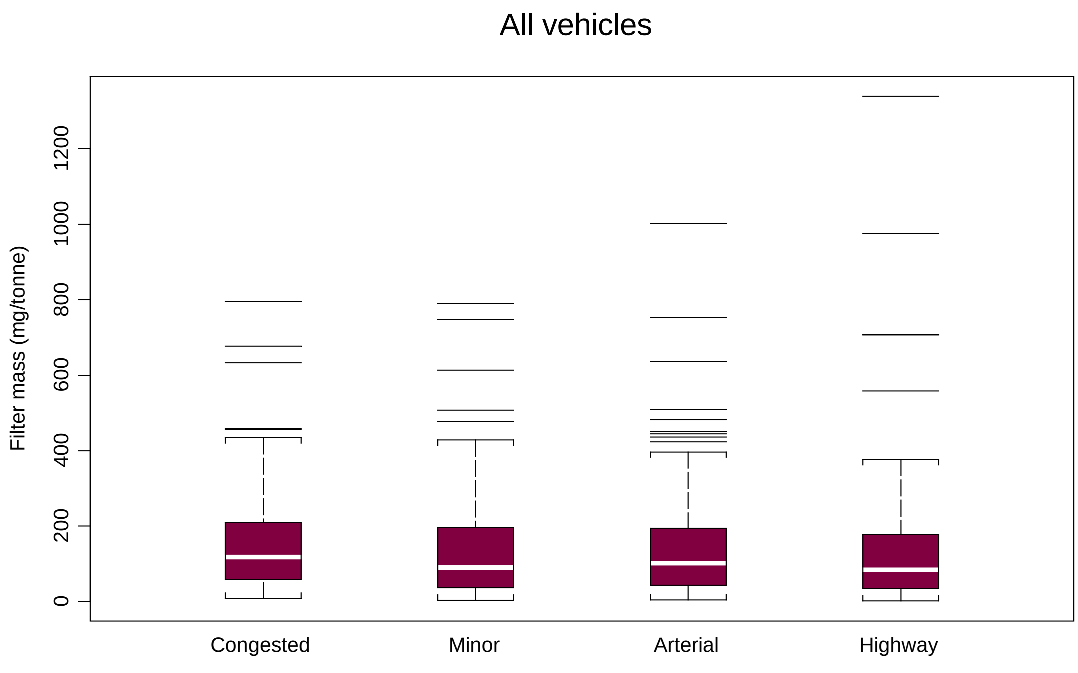


Figure 4-11: Particulate emissions by road flow segment for all vehicles on a mass normalised basis

The influence of vehicle operating mode (idle, acceleration, cruise and deceleration) has been evaluated for all the data. The overall response time of the Tapered Element Oscillating Microbalance (TEOM), nominally of the order of 2 seconds, was found to be ~12 seconds for the system configuration, which rendered transient analysis of particle information difficult. Use of the TEOM would require deconvolving the response characteristics from the measurements, a process that can be a lengthy undertaking. However, the Laser Light

Scattering Photometer (LLSP) did have a quick enough response and as very good correlations with the TEOM have been demonstrated (see Section 6) the LLSP data have been used for transient analysis.

The percentage contribution of particulate mass emissions produced during each road mode is presented in Table 4-1, and illustrated by six graphs representing each vehicle category.

Table 4-1: LLSP Particulate emissions (%) Contribution

Vehicle Class	Idle	Cruise	Accel > 1 m/s2	Decel > 1 m/s2
Congested				
MC (11)	6.7	72.9	16.9	3.4
ME (7)	7.5	70.3	16.6	5.5
NA (13)	7.7	64.9	21.4	5.9
NB (13)	1.6	84.5	9.6	4.3
NC (11)	6.8	85.3	3.7	4.1
NCH (8)	12.6	76.2	6.5	4.7
Minor				
MC (11)	0.3	66.7	28.2	4.8
ME (7)	0.1	83.6	12.0	4.3
NA (13)	0.4	75.5	22.5	1.6
NB (13)	0.2	80.5	14.0	5.3
NC (11)	1.2	89.1	6.6	3.1
NCH (8)	4.1	78.7	9.4	7.8
Arterial				
MC (11)	0.9	72.4	24.5	2.3
ME (7)	3.5	74.5	18.4	3.6
NA (13)	0.6	72.1	24.0	3.3
NB (13)	1.5	78.4	10.4	2.6
NC (11)	2.4	83.6	9.8	4.2
NCH (8)	3.0	80.7	10.9	5.5
Highway				
MC (11)	0.3	80.8	18.1	0.8
ME (7)	0.5	89.9	7.6	2.1
NA (13)	0.1	96.6	1.9	1.4
NB (13)	0.0	98.2	1.2	0.6
NC (11)	0.4	95.9	2.6	1.0
NCH (8)	0.3	94.4	3.9	1.4

In order to interpret the data the speed time profiles generated during each of the four road flow modes of the CUEDCs have been broken into periods of idle, cruise, and two rates of deceleration and acceleration > $\pm$ 0.5 m / s^2 and $\pm$ 1.0 m / s^2.

The following Figures provide a clear picture of where particulate mass emissions are generated during the operation of a vehicle during each of the road flow modes. Note: The > $\pm$ 1.0 m / s^2 rate has been plotted.

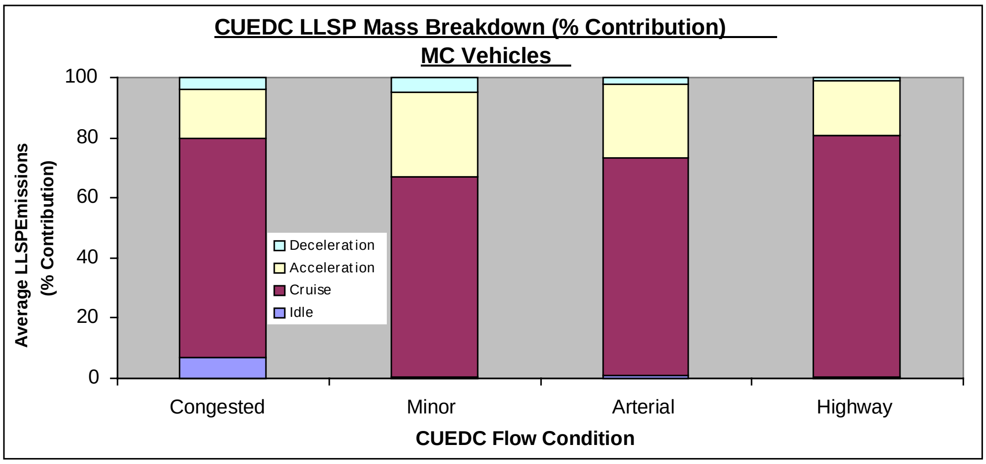


Figure 4-12: Particulate emissions across road flow segments – MC vehicles

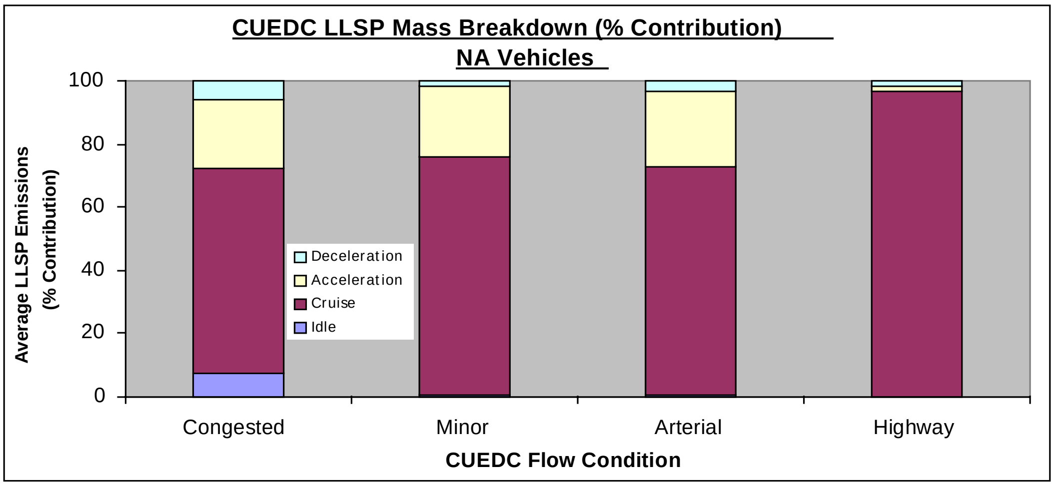


Figure 4-13: Particulate emissions across road flow segments – NA vehicles

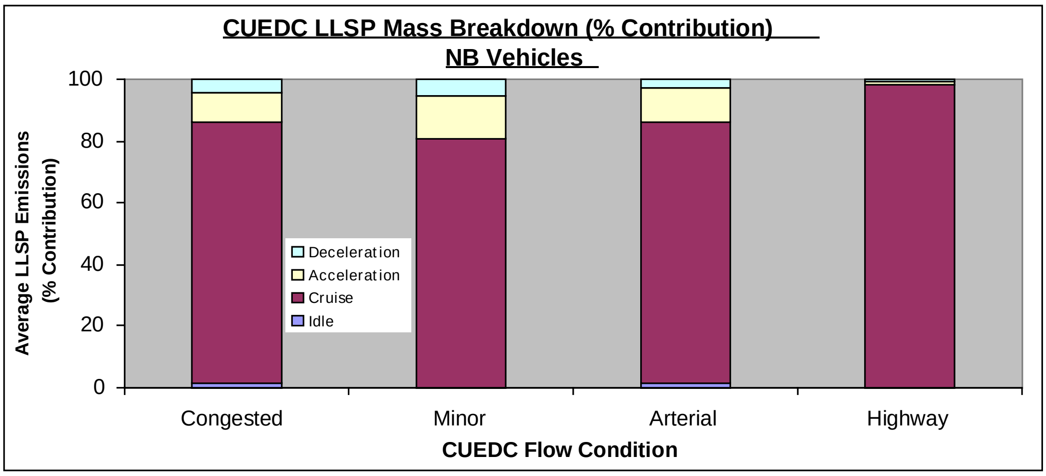


Figure 4-14: Particulate emissions across road flow segments – NB vehicles

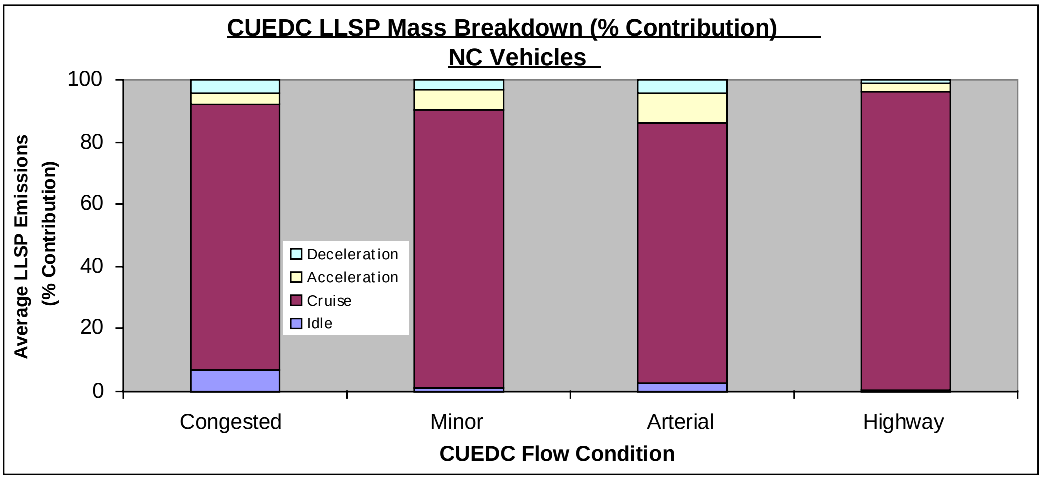


Figure 4-15: Particulate emissions across road flow segments – NC vehicles

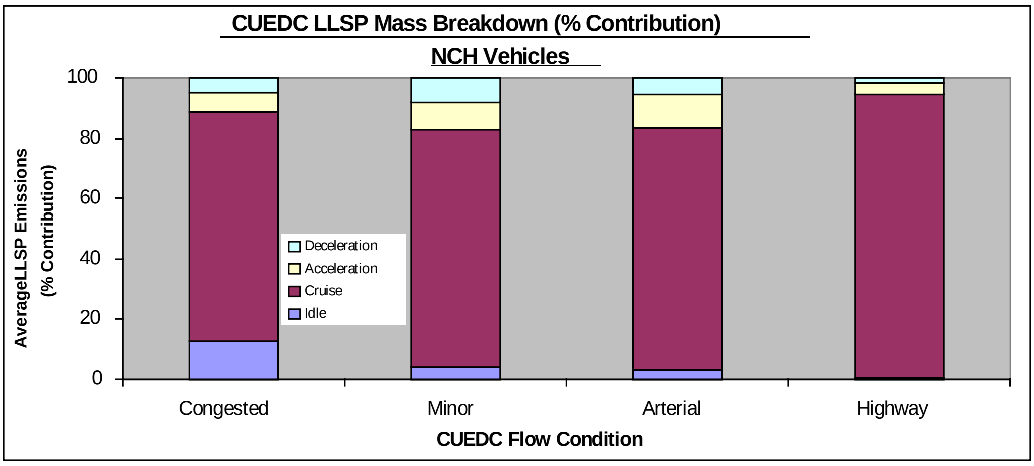


Figure 4-16: Particulate emissions across road flow segments – NCH vehicles

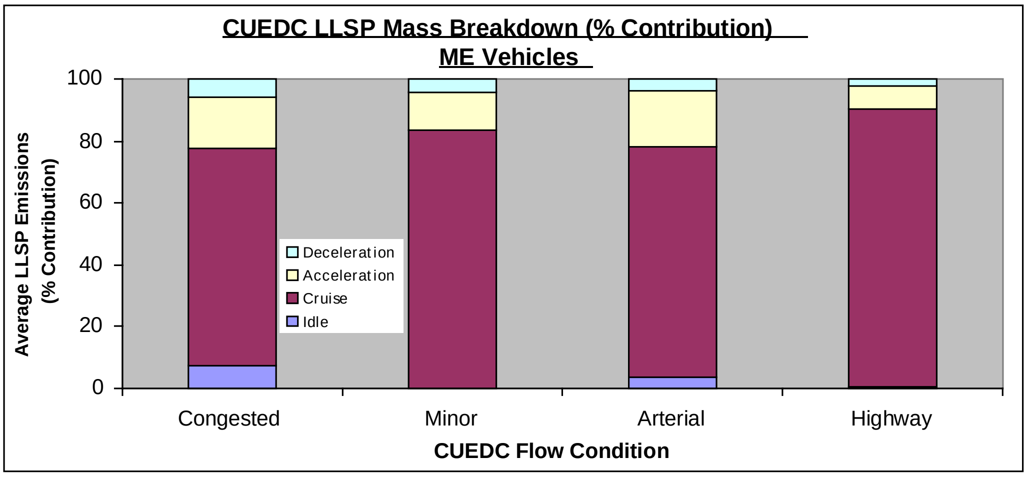


Figure 4-17: Particulate emissions across road flow segments – ME vehicles

For the acceleration and deceleration cut off at 1ms^{-2} the cruise mode dominates the Figures above and is by far the largest contributor to the total emissions. This reflects the larger amount of time defined as cruise in the drive cycle. Acceleration is the next largest contributing operating condition. Idle operating contributions vary widely between each vehicle category but more prevalent during the congested modes. Deceleration is more consistent across all modes and vehicle categories however relatively insignificant compared to the cruise mode.

For the cut off at 0.5 ms^{-2} less time is defined as cruise mode and this is reflected in the relative contribution of the cruise mode and acceleration to the total. This is illustrated in Appendix 4.

While the % contribution provides an overall assessment of where the majority of particulate mass is emitted during the CUEDC, the rates (grams/sec/tonne) at which the emissions are generated within each of the operating conditions (as well as their totals) have also been tabulated in Table 4-2 and graphed in Figure 4-18 to Figure 4-23. These have been normalised for the test mass of vehicles within each category.

The data in Table 4-2 show some broad overall features. The idle emission rates are generally the lowest, as expected. In order of increasing emission rates the acceleration modes are the highest followed by the cruise mode and the deceleration mode. While there are individual differences for the two acceleration cut offs the overall trends are similar.

Table 4-2*: LLSP Particulate emissions (mg/sec/tonne of test mass*)

Vehicle Class	Idle	Cruise	Accel > 1 m/s2	Decel > 1 m/s2	Total
Congested					
MC (11)	0.034	0.523	0.761	0.233	1.550
ME (7)	0.044	0.201	0.349	0.162	0.756
NA (13)	0.066	0.727	1.396	0.602	2.791
NB (13)	0.038	0.182	0.258	0.198	0.676
NC (11)	0.018	0.106	0.078	0.329	0.530
NCH (8)	0.007	0.027	0.053	0.030	0.116
Minor					
MC (11)	0.063	1.328	2.745	0.665	4.802
ME (7)	0.048	0.380	0.351	0.134	0.912
NA (13)	0.066	1.755	3.166	0.264	5.251
NB (13)	0.054	0.783	0.923	0.334	2.093
NC (11)	0.041	0.240	0.312	0.104	0.698
NCH (8)	0.036	0.082	0.082	0.086	0.285
Arterial					
MC (11)	0.036	1.486	3.330	0.372	5.223
ME (7)	0.040	0.493	0.541	0.080	1.154
NA (13)	0.043	2.036	3.565	0.617	6.261
NB (13)	0.029	0.840	1.044	0.153	2.066
NC (11)	0.024	0.263	0.333	0.112	0.733
NCH (8)	0.016	0.086	0.098	0.068	0.268
Highway					
MC (11)	0.051	1.850	4.642	0.258	6.802
ME (7)	0.042	0.483	0.538	0.139	1.201
NA (13)	0.092	2.786	2.315	0.895	6.089
NB (13)	0.037	1.414	0.961	0.331	2.742
NC (11)	0.018	0.374	0.319	0.102	0.813
NCH (8)	0.007	0.207	0.161	0.094	0.469

It is clear that the acceleration and cruise modes dominate the emission rates in all categories. However, in the large vehicle classes NC and NCH the deceleration rates become more dominant. This in part may be due to the relatively small flywheel used to replicate vehicle inertia on deceleration causing the driver of the test vehicle to occasionally depress the fuel pedal to maintain vehicle speed consistent with the drive trace speed.

The higher acceleration rates compared to cruise are not enough to significantly effect the % contributions discussed earlier, where the cruise mode dominates. The same can be said for the deceleration rates, where although higher than anticipated, the % contribution is low and overshadowed by the cruise and acceleration modes.

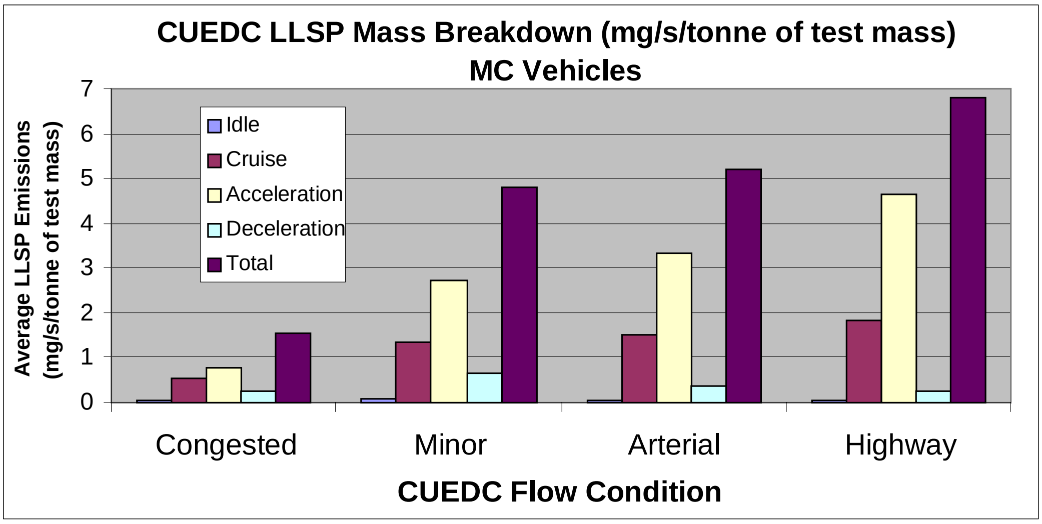


Figure 4-18: Particulate emissions across road flow segments – MC vehicles

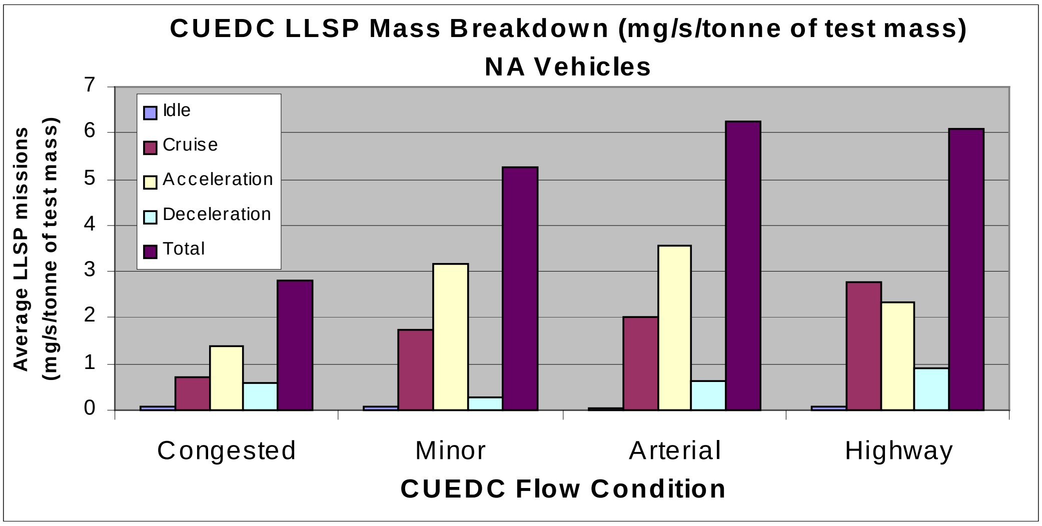


Figure 4-19: Particulate emissions across road flow segments – NA vehicles

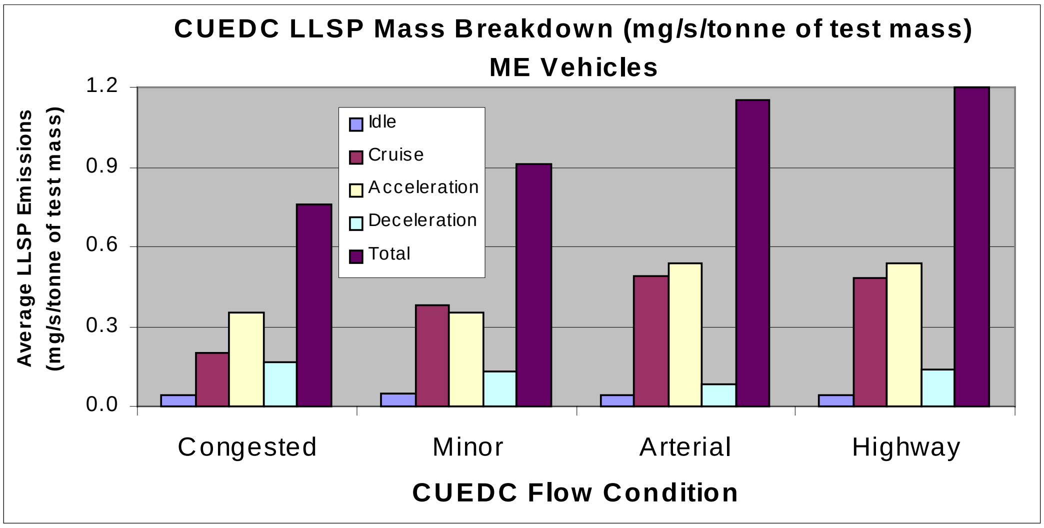


Figure 4-20: Particulate emissions across road flow segments – ME vehicles

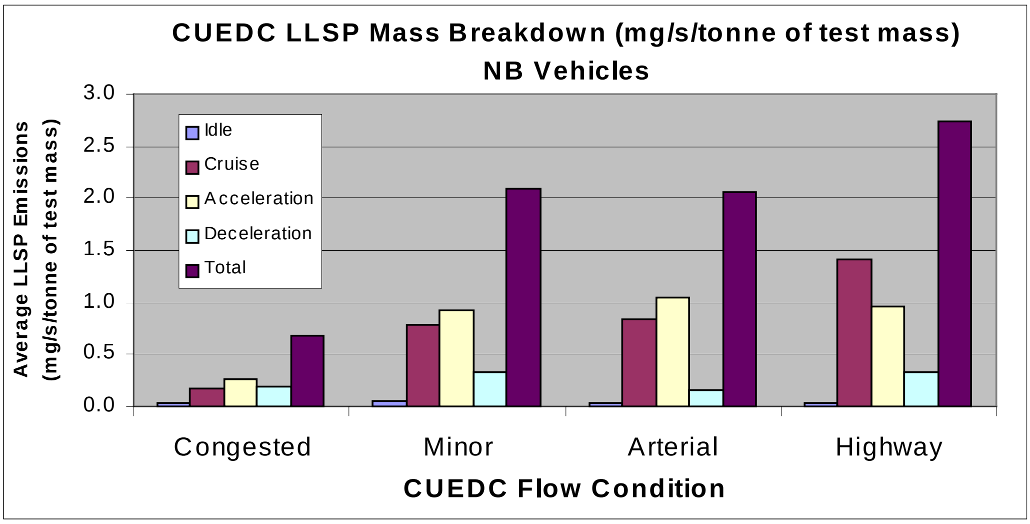


Figure 4-21: Particulate emissions across road flow segments – NB vehicles

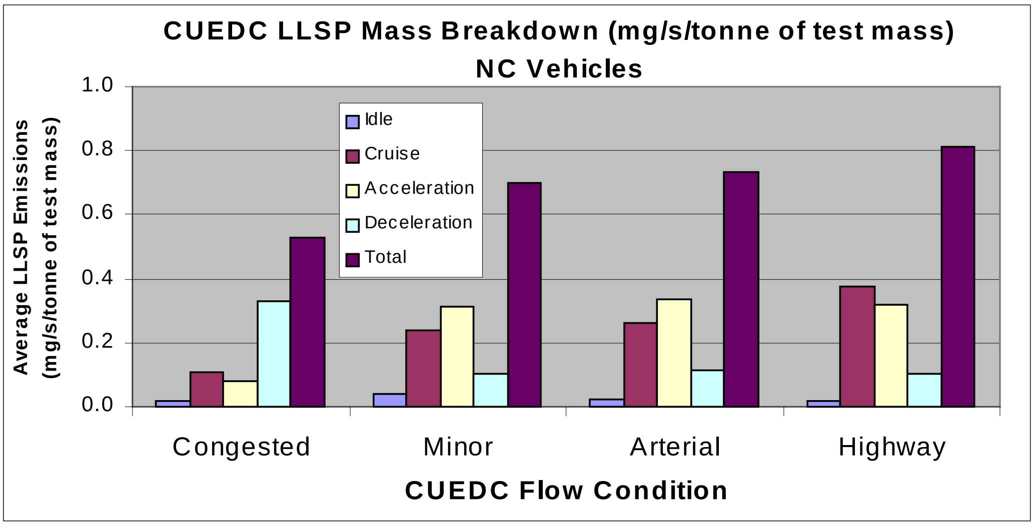


Figure 4-22: Particulate emissions across road flow segments – NC vehicles

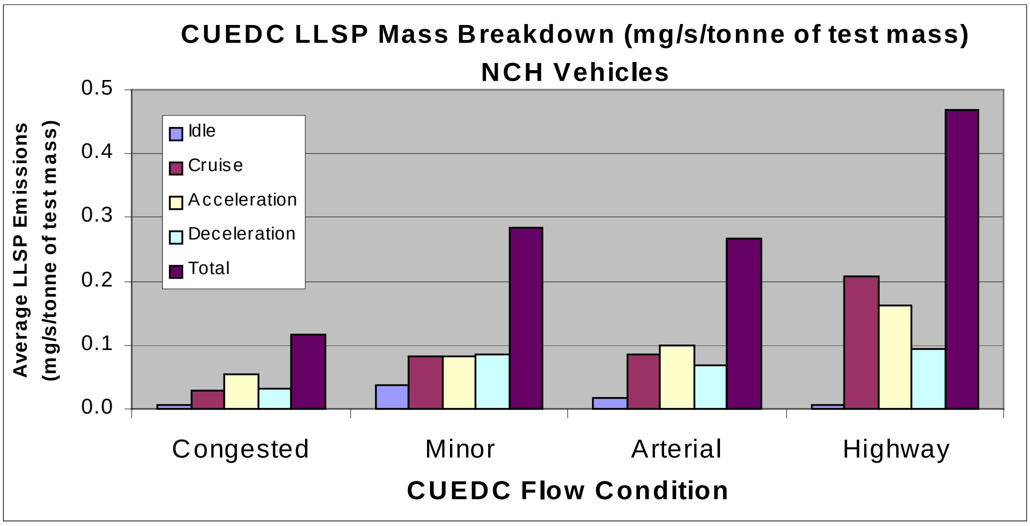


Figure 4-23: Particulate emissions across road flow segments – NCH vehicles

The variation in particulate emission levels across segments is also of interest, with the trend reversing between light and heavy vehicles. In the heaviest group of vehicles (NC and NCH), particulate emissions are considerably higher in the congested flow than in other modes. Moving to the medium (NB) category, there is little difference in particulate emissions between flow mode segments, while for some of the lightest vehicles, the trend is actually reversed, with the lowest particulate emissions in the congested segment.

4.2.2.2 Effect of Emission Standards

When looking at the main differences between Pre and Post ADR70 for particulate emissions, the Post ADR 70 buses (ME vehicle category) shows a tightening of the data set. This aligns somewhat with the introduction of tighter controls and more advanced engine technology used on these vehicles. However, it should also be noted that the buses make up a very small dataset.

The data sets are more scattered for the other vehicle classes and age groups. The majority of the scatter is towards the high end or the upper quartile. These higher values could possibly be vehicles in need of a tune or repair or just high values for the particular vehicle type and engine size.

The low variance in the NB category (>12 < 25 tonne rigid trucks) Post ADR70 results is striking when compared to the Pre ADR70 data sets. Conversely, the NA category vehicles show a higher variance in the Post ADR70 data.

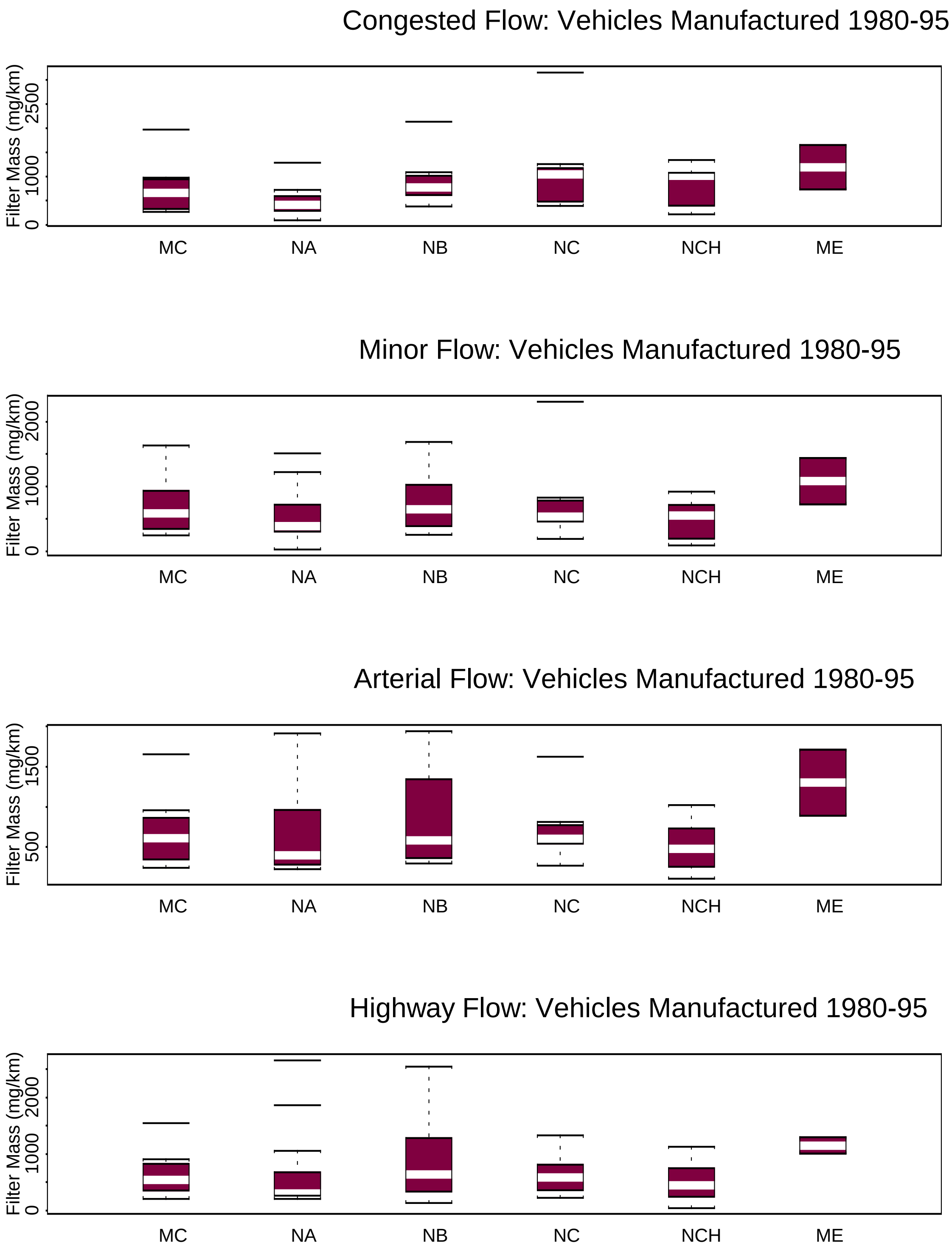


**Figure 4-24: Particulate emissions by CUEDC road flow mode –
Pre ADR70 (1980-95)**

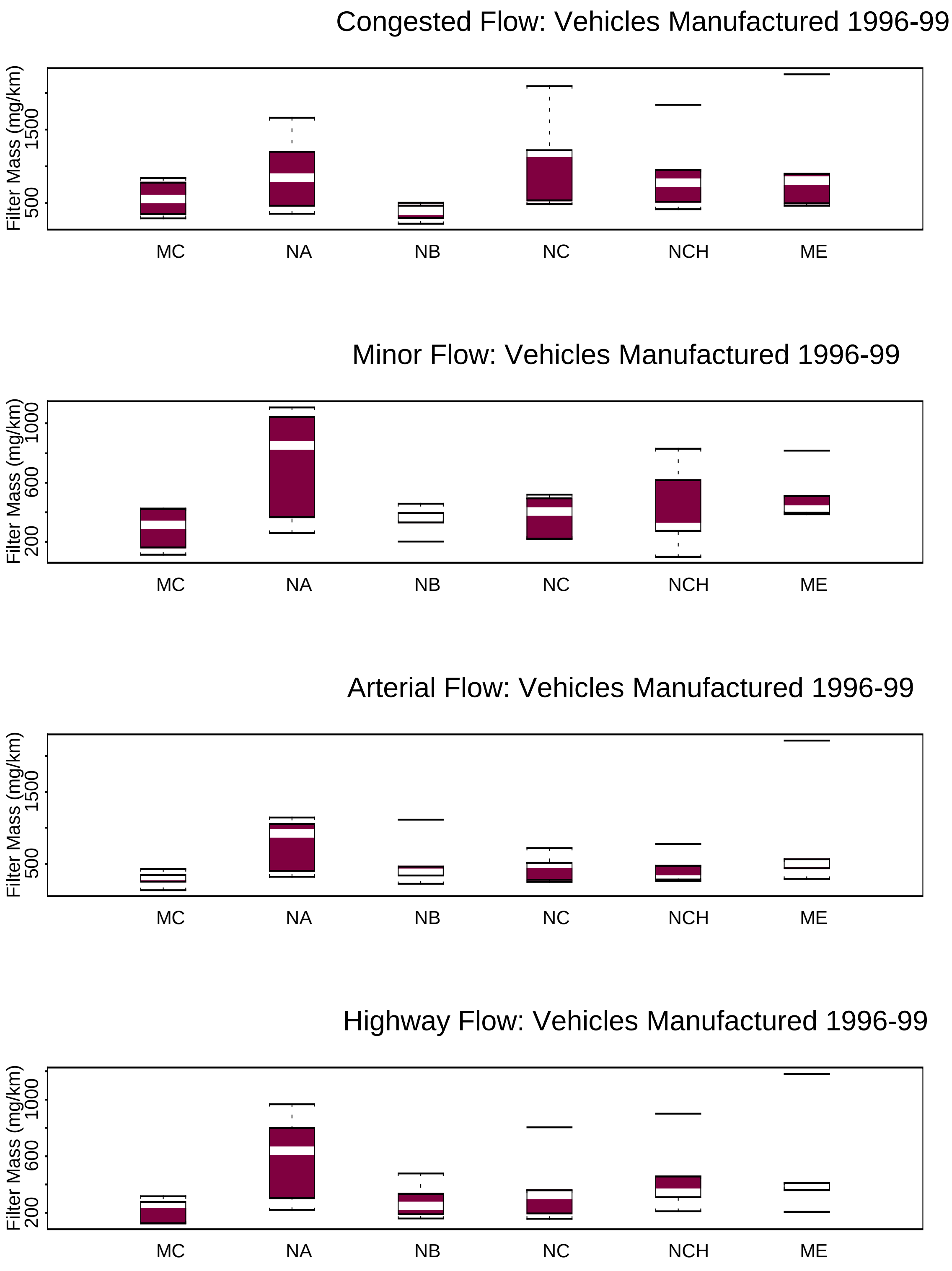


Figure 4-25: Particulate emissions by CUEDC road flow mode – Post ADR70 (1996-99)

4.2.3 Effect of Accumulated Distance Travelled

As indicated by Figure 4-26 below the very high particulate emissions levels from a minority of vehicles, particularly in the light-duty (MA and NA) categories and to a lesser extent NB, is most evident. The scatter in the data show that there is little relationship between distance travelled and particulate emissions. This suggests that irregular maintenance and state of repair of vehicles is more likely the cause of excessive emissions than distance travelled.

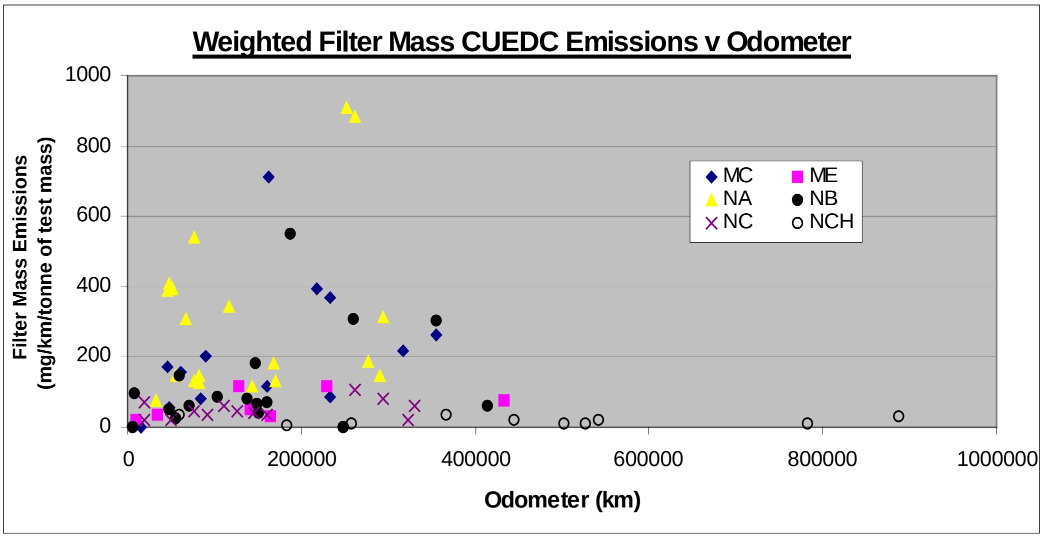


Figure 4-26: CUEDC Particulate emissions vs odometer – by ADR category

4.2.4 Particle Emissions by Size Fraction

4.2.4.1 Scanning Mobility Particle Size Analyser Results

Here, results are presented for the mean initial particle size. This ranges from a low of ~ 30 nm to a high of ~ 250 nm, showing that significant variability is exhibited by the particles initially formed, after some agglomeration has proceeded. The results for each vehicle tested, and the average results for each age group within the six ADR categories, are provided in Table 4-3 and plotted in Figure 4-28 and Figure 4-31.

What is evident is that the larger NC and NCH vehicles generate smaller particles than the other vehicle categories, but it is difficult to determine whether this result is statistically significant, or, as discussed above, due to other factors which affect particle size apart from the diesel design parameters.

Plots of particle size vs odometer and vehicle age are also provided in Figure 4-29 and Figure 4-30, but no relationship is evident. Overall, the average particle size is ~100 nanometers diameter.

Little correlation was also observed between initial particle size and the mass of the total particulate material determined gravimetrically by weighing the filters collected during the D550 test (see Figure 4-31). However, Figure 4-31 also shows that high emitting vehicles tend to have larger initial mean particle diameters; this could be due to agglomeration in the vehicle exhaust system even before sampling occurred.

In all cases particle size increased with time after sampling. Figure 4-32 - Figure 4-34 show examples for a range of initial particle size distributions, ranging from less than ~ 50 nm (Figure 4-32), ~ 100 nm (Figure 4-33) and 150 nm (Figure 4-34). The increase in particle diameter, and decrease in particle number (counts) with time is probably due to agglomeration, and underscores the potential importance of the size distribution of the ambient atmospheric aerosol in determining the ultimate size of particles emitted from diesel vehicles.

Table 4-3: ***SMPS averages (nm)***

	1980-89	1990-95	1996-99
MA	124	162	170
ME	159	-	76
NA	171	132	124
NB	146	138	117
NC	72	63	94
NCH	51	42	76

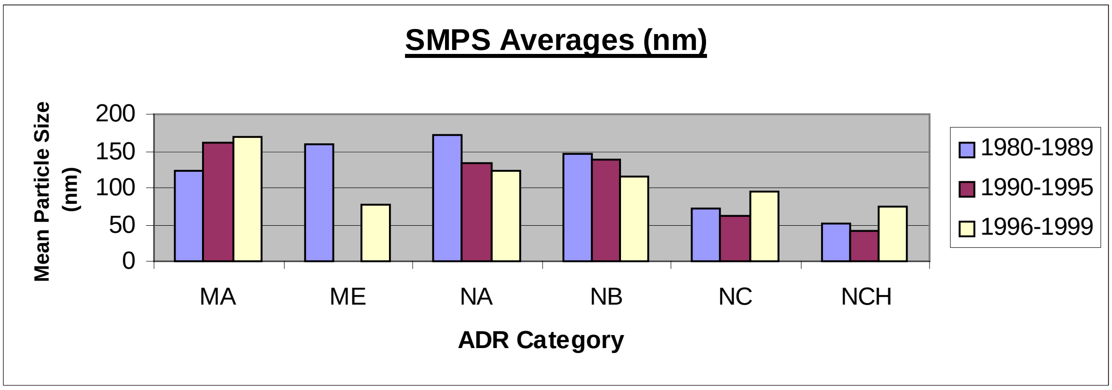
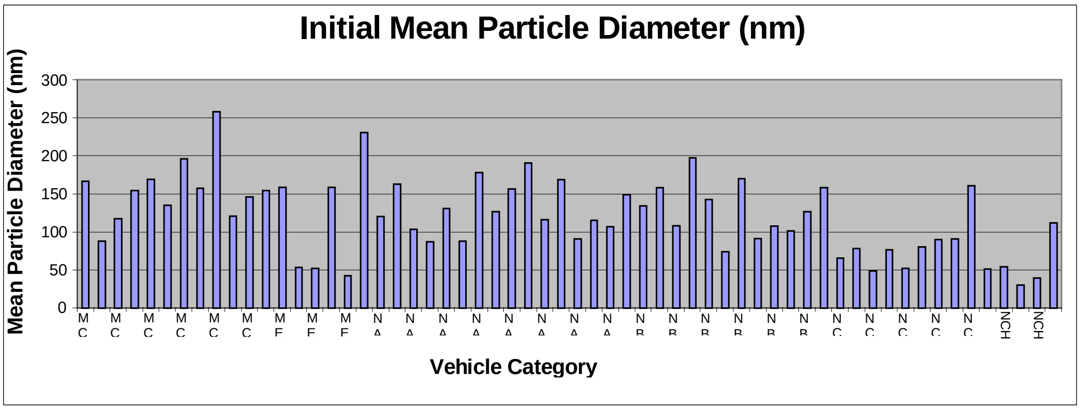


Figure 4-27: SMPS mean particle size by ADR/Year category



*Data is sorted in age category and vehicle age from left to right

Figure 4-28: SMPS initial particle size for all vehicles

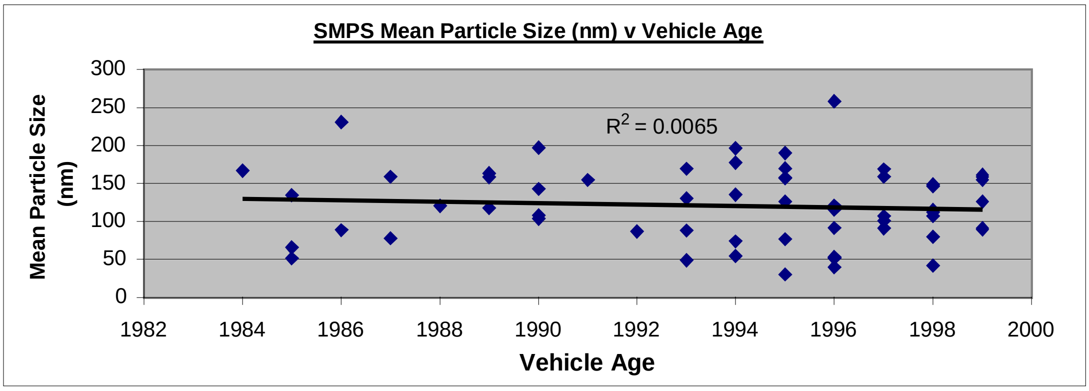


Figure 4-29: SMPS mean particle size vs vehicle age

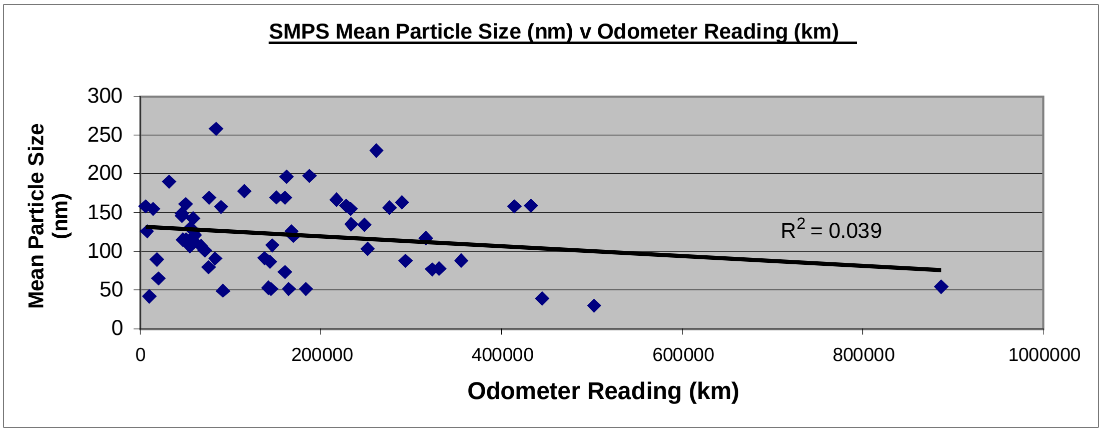


Figure 4-30: SMPS mean particle size vs odometer

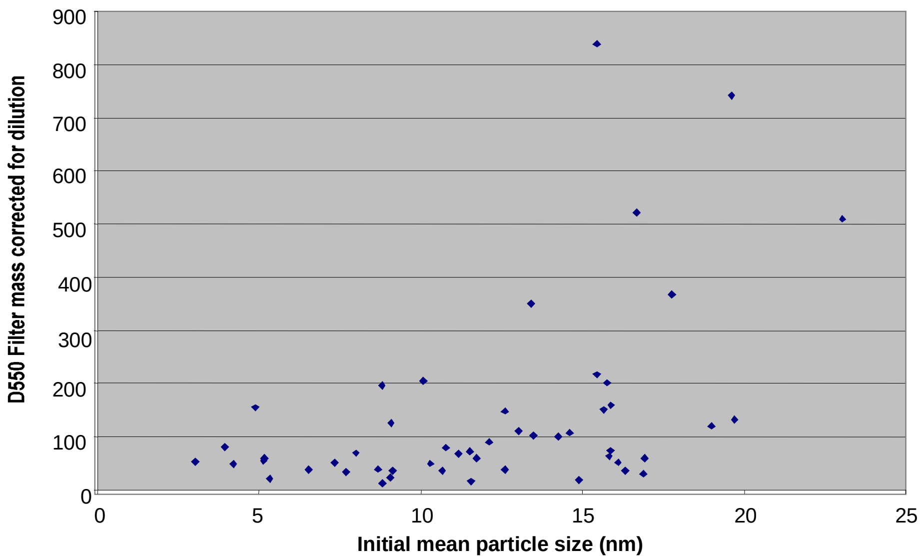


Figure 4-31: D550 Particulate emissions vs initial mean particle size

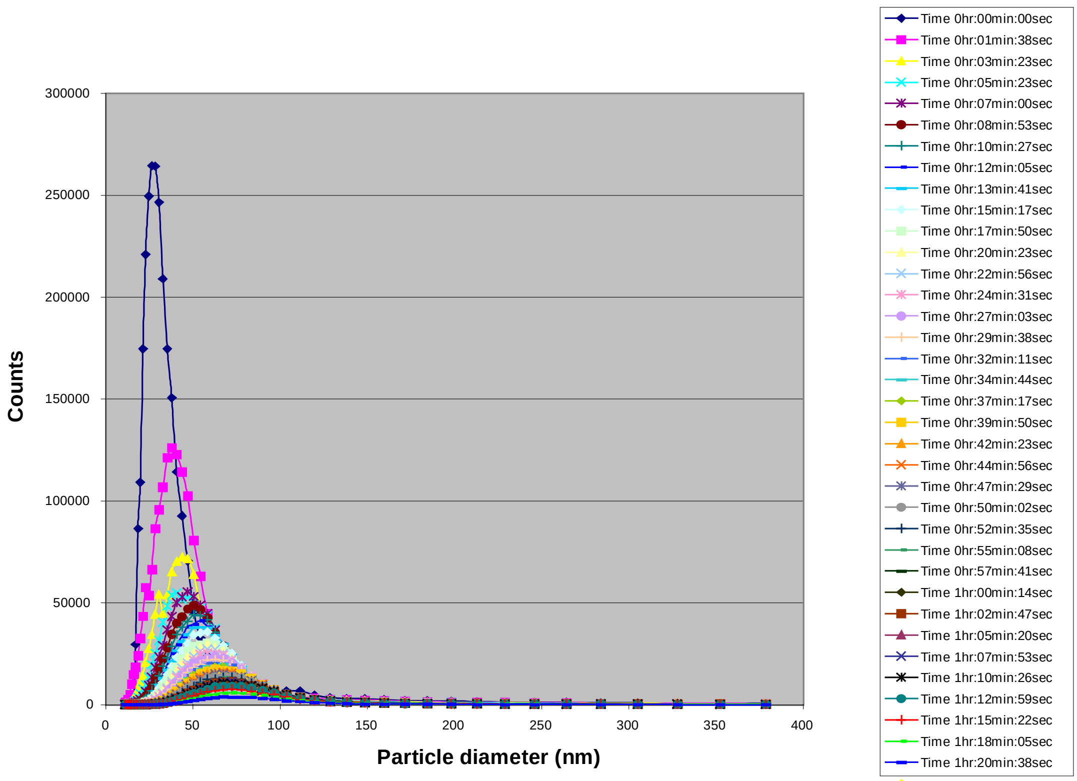


Figure 4-32: SMPS growth in particle size with time after sampling 1995 NCH category vehicle (38t)

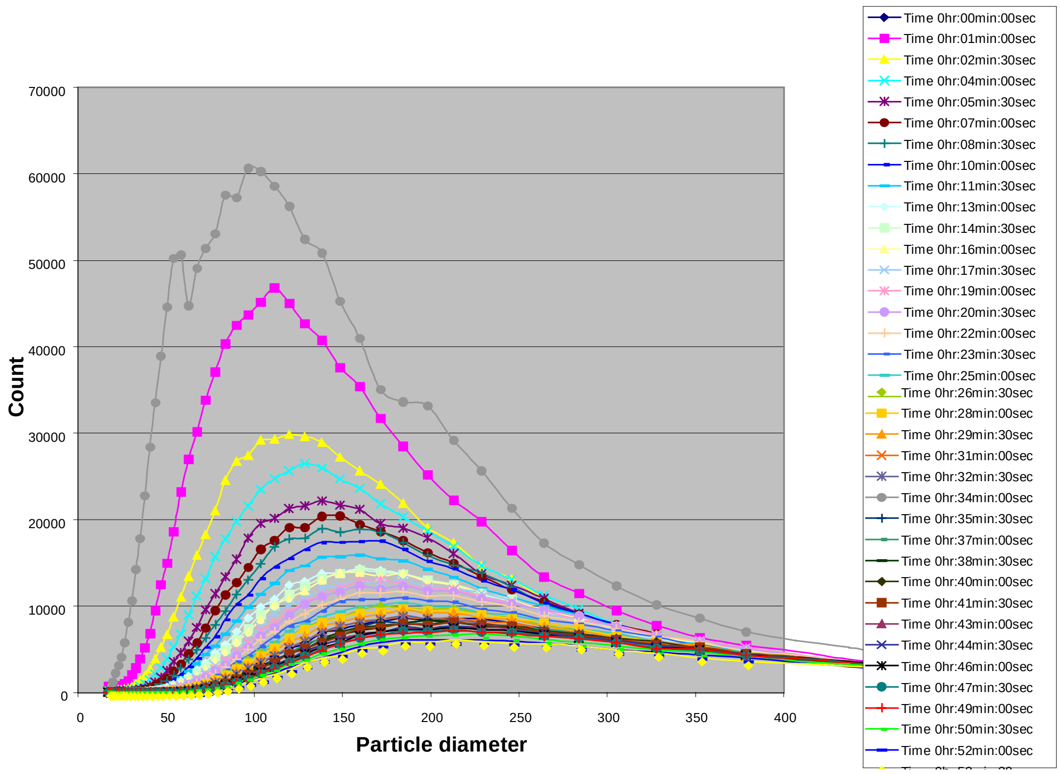


Figure 4-33: SMPS growth in particle size with time after sampling - 1995 NA category vehicle (2.7t)

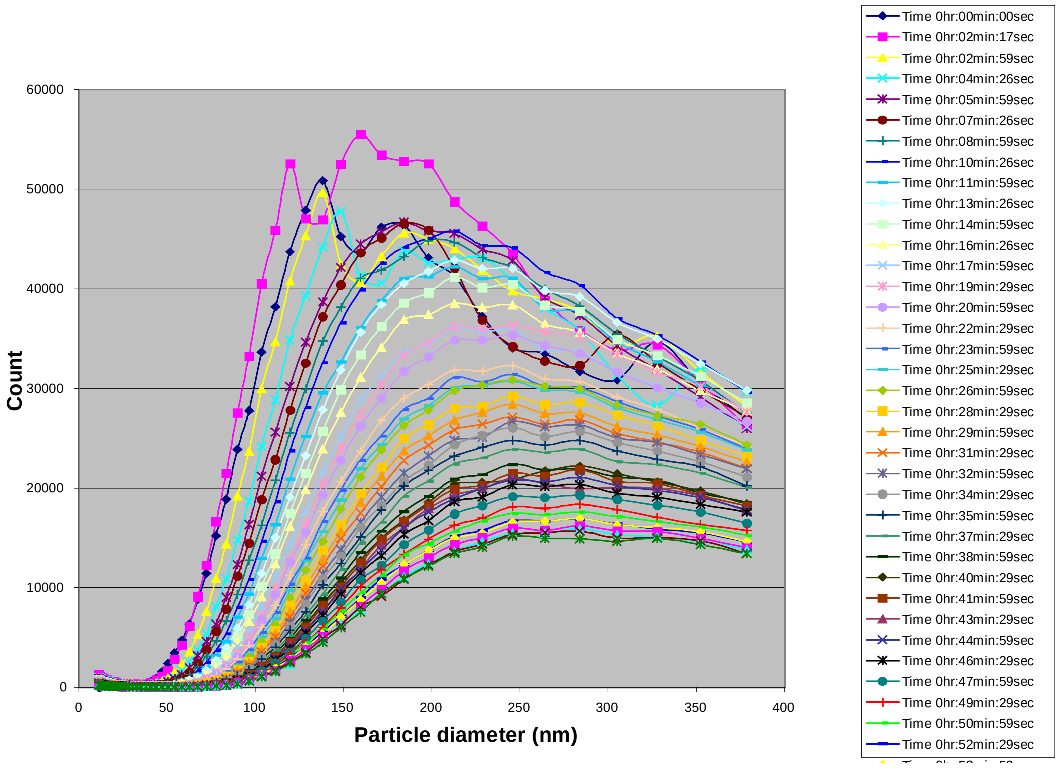


Figure 4-34: SMPS growth in particle size with time after sampling – 1996 NA category vehicle (2.7t)

4.2.4.2 Aerodynamic Particle Size Results

Figure 4-35, Figure 4-36 and Figure 4-37, show particulate size results from the particulate size measuring instrument -APS.

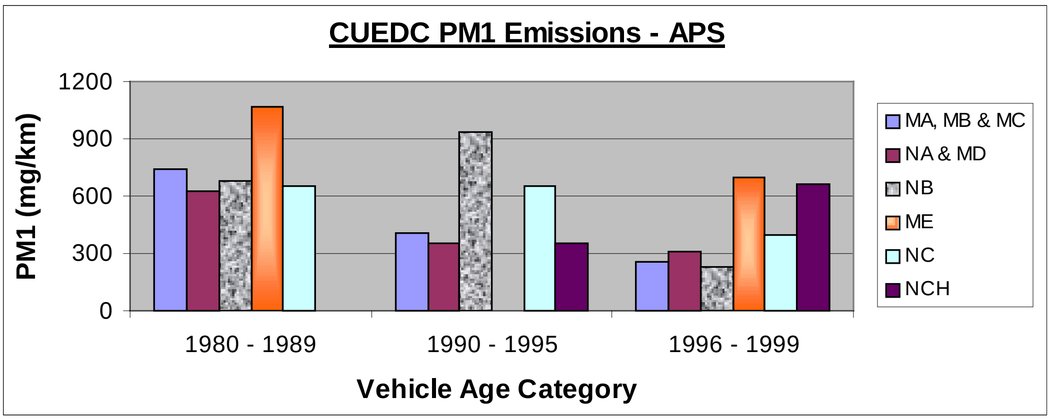


Figure 4-35: CUEDC PM_1 emissions

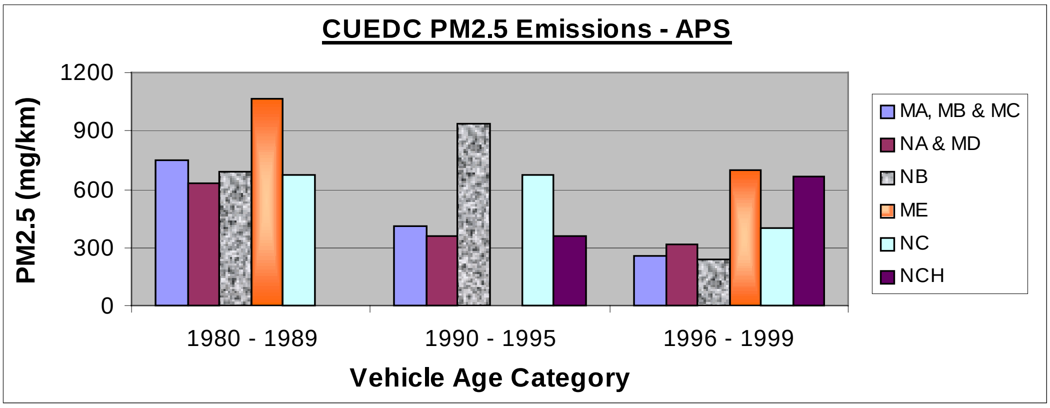


Figure 4-36: CUEDC $PM_{2.5}$ emissions

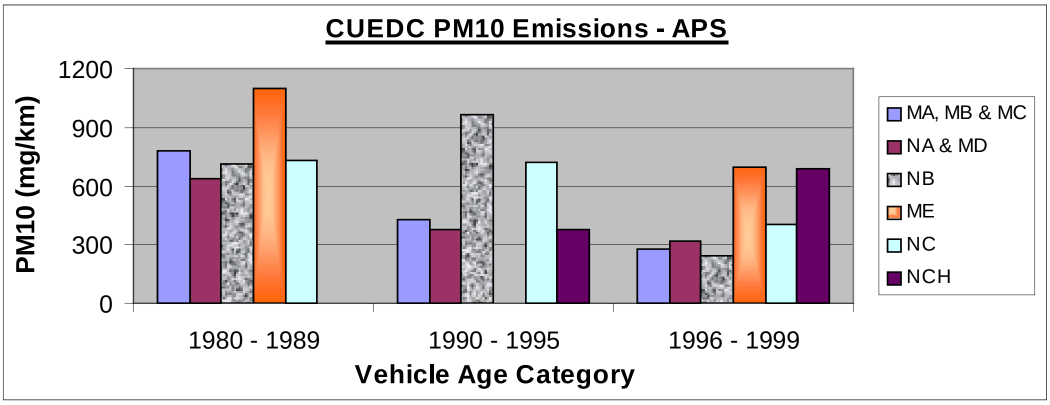


Figure 4-37: CUEDC PM_{10} emissions

The most striking aspect of this series of bar charts is that they appear, at first glance, to be identical. In fact, they are all slightly different, with the PM_1 averages slightly lower than the $PM_{2.5}$, which are in turn lower than the PM_{10}.

The differences are, however, quite small and underline the fact that most diesel exhaust particulate matter is in the ultra-fine range, below 1 micron in diameter. This is consistent with the California Air Resources Board report that while 98% of diesel particulate by mass is PM_{10}, 94% is $PM_{2.5}$ and 92% is PM_1 (CARB 1998).

4.2.5 Particulate Emission as a Function of Engine Power Output

While acceleration has been used in the analysis of the data above, it can be shown that instantaneous vehicle power is a better parameter against which to correlate particulate mass emissions. This is illustrated for the current data in Figure 4-38 below.

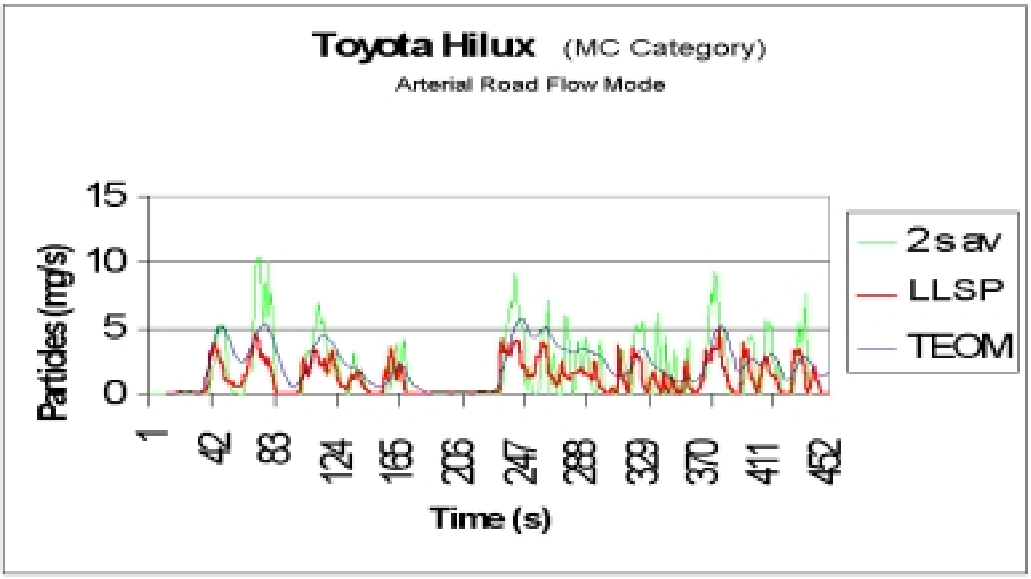


Figure 4-38: Particle emission rate over arterial road flow mode

The data in Figure 4-38 show the instrumental results for the TEOM and the LLSP for a vehicle undergoing the Arterial road flow mode of the CUEDC. Also shown is a comparison with a modeled particle emission rate based on the instantaneous power exerted by the vehicle. The algorithm used for modeling the emission, P, has the form P=a+bZ, where Z is the total instantaneous power expended by the vehicle and was obtained from the dynamometer data average over 2 seconds. It can be seen that the shape of the time series of the LLSP data is very similar to that of the model. This shows that the particle emissions are power related. In addition the data also illustrate that the LLSP follows the power curve much more closely than the TEOM is able to do, because of the faster response time as discussed above.

In the light of the above result we have also carried out a preliminary analysis of the LLSP data in terms of the power of the vehicle. Table 4-4 show the data analysed as a function of the maximum power expended during the CUEDC.

Table 4-4: Particulate Mass Emission Rates (mg/s) as a function of Maximum Test Power (P_{max})

Vehicle Class	-0.4 P_{max}	-0.2 P_{max}	-0.1 P_{max}	0.0 P_{max}	0.1 P_{max}	0.2 P_{max}	0.4 P_{max}	0.6 P_{max}	0.8 P_{max}
Congested									
MC (11)	1.57	0.81	0.22	0.93	1.47	2.10	2.12	5.86	2.99
ME (7)	1.32	1.77	0.71	1.10	3.61	3.76	5.76	8.71	13.92
NA (13)	1.48	1.43	0.56	0.78	1.92	2.47	3.03	3.29	9.00
NB (12)	1.74	0.75	0.44	0.72	1.32	1.87	2.23	3.09	3.78
NC (10)	1.47	1.60	0.68	1.03	1.79	3.01	2.38	4.67	5.08
NCH (7)	1.50	3.27	0.54	0.97	1.77	1.67	2.76	3.61	2.75
Minor									
MC (11)	1.81	1.40	0.86	1.46	1.82	2.24	2.80	4.06	6.59
ME (7)	1.60	1.18	1.32	1.58	2.61	3.86	5.46	9.22	13.39
NA (13)	0.89	1.22	0.69	1.68	1.88	3.03	3.99	7.05	8.71
NB (13)	1.28	1.27	1.00	1.77	2.08	2.67	3.31	4.60	8.70
NC (10)	1.21	1.63	1.26	1.59	2.18	2.78	3.04	4.37	7.22

Vehicle Class	-0.4 P_{max}	-0.2 P_{max}	-0.1 P_{max}	0.0 P_{max}	0.1 P_{max}	0.2 P_{max}	0.4 P_{max}	0.6 P_{max}	0.8 P_{max}
NCH (7)	1.52	3.34	2.00	2.14	2.48	2.19	3.18	2.78	3.75
Arterial									
MC (11)	1.11	1.44	0.39	1.75	1.57	1.97	3.35	4.11	6.88
ME (7)	1.31	0.98	0.73	1.49	2.80	4.46	7.12	9.98	14.05
NA (13)	1.56	1.73	0.67	2.05	2.39	3.29	4.46	6.42	9.55
NB (3)	0.75	1.10	0.30	1.33	1.42	1.49	2.23	3.41	6.77
NC (10)	1.18	1.37	0.75	1.90	1.69	2.34	2.61	3.49	7.19
NCH (7)	1.57	3.28	1.06	1.28	1.54	2.11	2.13	3.05	6.47
Highway									
MC (11)	1.48	1.26	0.76	2.19	2.39	2.41	2.72	3.04	7.48
ME (7)	1.76	1.61	1.34	2.04	2.65	3.42	5.00	8.47	14.04
NA (13)	1.20	2.43	2.09	2.37	2.47	3.38	4.47	7.20	10.72
NB (13)	1.39	1.48	1.43	2.25	1.82	2.01	2.32	3.47	8.03
NC (10)	1.71	1.25	1.38	2.29	2.10	2.66	3.53	4.02	7.83
NCH (7)	2.16	2.76	2.37	2.71	3.22	3.59	3.68	3.87	9.20

Note:- P_{max} is the proportion of maximum power exerted on each test vehicle over all the road flow modes and the corresponding emission rate in that condition. The positive values (0.0 to 0.8) are during acceleration while the negatives (-0.1 to -0.4) are during deceleration.

The data in Table 4-4 show that the largest emission **rates** are generally associated with the largest power expenditure at 0.8 Pmax. In addition the vehicles in the ME (buses) and NA (Rigid Trucks <12tonne) classes contribute the largest emissions when the vehicles are under power.

The relationship between particulate emissions and vehicle power is further highlighted in Table 4-5. This shows the contribution of each power classification to the **total** emissions for each mode of the CUEDC for each vehicle class.

Table 4-5: Emission (mg) as a function of Maximum Test Power (Pmax)

Vehicle Class	-0.4 P_{max}	-0.2 P_{max}	-0.1 P_{max}	0.0 P_{max}	0.1 P_{max}	0.2 P_{max}	0.4 P_{max}	0.6 P_{max}	0.8 P_{max}
Congested									
MC (10)	7.8	14.3	44.5	50.1	34.2	36.2	18.8	18.9	7.4
ME (8)	1.0	16.6	113.5	92.2	56.4	78.2	102.0	75.0	74.2
NA (13)	20.9	33.2	72.3	50.7	47.6	72.5	51.2	31.4	88.4
NB (13)	6.8	7.5	34.9	63.7	41.5	54.3	23.1	13.6	42.4
NC (11)	1.0	7.9	95.2	126.8	32.7	60.0	28.8	30.9	36.6
NCH (8)	0.0	2.8	45.1	77.5	19.6	26.6	23.5	15.8	21.4
Minor									
MC (10)	58.1	29.0	47.2	62.7	56.6	116.1	115.4	116.6	717.6
ME (8)	17.7	45.4	110.6	137.1	118.7	357.5	356.6	448.4	494.6
NA (14)	36.6	33.3	63.8	83.7	71.9	218.7	227.0	294.0	732.3
NB (14)	42.6	31.6	43.8	58.8	49.4	134.2	137.2	135.4	942.8
NC (11)	22.1	47.5	108.7	112.3	88.9	200.6	198.8	264.5	644.6
NCH (8)	17.4	91.6	220.9	177.1	84.8	94.4	87.6	78.3	315.8
Arterial									
MC (10)	38.7	32.0	46.0	46.6	49.4	98.4	126.1	111.1	832.9
ME (8)	13.1	33.4	133.3	76.4	61.1	124.9	158.8	210.8	894.3

Vehicle Class	-0.4 P_{max}	-0.2 P_{max}	-0.1 P_{max}	0.0 P_{max}	0.1 P_{max}	0.2 P_{max}	0.4 P_{max}	0.6 P_{max}	0.8 P_{max}
NA (14)	65.6	42.3	69.2	67.8	67.7	166.3	162.8	183.3	893.4
NB (14)	13.8	19.3	38.3	41.2	29.3	50.9	54.0	73.9	574.4
NC (11)	30.1	35.7	88.0	75.6	51.6	96.8	98.5	113.7	713.0
NCH (7)	11.1	43.3	154.3	113.2	57.8	85.5	76.6	66.6	288.2
Highway									
MC (10)	57.7	29.0	46.8	43.6	47.8	96.7	126.7	153.3	1567.4
ME (8)	28.0	38.4	85.6	98.1	94.1	222.9	267.1	317.6	1062.8
NA (14)	28.6	23.5	36.2	44.4	66.6	207.2	295.3	553.1	1548.7
NB (14)	23.6	14.8	26.5	32.6	28.0	69.3	134.3	314.9	2608.1
NC (11)	34.5	33.7	88.0	82.7	73.3	123.0	160.2	195.6	1777.7
NCH (7)	20.2	32.4	66.5	80.6	63.0	107.1	122.2	168.9	1453.5

The data in Table 4-5 show that the total emissions, which allow for the time spent by each vehicle in each power range for the CUEDC, are most heavily influenced by the higher power expenditure. The data also show that emission increase exponentially from 0.0 to 0.8 of Pmax with a very significant increase in emissions when vehicles are operated above 0.6 Pmax i.e. at 0.8 Pmax. Comparing the last two columns clearly illustrates this point.

The effect of this has implications when considering emission contributions from vehicles operating under full load in urban areas at high power levels.

4.3 Smoke Opacity

4.3.1 Effect of Year of Manufacture and Vehicle Mass

As with particulate emissions, Figure 4-39 and Figure 4-40 show a general trend towards lower smoke emissions in the newer vehicles, except for the light commercials (NA category).

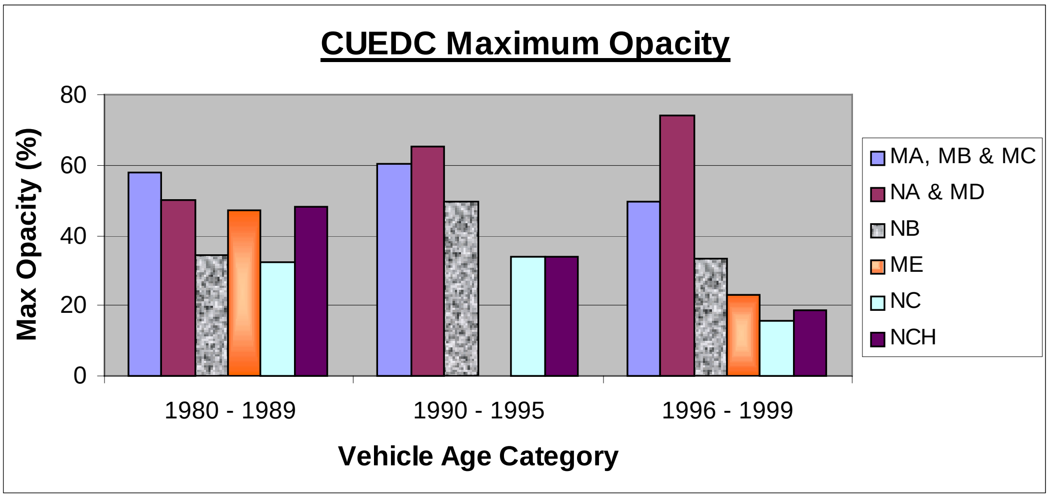


Figure 4-39: CUEDC maximum opacity

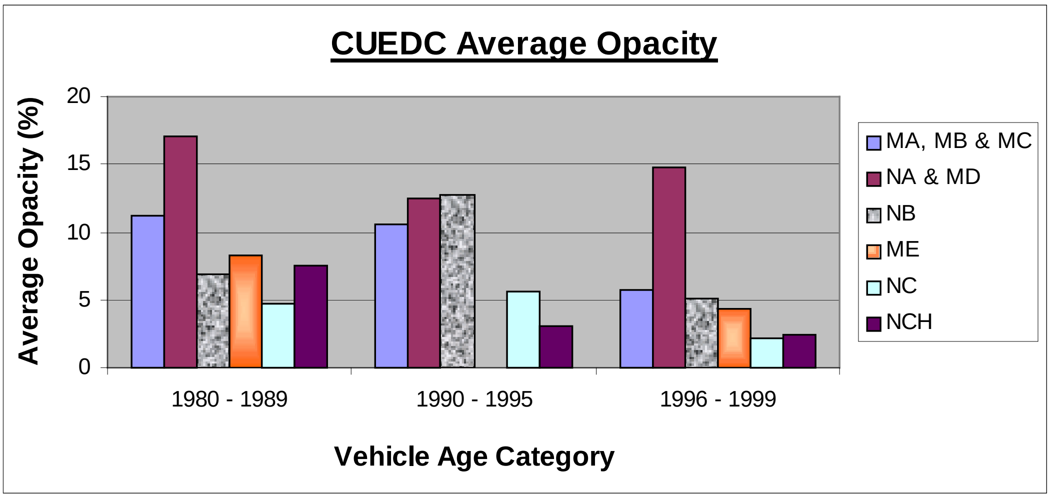


Figure 4-40: CUEDC average opacity

Although, as will be seen in later sections, exhaust smoke opacity measurements are a very poor indicator of fine particulate emission from individual vehicles, there is a common trend in the NA category vehicles to both high particulates and high opacity. This trend is apparent in both the average and maximum opacity measurements and when vehicle age is evaluated as presented below in Figure 4-41. A similar trend applies where a number of high emitters across all ages tend to scatter the data. As seen in the next chart these vehicles are predominantly the lighter vehicles.

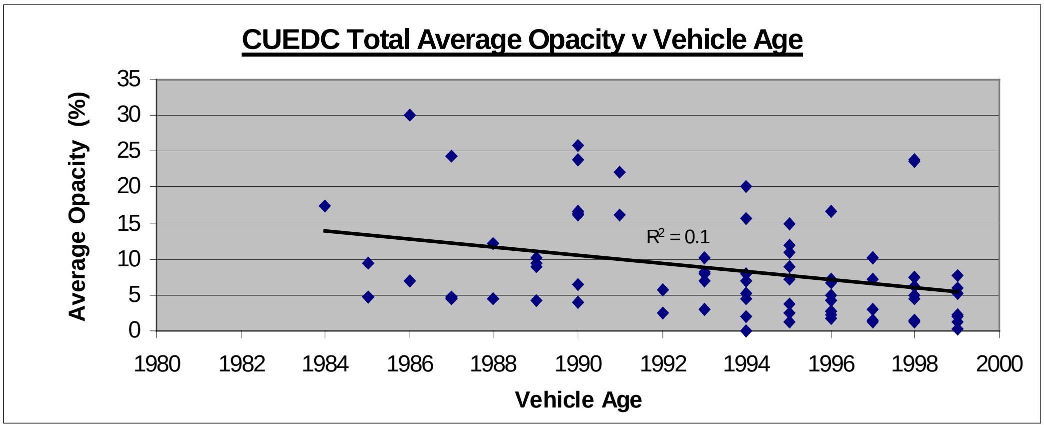


Figure 4-41: Average opacity by vehicle age

The extent to which the light vehicles dominate the overall opacity figures on a test mass basis can be seen in Figure 4-42 below, where vehicles of less than 3.5 tonne GVM (ADR categories MC and NA) consistently represent the group with highest opacity levels.

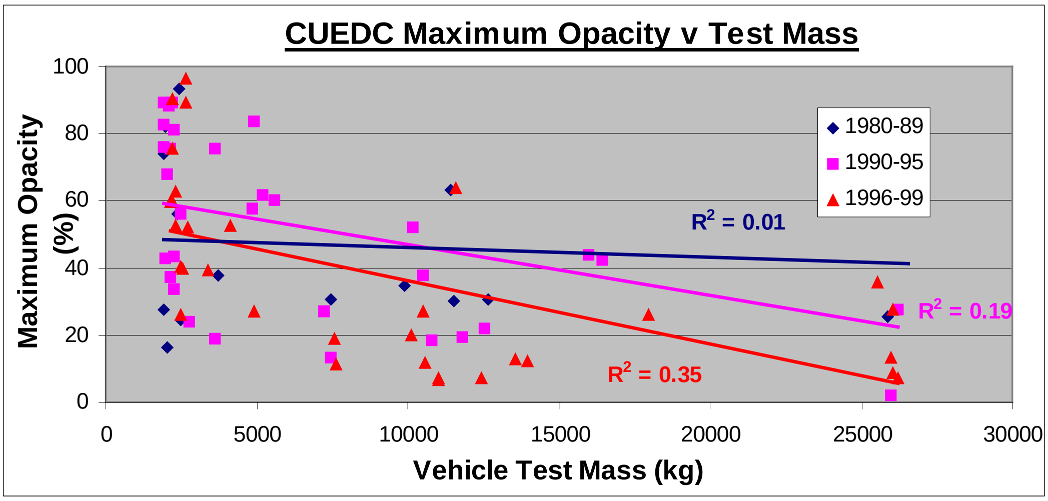


Figure 4-42: CUEDC maximum opacity vs vehicle test mass

Exhaust smoke opacity is not inherently a function of vehicle mass, as evidenced by the weak correlations shown. Rather, high exhaust smoke is an indication of marginal design and/or poor maintenance practices. The data points show how heavily the trend lines are influenced by a minority of vehicles with very high opacity levels almost all of which are in the lighter categories.

The findings of this project reflect the patterns of infringement notices issued under the NSW EPA's in-service 'smoky vehicle' enforcement programs, viz; 4-wheel drive and light commercial vehicles are highly over-represented in observations of vehicles emitting excessive smoke (NSW EPA 1999).

Again, an effective I/M program that accurately measures exhaust opacity would be a very powerful tool in reducing emissions from that sector of the vehicle population that produces excessive emissions through poor maintenance. This is further demonstrated by the variation in smoke levels recorded for the fleet and the proportion of vehicles emitting smoke at many times greater than the fleet average.

4.3.2 Effect of Road Flow Conditions

4.3.2.1 Variation of data over the CUEDCs

The boxplot below (Figure 4-43) illustrates the variation in smoke opacity across each of the four road flow segments. The plot clearly shows there are a number of very high emitting vehicles particularly in segment 4 - highway road flow.

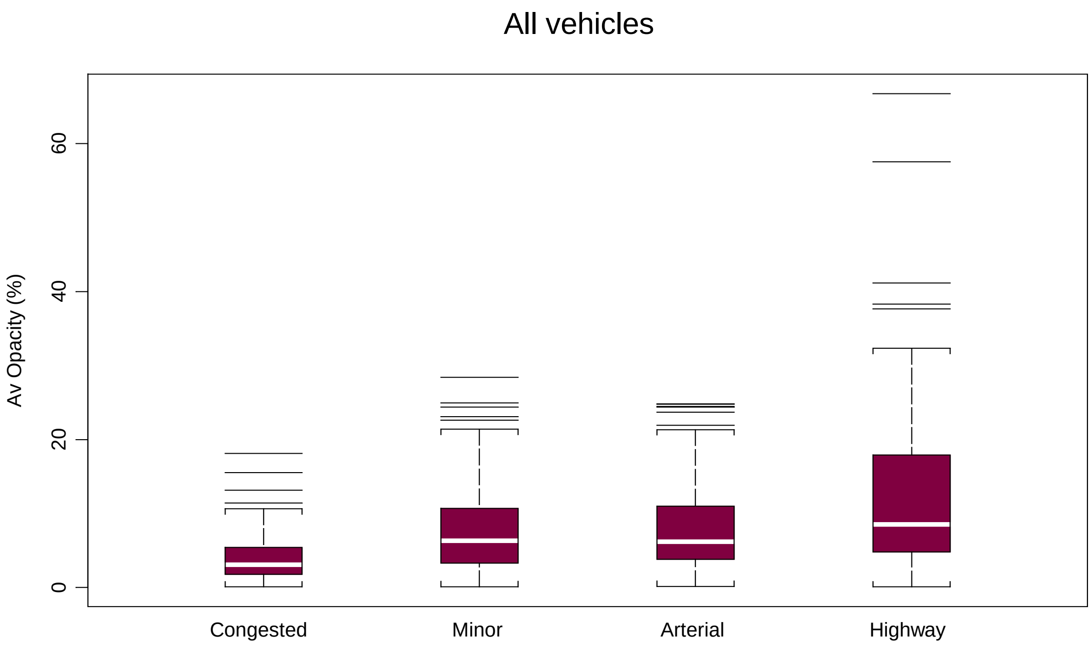


Figure 4-43: Smoke opacity emissions by road flow segment for all vehicles on a mass normalised basis

4.3.2.2 Effect of Emission Standards

Figure 4-44 and Figure 4-45 illustrate the data sets for each ADR weight category pre and post ADR70 respectively and reflect the trend towards slightly lower smoke emissions in post-ADR70 vehicles.

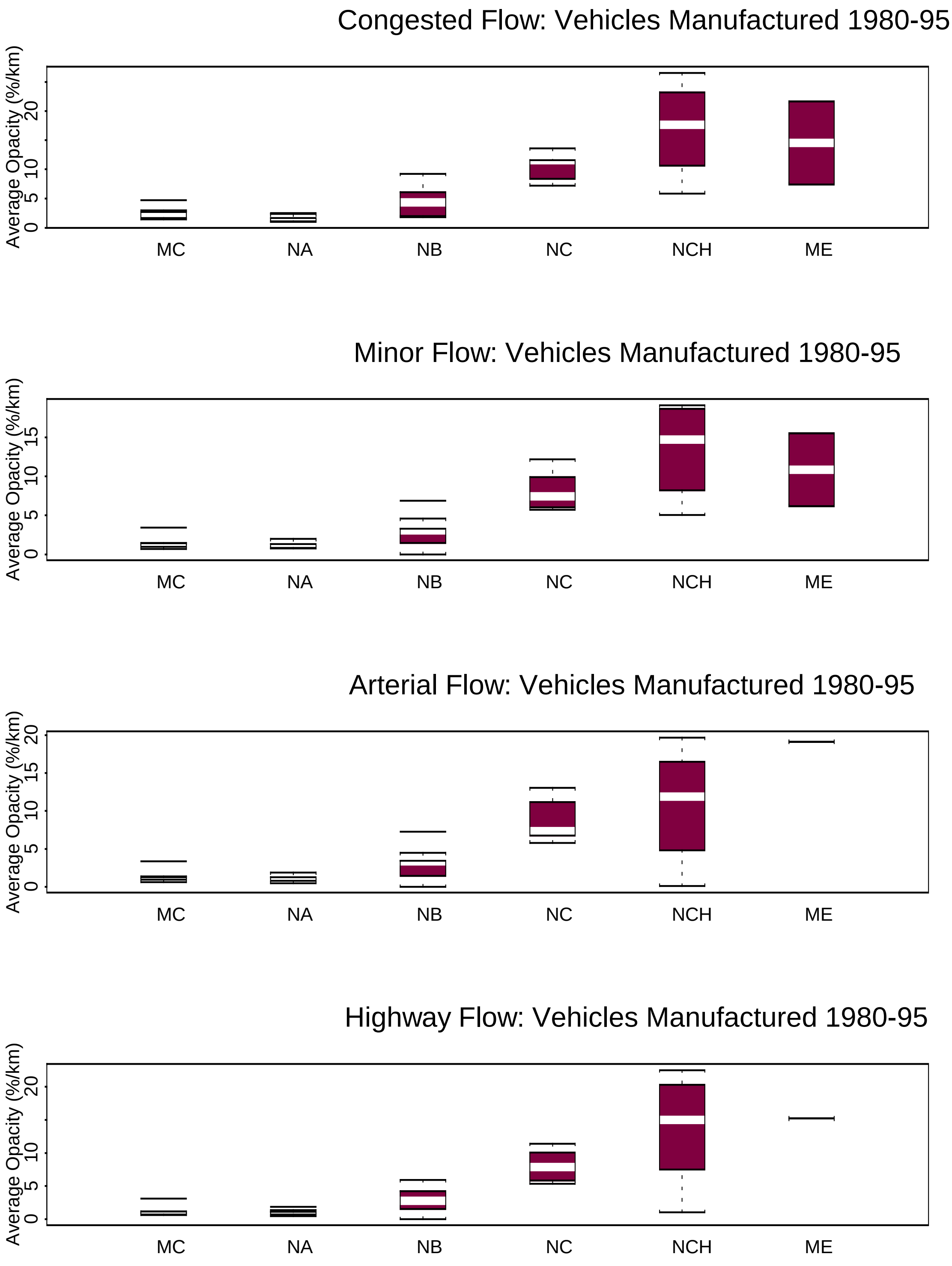


Figure 4-44: Average Smoke Opacity by CUEDC road flow mode – Pre ADR70 (1980-95)

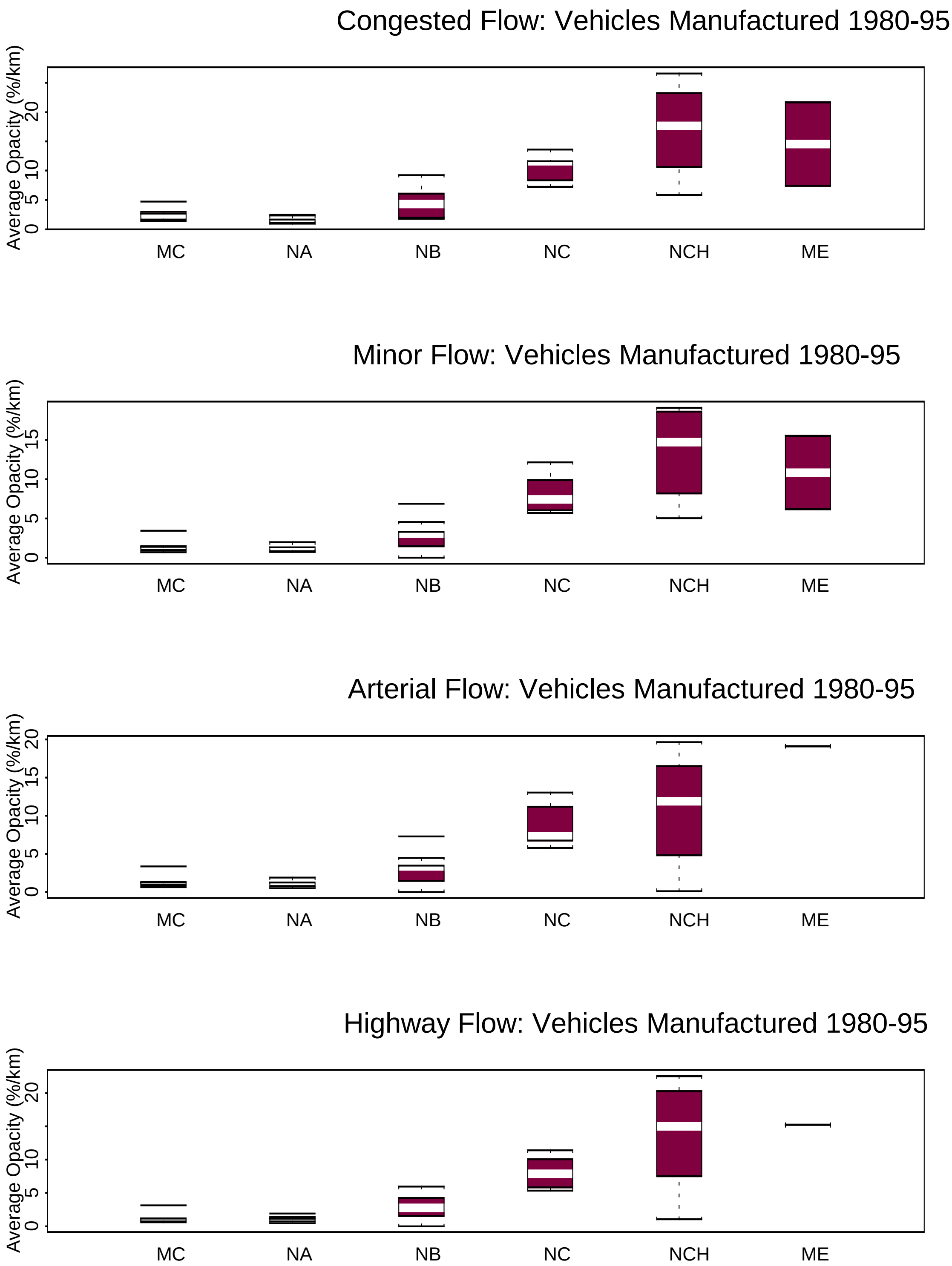


Figure 4-45: Average Smoke Opacity by CUEDC road flow mode – Post ADR70 (1980-95)

4.3.3 Effect of accumulated distance travelled

As noted in Section 4.2.3, the very high particulate emissions and average opacity (Figure 4-46 below) levels from a minority of vehicles, particularly in the light-duty (MA and NA) categories and to a lesser extent NB, is most evident.

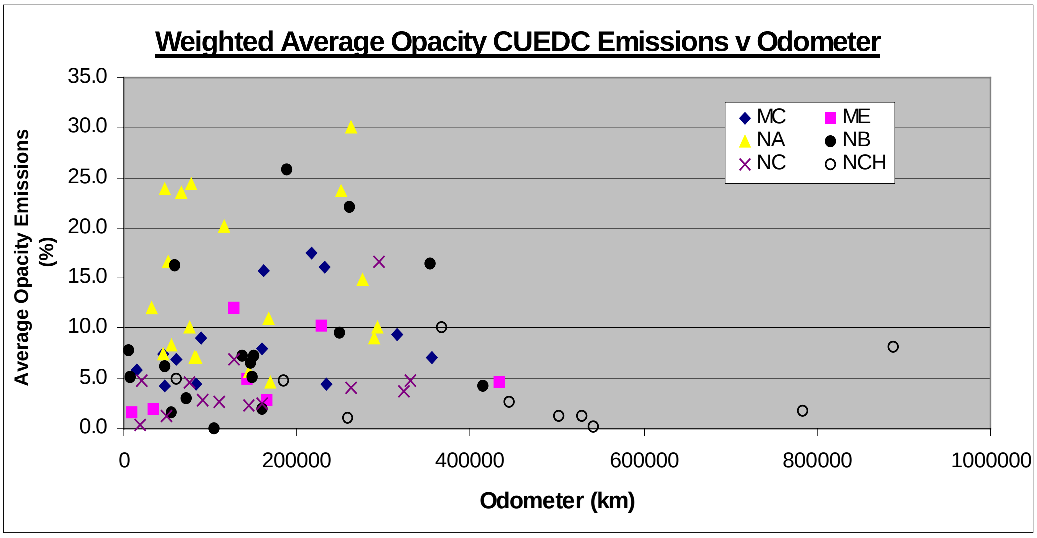


Figure 4-46: CUEDC Average Opacity Emissions v Odometer – by ADR category

4.4 TOTAL HYDROCARBONS (THC)

4.4.1 Effect of Year of Manufacture and Vehicle Mass

Although atmospheric hydrocarbon pollution from diesel vehicles is not a major issue at present (gasoline, LPG and CNG vehicles are the dominant sources), the number of vehicles running on diesel fuel is increasing.

As is shown in Figure 4-47, the general level of THC emissions from diesel vehicles is quite low, and is in fact about the same as might be expected from a Euro-1 standard petrol car.

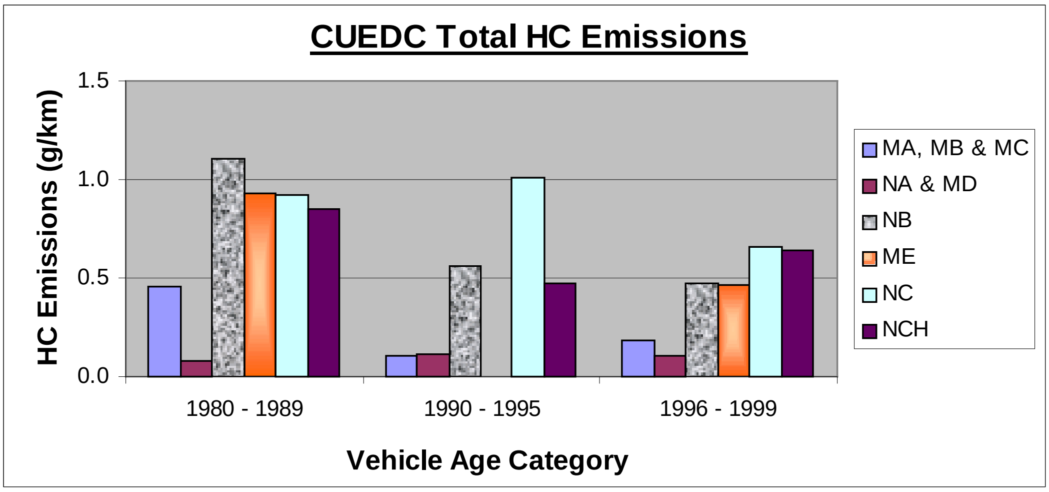


Figure 4-47: CUEDC THC Emissions

Once again, the bar chart above and the scatter plot in Figure 4-48 do not illustrate any emission trend across mass or age groups.

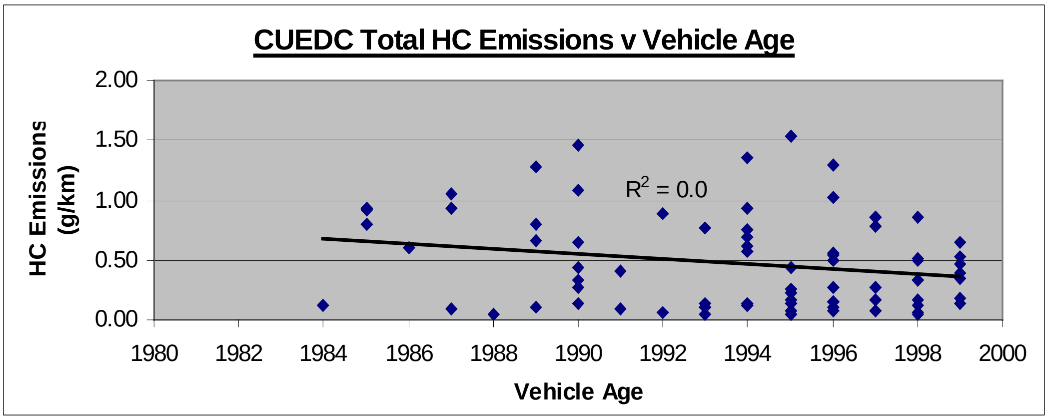


Figure 4-48: CUEDC THC emissions by vehicle age

Linking emission levels to actual vehicle test mass as in Figure 4-49, does however provide a more useful indication of hydrocarbon emission trends.

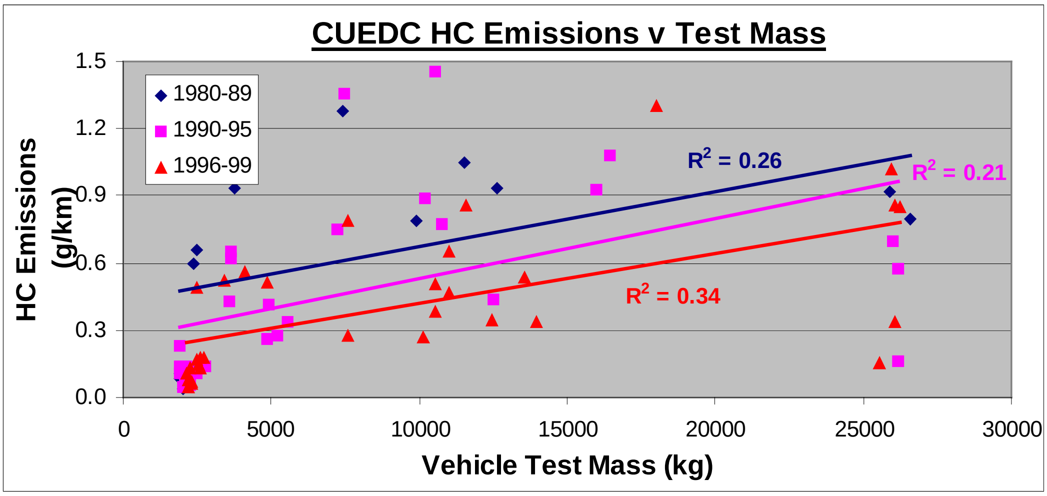


Figure 4-49: CUEDC HC Emissions v Vehicle Test Mass.

Although there is a great deal of scatter in the data, the overall trends show increasing hydrocarbon emissions with increasing mass. The charts also indicate a small, but consistent reduction in HC emissions in the newer vehicle age groups.

4.4.1.1 Effect of emission standards

Figure 4-50 and Figure 4-51 illustrate that there has not been any significant effect on THC emissions due to the introduction of tighter emission standards by ADR70.

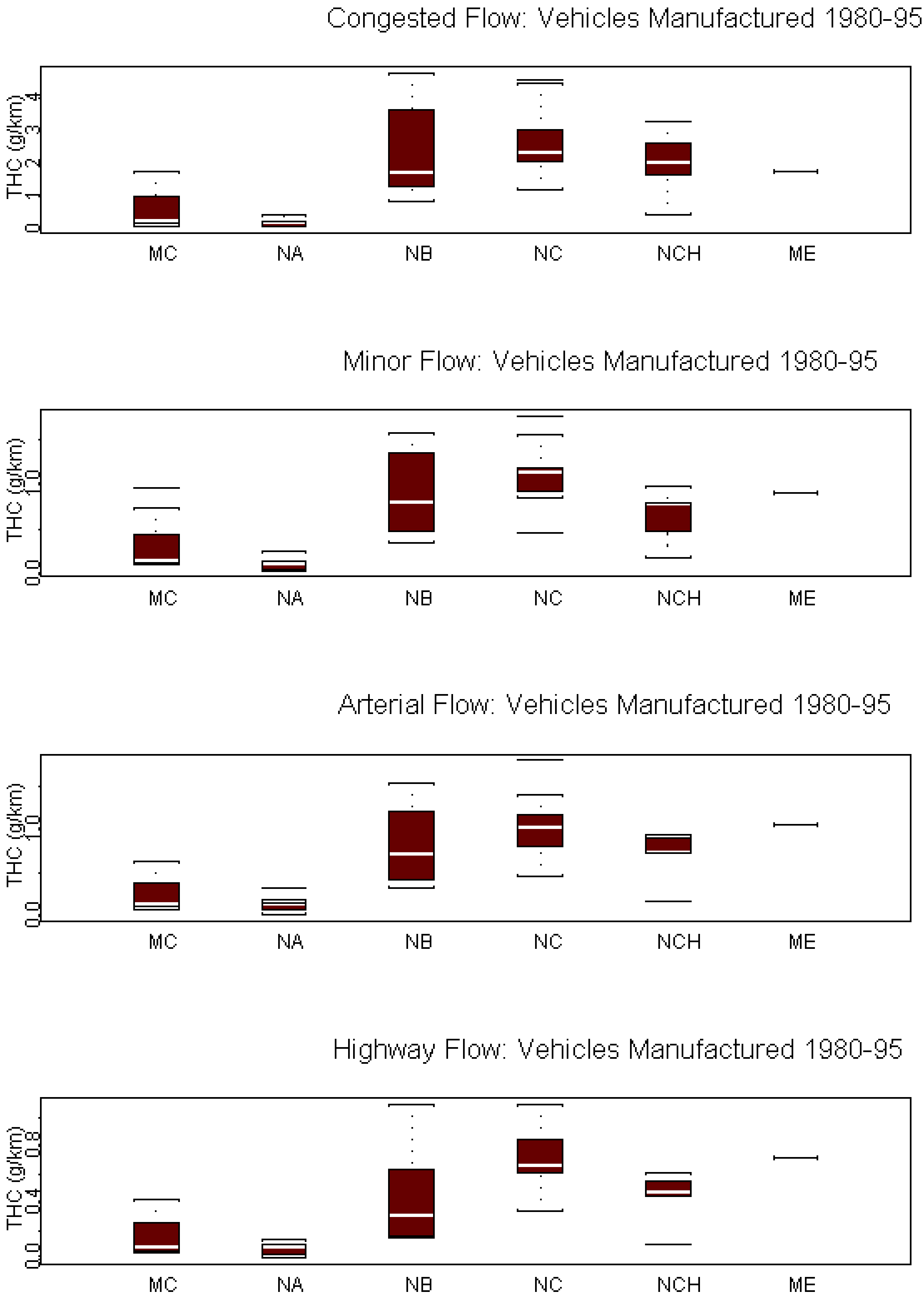


**Figure 4-50: THC Emissions by CUEDC road flow mode –
Pre ADR70 (1980-95)**

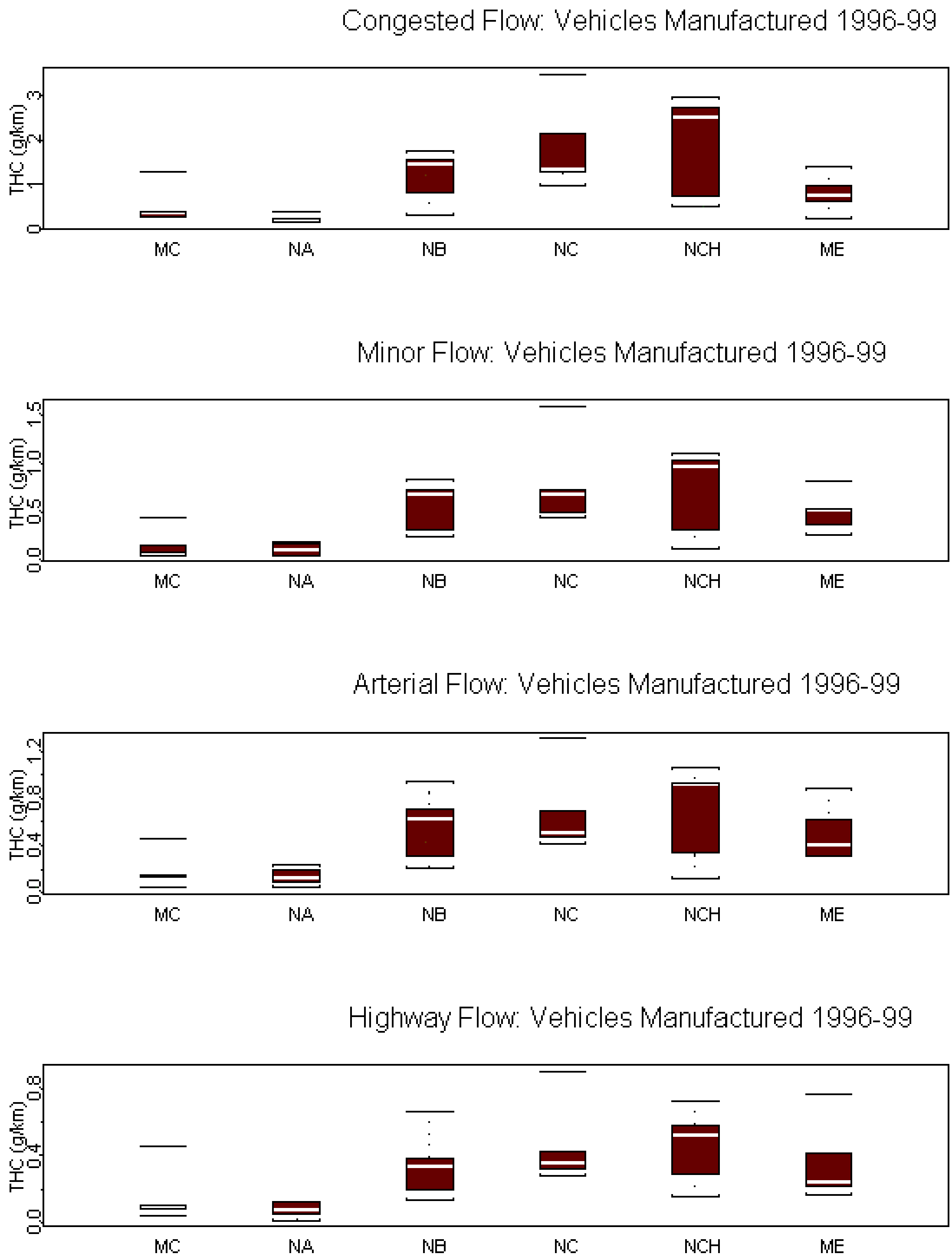


Figure 4-51: THC Emissions by CUEDC road flow mode – Post ADR70 (1996-1999)

4.4.2 Effect of Road Flow Conditions

Emissions of total hydrocarbons (THC), which are very sensitive to transient engine loading, fall sharply in the smooth highway cycle, despite much higher engine power in this segment (see Figure 4-52). The stop start nature of the congested flow segment has a dramatic effect on THC emissions compared to more fluent operating modes.

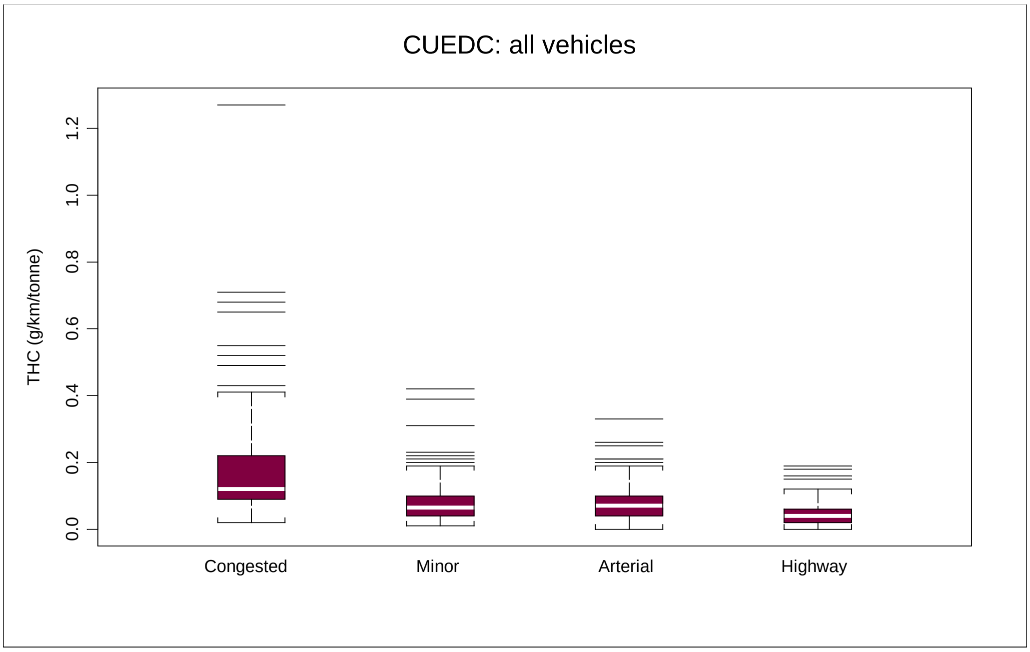


Figure 4-52: Mass normalised THC emissions by road flow segment for all vehicles

4.4.3 Effect of Accumulated Distance Travelled

As evidenced by Figure 4-53 below hydrocarbon emissions did not show any strong relationship with distance travelled. Although, there was a slight trend for some vehicle groups (NB, NC, ME) to show evidence of increasing with accumulated distance travelled.

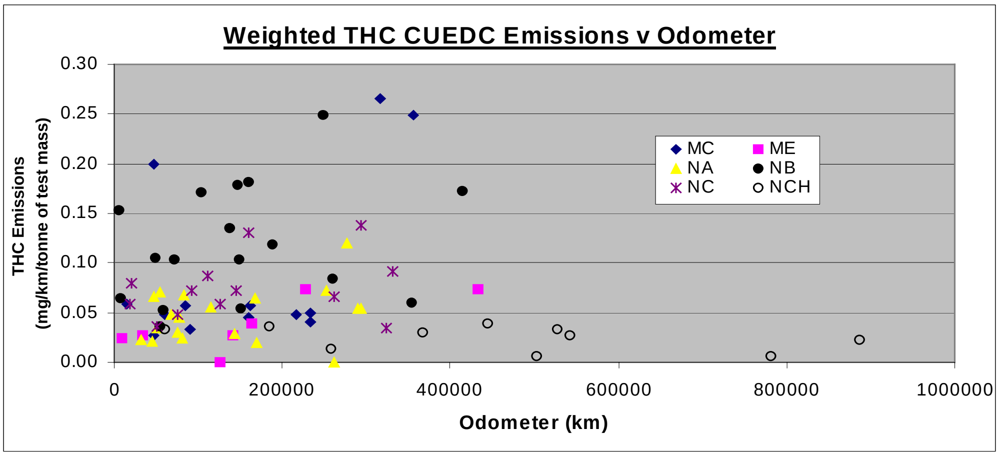


Figure 4-53: CUEDC THC emissions vs odometer by ADR category

4.5 CARBON MONOXIDE (CO)

4.5.1 Effect of Year of Manufacture and Vehicle Mass

Carbon monoxide (CO) emissions are no longer a serious problem in Australian cities, mainly because of the long-term impacts of ADR controls on petrol vehicle for this pollutant. Diesel vehicles are inherently low emitters of CO due to the principle of compression ignition engine operation where the engine has excess air in which to burn the fuel. The low values are apparent from Figure 4-54 which shows their emission levels typically in the same order as those from a Euro-standard Motor car (ranging from 2 to 5 grams depending on the emission standard - Euro 1, 2, 3 or 4).
also indicate a continuing downward trend in CO emissions for newer vehicles. The data presented in Figure 4-55 also indicate a continuing downward trend in CO emissions for diesel vehicles.

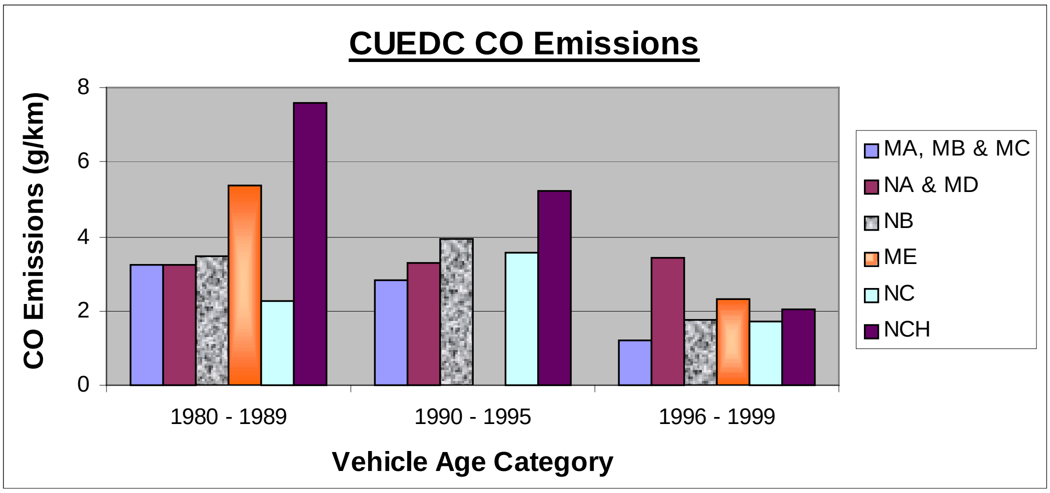


Figure 4-54: CUEDC CO Emissions

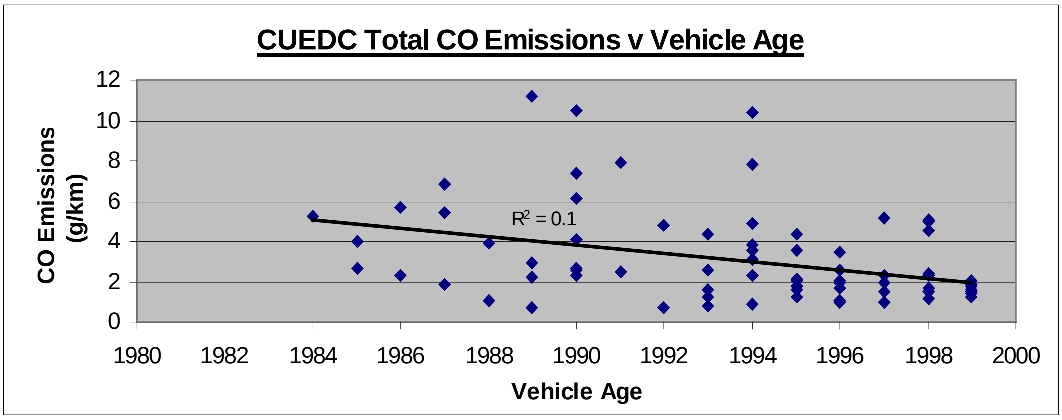


Figure 4-55: CUEDC CO Emissions by vehicle age

However it is still difficult to obtain a clear picture of the fleet emission profile from the above charts and so again the data are plotted against vehicle test mass from which a more useful picture emerges. Refer Figure 4-56 below.

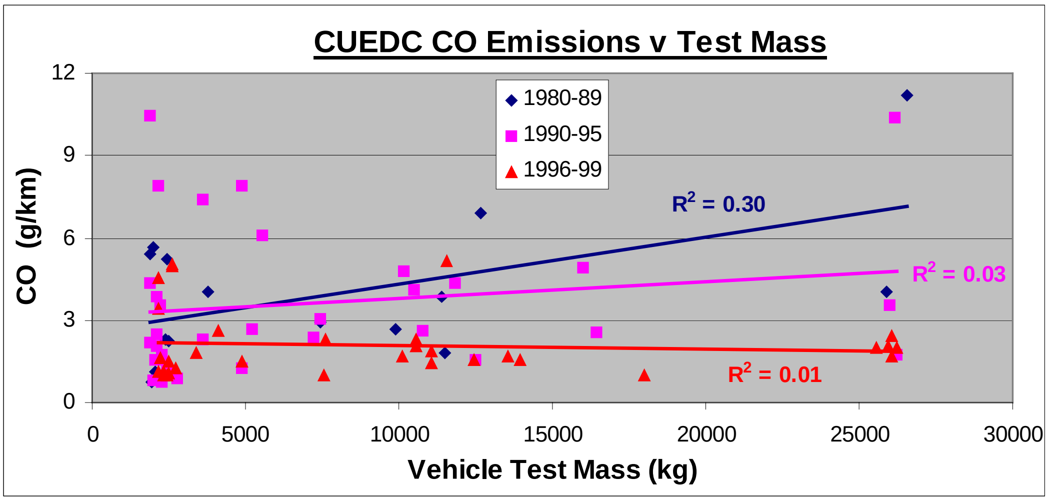


Figure 4-56: CUEDC CO emissions vs vehicle test mass

The older (pre-1990) vehicles exhibit a fairly consistent trend in CO emissions, albeit with considerable scatter. For these vehicles, CO levels rise with vehicle mass, reflecting the higher power levels required for the heavier vehicles to follow the CUEDC drive cycle.

However, vehicles built after 1990 start to exhibit the trend seen for other pollutants: the light vehicles have disproportionately high emissions, compared with mid-range and heavy duty examples from the same age group.

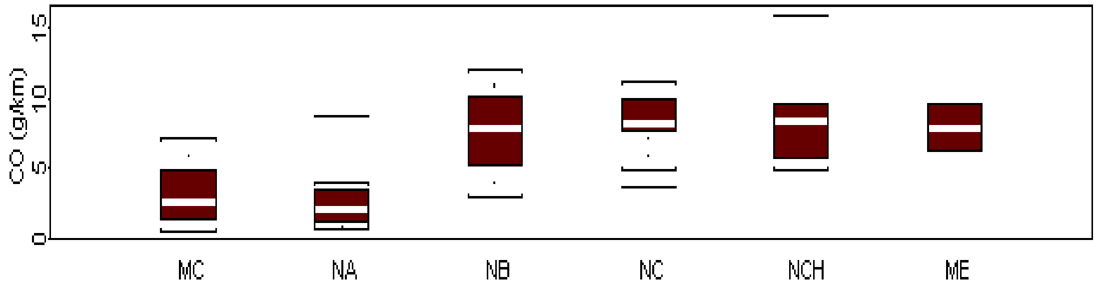
It is not possible, from the data collected in this study, to assess the extent to which improved maintenance might reduce CO emissions. However, given that high CO emissions are a characteristic of poor fuel combustion, as are high levels of particulates and smoke, then it may be anticipated that effective repairs and adjustments to fuel injectors and / or other fuel system components could have a significant impact.

4.5.1.1 Effect of Emission standards

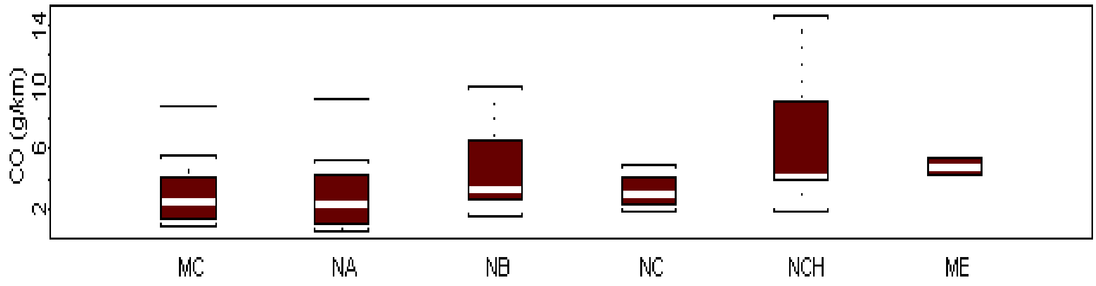
The pre ADR70 (1980-1995) vehicle profile is one of an even distribution of emissions across all weight categories which is likely due to the consistent level of engine technology used prior to the introduction of emission control measures. The efficiency of combustion and generation of CO appears to be similar across all sizes of engines employed during this period as engine manufacturers and emission control authorities focused on light-duty petrol standards.

The most significant aspects that seamed to have occurred as a result of the introduction of emission standards is the reduction in the larger NCH (>25t) and ME (>12t route buses) category vehicles but somewhat counteracting that is the rise and scatter in emissions from the NA (12-25t) category vehicles.

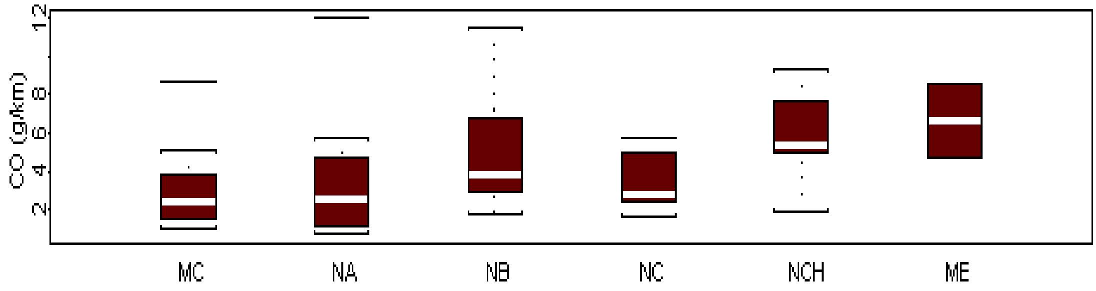
Congested Flow: Vehicles Manufactured 1980-95



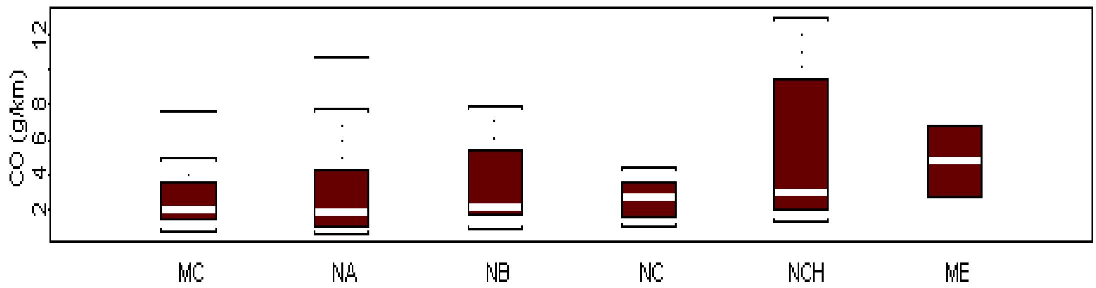
Minor Flow: Vehicles Manufactured 1980-95



Arterial Flow: Vehicles Manufactured 1980-95



Highway Flow: Vehicles Manufactured 1980-95



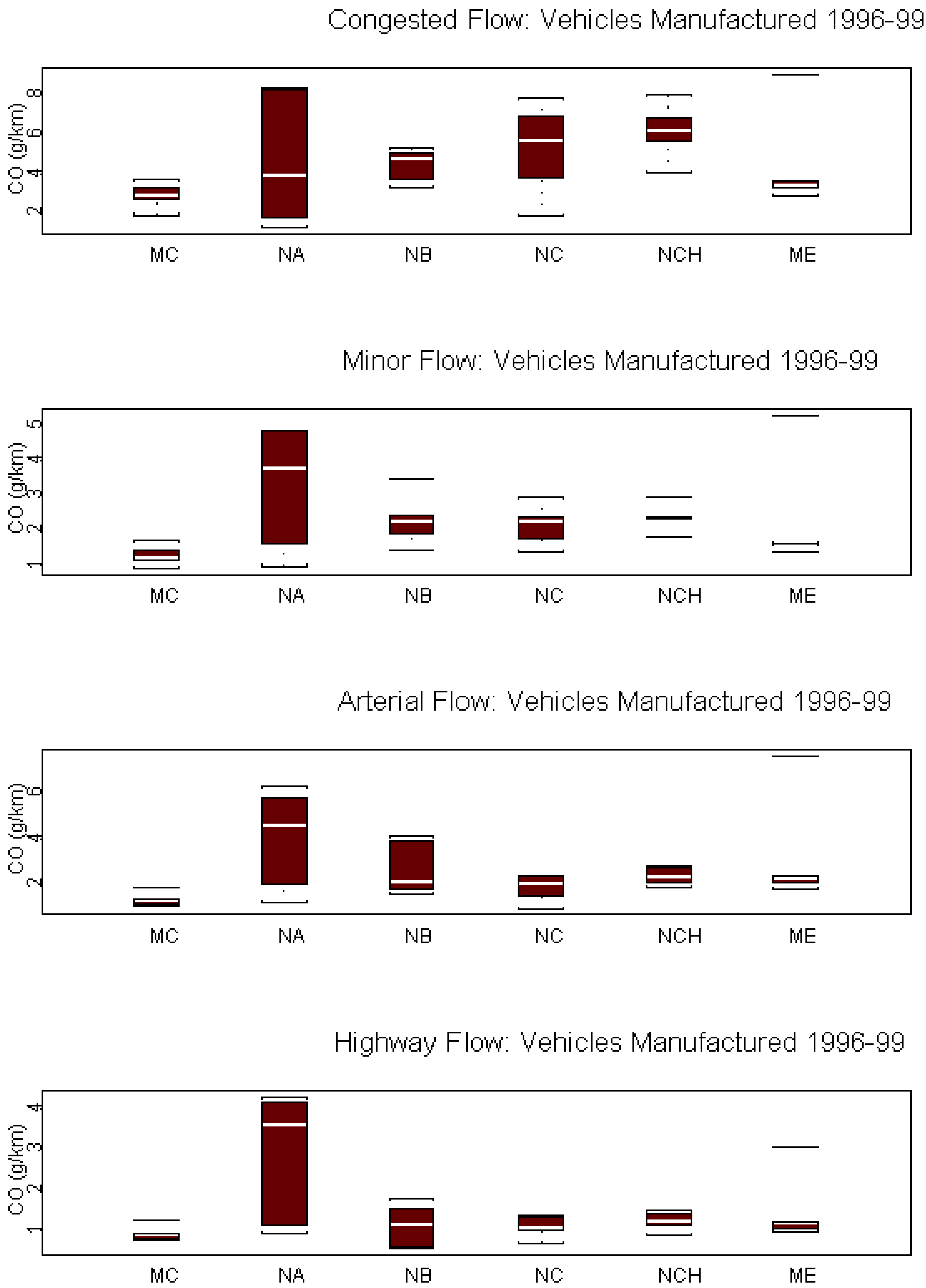


Figure 4-58: CO Emissions by CUEDC road flow mode – Post ADR70 (1996-99)

4.5.2 Effect of Road Flow Conditions

Carbon Monoxide emissions appear relatively unaffected by road flow conditions as evidence by the data presented in Figure 4-59 below. What is interesting is the degree of variance and range of the data across all modes

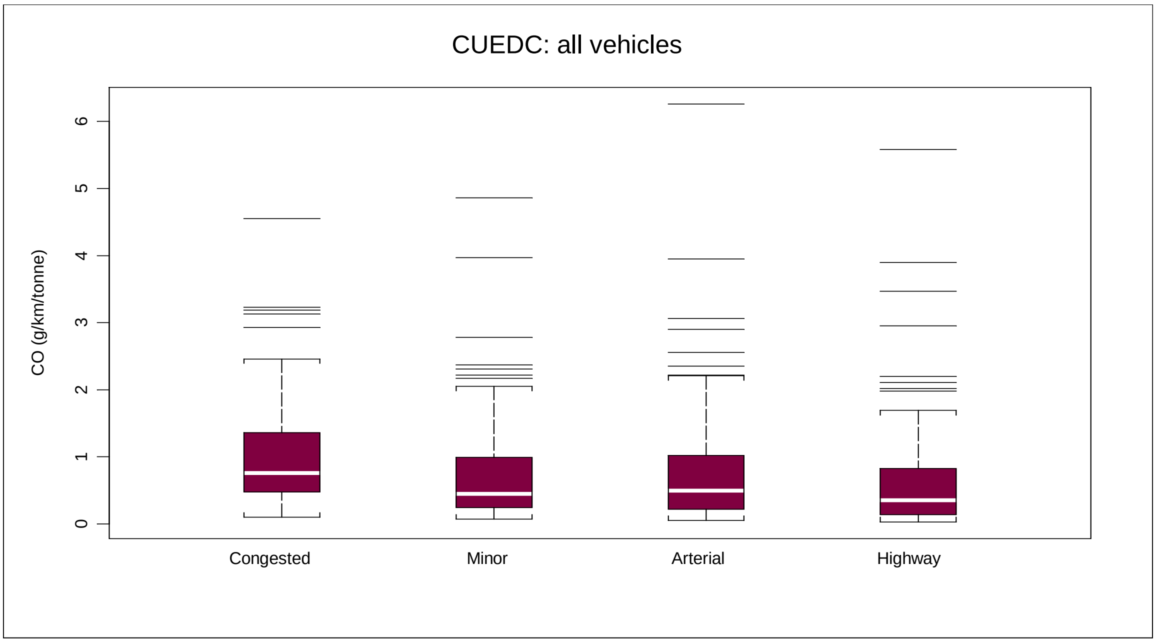


Figure 4-59: CO emissions by road flow segment for all vehicles on a mass normalised basis

Unlike the THC emissions previously discussed the smoother traffic flows of the highway mode only slightly effected (reduced) CO emissions compared to the slower and stop start nature of the congested mode.

4.5.3 Effect of Accumulated Distance Travelled

As previously reported for all other emissions, the higher the distance travelled by a vehicle does not relate to higher CO emissions. Figure 4-60 below shows a high degree of scatter in the data that again suggests other factors rather than distance increases the level of emissions generated by a vehicle.

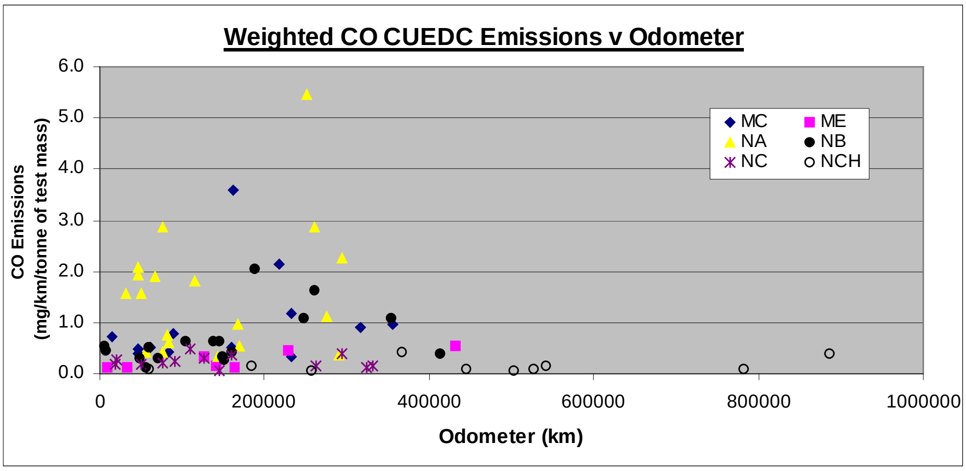


Figure 4-60: CUEDC THC emissions vs odometer by ADR category

4.6 CARBON DIOXIDE (CO2) AND FUEL CONSUMPTION

4.6.1 Effect of Year of Manufacture and Vehicle Mass

Carbon dioxide emissions, as a direct and highly predictable product of fuel combustion, are almost directly proportional to fuel consumption. For this reason both these characteristics are dealt with in the same section and the data presented by Figure 4-61, Figure 4-62 and Figure 4-63.

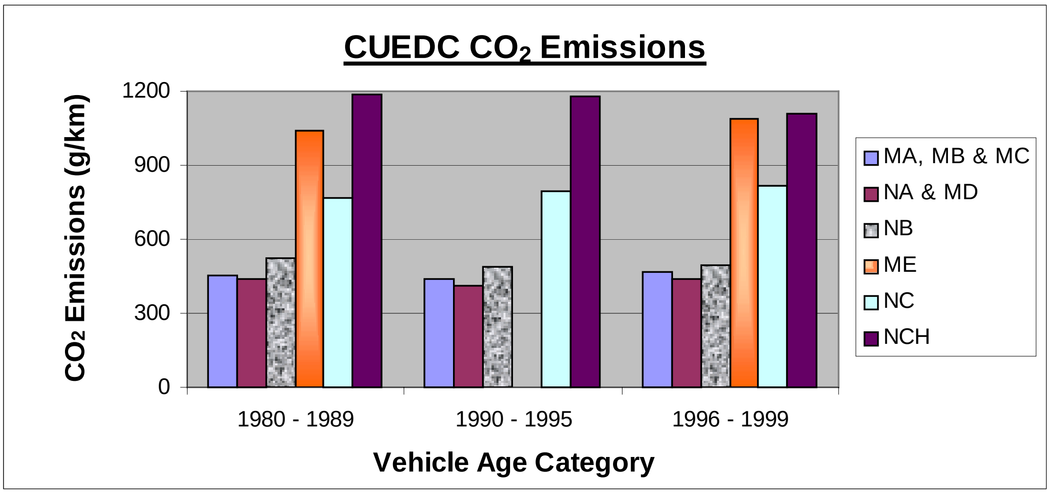


Figure 4-61: CUEDC CO_2 emissions

As expected the larger heavier vehicles emit higher levels of CO_2 and therefore consume more fuel. However what is interesting is the similarities across age groups with little change occurring from 1980 to 2000 as illustrated by the relatively flat line in the vehicle age charts (Figure 4-62 and Figure 4-63) below.

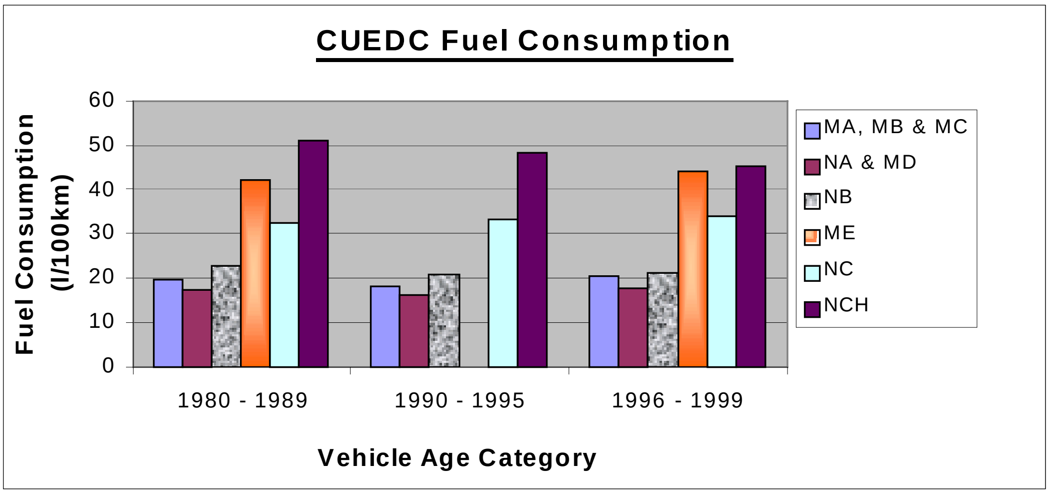


Figure 4-62: CUEDC fuel consumption

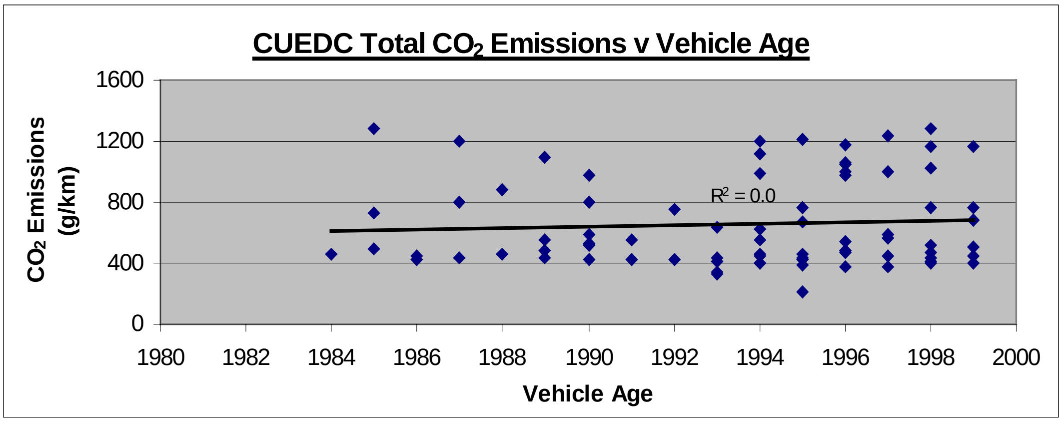


Figure 4-63: CUEDC CO_2 emissions by vehicle age

Given that the energy, and hence fuel, required to propel a vehicle is very closely linked to vehicle mass (at least for low speed operations), a fairly close relationship between fuel consumption (or CO2 emissions) can be expected. Figure 4-64 following, comparing fuel consumption (CO_2) with vehicle mass, confirms this relationship.

It is also evident that emissions on a grams/km/tonne basis increase with decreasing ADR weight category i.e. the heavier vehicles (NCH) emit ~50 g/km/t followed by the next weight category (NC) until the light-duty MC category at ~200g/km/t.

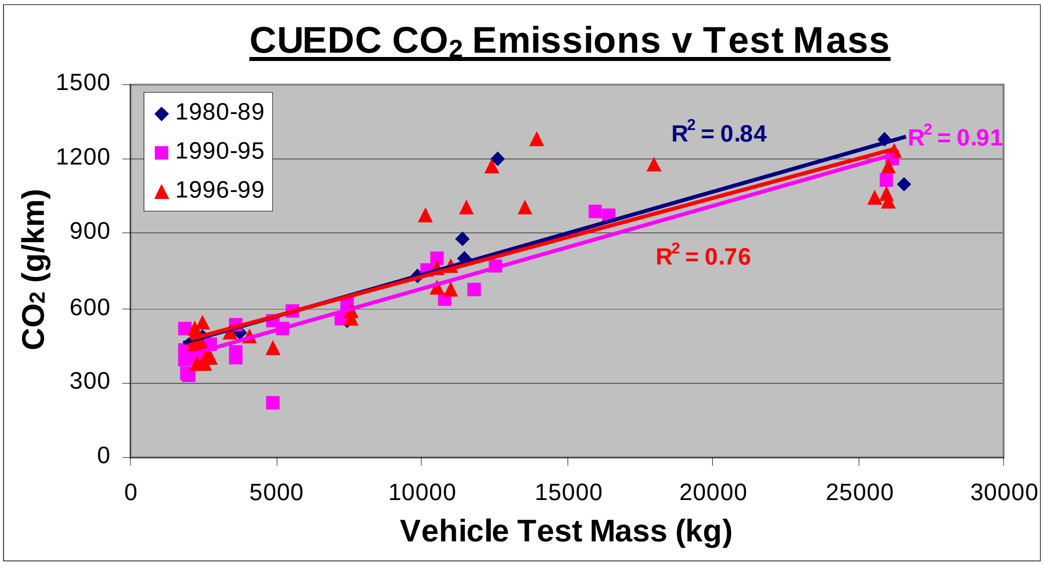


Figure 4-64: CUEDC CO_2 Emissions v Vehicle Test Mass

Unlike other emissions, however, CO2 (and hence fuel consumption) appear not to have changed significantly over the past 20 years. It is remarkable that the slope and intercept values of all three of the above trend lines are extremely close, particularly given the relatively small number of vehicles in each group.

4.6.1.1 Effect of Emission Standards

Unlike the previously reported changes in CO emissions as a possible consequence of changes in emission standards the CO2 profiles are very similar with no significant variation. All vehicle weight categories except the ME (>12t route buses) category display a tight grouping of results.

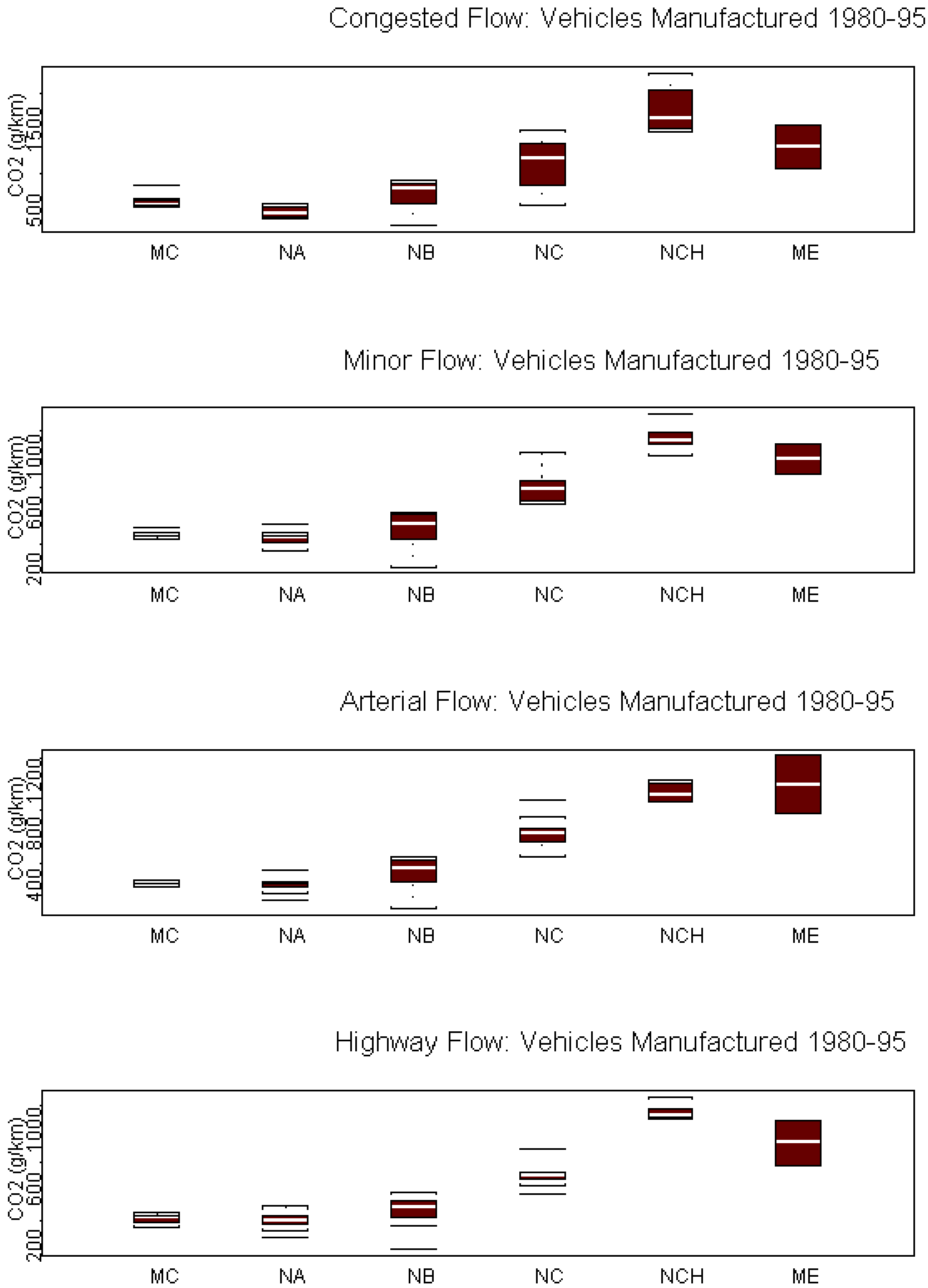


Figure 4-65: CO_2 Emissions by CUEDC road flow mode – Pre ADR70 (1980-95)

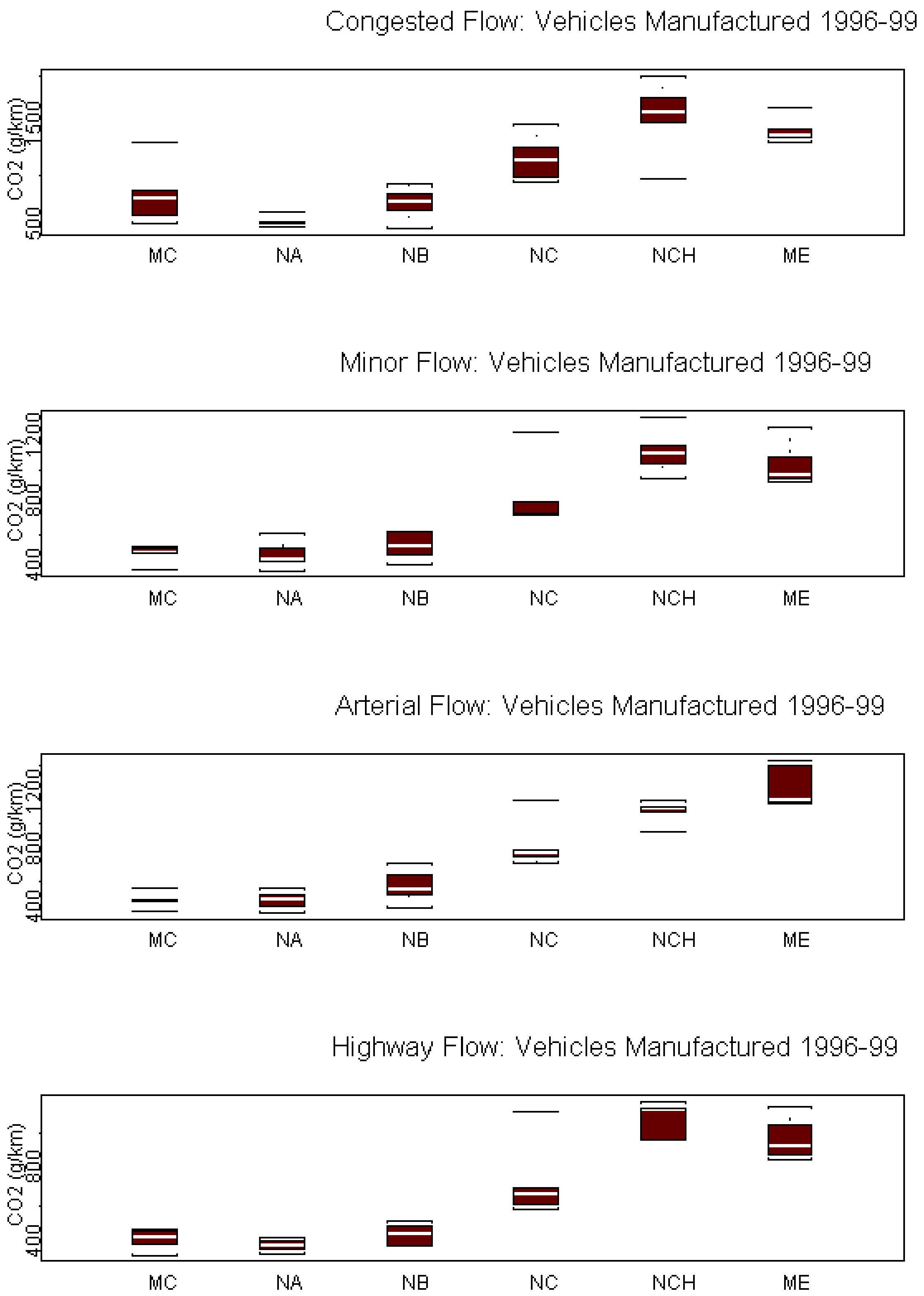


Figure 4-66: CO_2 Emissions by CUEDC road flow mode – Post ADR70 (1996-99)

4.6.2 Effect of Road Flow Conditions

Fuel consumption, and hence greenhouse gas emissions of CO2, is consistently higher in congested flow than for the other three modes (Figure 4-67).

These findings point to the very real savings that can be achieved in both pollutant and greenhouse gas emissions from measures to improve and smooth traffic flows in urban areas.

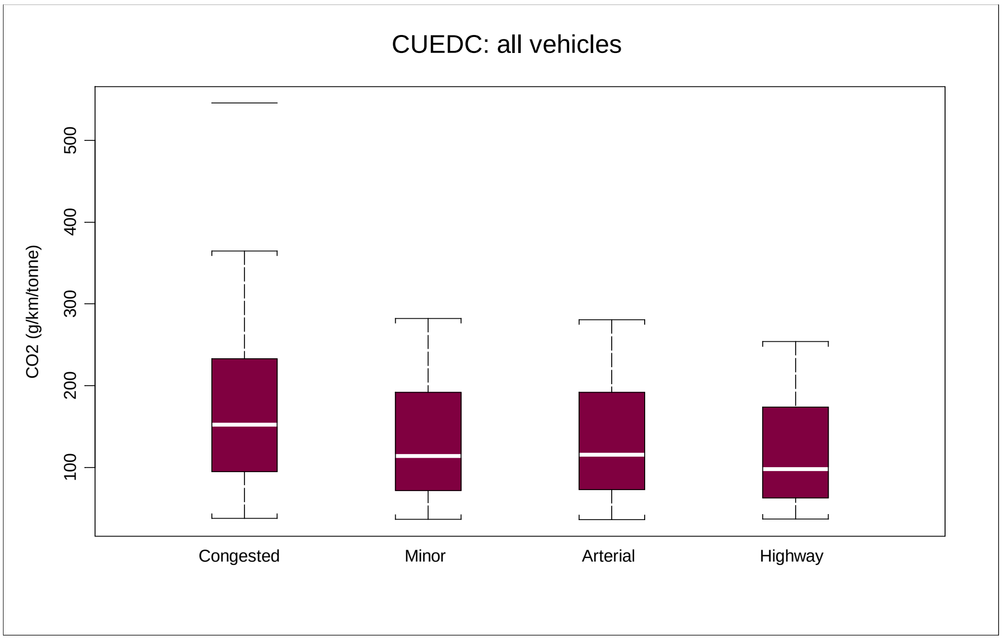


Figure 4-67: CO_2 emissions by road flow segment for all vehicles on a mass normalised basis

4.6.3 Effect of Accumulated Distance Travelled

For NA vehicles, there is an apparent slight increasing trend in CO_2 emissions with odometer, albeit with a fairly low correlation (Figure 4-68). This might be a result of improving technology in later year models even though this is not evident in other emission trends or it might be a result of inadequate maintenance or durability. It is harder to suggest a plausible explanation for the reverse trend in MC-category vehicles.

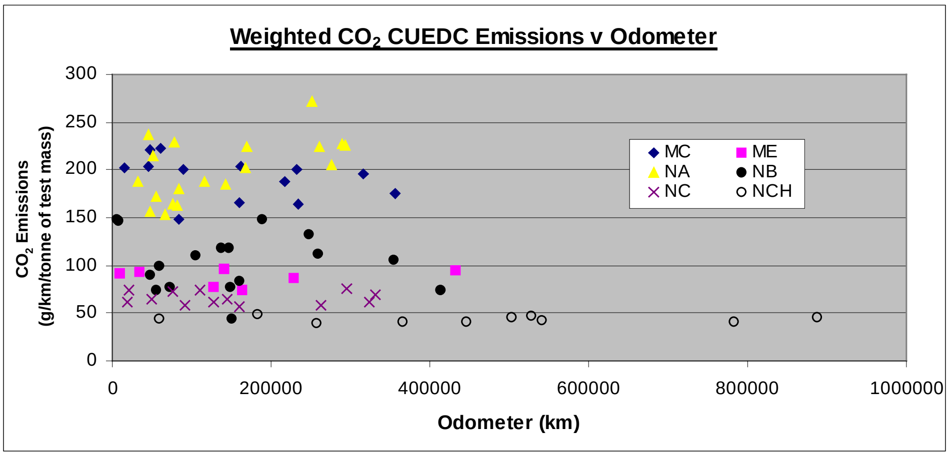


Figure 4-68: CUEDC CO_2 emissions vs odometer – by ADR category

However, the trends are so weak that it is fair to say that there is no change in CO_2 emissions with accumulated distance travelled from any of the ADR vehicle categories.

4.7 SUMMARY

The data collected during the project delivers a wealth of information not previously available in Australia. It provides objective, realistic measurements of actual diesel vehicle performance for every significant combination of vehicle ADR category and age group, in the four most prevalent types of driving condition. The range of pollutants measured is also comprehensive (in particular the various measurements of particulate matter) that provides a sound foundation for developing an emission profile of the diesel fleet as demonstrated by the summary results presented in Table 4-6 below.

Note: there were no vehicles tested in the ME category (buses) 1990 –1995.

Table 4-6: CUEDC Results Summary

ADR Category	Age Group	No of Tests	O_2 raw (g/km)	CO_2 (g/km)	CO (g/km)	NOx (g/km)	HC (g/km)	LLSP (mg/km)	TEOM - total (mg/km)	Filter (mg/km)	Ave Opacity (%)	Max Opacity (%)	APS (mg/km) (<1 um)	APS (mg/km) (<2.5 um)	APS (mg/km) (<10 um)	Fuel Cons (l/100km)
MA - MC	80 - '89	3	494.4	454.1	3.2	1.7	0.5	360.9	543.5	708.9	11.3	58.2	742.5	745.6	777.3	19.5
	90 - '95	5	475.0	436.9	2.8	1.1	0.1	393.6	606.2	660.3	10.6	60.2	405.5	409.3	424.4	17.9
	96 - '99	5	504.5	464.8	1.2	1.3	0.2	148.1	220.2	266.3	5.8	49.6	255.9	256.7	273.3	20.5
NA & MD	80 - '89	4	481.4	442.5	3.2	1.3	0.1	457.7	459.9	829.9	17.0	50.0	623.1	626.2	637.2	17.1
	90 - '95	9	446.4	410.2	3.3	1.0	0.1	441.7	495.9	538.4	12.5	65.1	354.1	356.9	373.9	16.3
	96 - '99	6	470.6	438.5	3.4	1.8	0.1	362.4	605.9	702.9	14.8	74.1	312.0	313.2	318.7	17.6
NB	80 - '89	2	570.8	523.8	3.5	3.1	1.1	161.6	308.3	440.2	6.9	34.2	682.2	687.7	709.4	22.6
	90 - '95	9	535.3	490.5	3.9	3.0	0.6	425.0	636.7	905.6	12.7	49.7	933.4	939.9	967.4	20.8
	96 - '99	6	541.1	496.3	1.8	4.2	0.5	139.8	243.7	302.0	5.2	33.5	232.3	234.1	244.6	21.3
ME	80 - '89	2	1134.5	1038.6	5.4	16.6	0.9	679.3	910.9	1161.6	8.3	46.9	1065.7	1067.9	1100.8	41.9
	90 - '95	0														
	96 - '99	5	1182.7	1085.3	2.3	9.2	0.5	376.6	494.1	602.3	4.3	23.2	694.0	694.7	698.2	44.1
NC	80 - '89	2	838.0	766.7	2.3	9.1	0.9	312.0	548.9	703.7	4.7	32.6	655.3	672.8	726.2	32.2
	90 - '95	7	871.6	798.4	3.6	7.9	1.0	436.7	557.7	715.8	5.6	33.6	654.1	671.2	719.6	32.9
	96 - '99	5	885.7	813.7	1.7	5.8	0.7	163.1	285.7	422.0	2.1	15.7	396.2	396.6	402.3	34.0
NCH	80 - '89	2	1294.6	1187.3	7.6	13.3	0.9	261.6	513.2	531.8	7.5	47.9				51.1
	90 - '95	3	1286.7	1176.5	5.2	15.4	0.5	209.9	457.3	525.0	3.1	33.8	350.0	355.0	381.7	48.3
	96 - '99	5	1204.4	1107.2	2.0	8.0	0.6	201.6	369.7	453.3	2.4	18.4	663.0	664.0	687.2	45.4

The complete database is presented by way of tables in Appendix 4 (Tables A4-1 to A4-17) which summarise the CUEDC results, dissected by road flow modes, for gaseous pollutant emissions, particulates and fuel consumption. Together, these charts provide the basis for a comprehensive model of diesel vehicle pollutant and greenhouse emissions in Australia.

Table 4-7 is an example of the data summaries contained in Appendix 4, and presents results for the 3.5 to 12 tonne GVM vehicles first registered between 1990 and 1995.

Table 4-7: An example of tables presented in Appendix 4 – Summary of CUEDC Results for NB Vehicles

NB Vehicles (1990-95)	No of Data Pts	Average CUEDC Results				
		Cong'd	Minor	Arterial	Hwy	Weighted Total
NOx (g/km)	9	4.36	3.05	3.18	2.85	3.02
CO (g/km)	9	7.17	4.36	4.74	3.27	3.92
CO_2 (g/km)	9	711	508	522	457	491
O_2 (g/km)	9	777	554	570	498	535
THC (g/km)	9	1.75	0.69	0.68	0.39	0.56
Opacity - Average (%)	8	4.01	11.8	10.6	24.3	12.7
Opacity - Maximum (%)	8	32.	55.2	53.8	58.	49.7
Cumulative Power (kWh)	9	0.34	1.66	1.37	4.67	2.01
Cumulative Power (kWh/ tonne of test	9	0.07	0.34	0.28	0.95	0.41
Fuel Consumption	9	27.1	19.2	19.8	17.2	20.8
Fuel Consumption (l/100km/ tonne of test	9	5.43	3.9	4.01	3.53	4.22
Fuel Consumption (l/kWh)	9	0.86	0.47	0.47	0.44	0.47
Filter Mass (g/km)	9	877	790	883	956	906
LLSP Mass (g/km)	8	318	444	398	436	425
APS - PM1.0 (g/km)	6	621	753	773	934	933
APS - PM1.0 (g/kg fuel)	5	2414	4113	4434	5718	5261
APS - PM1.0 (g/kWh)	5	1924	1837	1829	2385	2369
APS - PM2.5 (g/km)	6	625	757	777	941	940
APS - PM2.5 (g/kg fuel)	5	2426	4136	4460	5761	5298
APS - PM2.5 (g/kWh)	5	1934	1847	1841	2403	2385
APS - PM10 (g/km)	6	646	786	808	968	967
APS - PM10 (g/kg fuel)	5	2510	4298	4639	5950	5463
APS - PM10 (g/kWh)	5	2001	1919	1917	2478	2459
TEOM - Total (g/km)	9	582	631	592	657	637

4.7.1 Key Emission Profile Findings:

1. It has shown to be important to assess the fleet on a test mass per kilometre basis rather than just on a grams per kilometre travelled basis. The emission profile and therefore potential areas to focus reduction strategies change when the payload of the vehicle (test mass) is taken into account.

2. Smaller, lighter vehicles tend to be higher emitters of particulate while the larger heavier vehicles are higher NOx emitters.

3. In the main areas of concern (NOx and Particulates), new engine technologies are delivering lower Particulate emissions. However, there has been little if any overall reduction in average NOx emissions over the last two decades.

4. All vehicle sizes, ages and weight categories are peppered with high emitting vehicles many times above the average for the particular group. This is particularly evident in the light commercial group where the data is very scattered.

5. Overall the data indicates that very significant emission reductions can be achieved from measures to improve and smooth traffic flows in urban areas.

6. In all cases accumulated distance travelled has no effect on emission performance suggesting other factors such as the vehicles state of tune or level of maintenance has a far greater effect. This is discussed further in the next section.

4.7.2 Effect of Accumulated Distance Travelled

The correlation coefficients derived for each vehicle category and all vehicles are shown in Table 4-8 below. It is clear from the data and the correlations presented below that other issues than accumulated distance travelled are the cause of a vehicle polluting.

Table 4-8: CUEDC Emissions vs Odometer

	CUEDC Emissions v Odometer - R^2 values			
ADR Category	Average NOx (g/km/tonne of test mass)	Average CO_2 (g/km/tonne of test mass)	Filter mass (mg/km/tonne of test mass)	Average Opacity (%)
MC	0.11	0.13	0.15	0.12
NA	0.03	0.32	0.08	0.01
NB	0.05	0.02	0.11	0.10
ME	0.23	0.01	0.21	0.06
NC	0.02	0.00	0.13	0.22
NCH	0.11	0.00	0.00	0.00
All Vehicles	0.01	0.09	0.00	0.00

The resulting scatter plots from the data summarised in Table 4-8 above, are presented in Appendix 4 as Figures 4.22 to 4.31.

4.7.3 Road Flow Modes

The following points are made in relation to the four road modes of the CUEDC:

- Congested driving, because of its highly inefficient stop-go nature, with many idle periods, results in high emission rates for all gaseous pollutants and fuel consumption.
- Emissions of NOx, which are linked to combustion temperatures, do not reduce by a significant amount in the more free-flowing segments, reflecting their higher engine loads.
- Total hydrocarbons (THC), which are very sensitive to transient engine loading, fall sharply in the smooth freeway cycle, despite much higher engine power in this segment.
- The variation in particulate emission levels across segments is also of interest. In the heaviest group of vehicles (NC and NCH), particulate emissions are considerably higher in the congested flow than in other modes, while for some of the lightest vehicles, the trend is actually reversed, with the lowest particulate emissions in the congested segment.
- Fuel consumption, and hence greenhouse emissions of CO_2, is consistently higher in congested flow than for the other three modes.

4.7.4 Data Analysis Issues

While many reasons can be discussed regarding the shape and scatter of the data, it is important to consider the large variance between vehicle makes, models and mass (GVM) within each vehicle ADR category. The mass of the vehicles within each ADR category varies greatly (as much as 12 tonnes).

While throughout the report it has been attempted to present results pertaining to vehicle weight category (based on the ADR GVM groupings) and mass normalised (based on test mass), the individual vehicle to vehicle variances are still to be explored. However, a much larger data set is required to investigate down to this level of detail. Therefore, readers interrogating the database should be cautious about drawing any conclusions at these lower levels until the sample size can be increased through further testing of the fleet.

5. ANALYSES OF RESULTS – IN-SERVICE TESTS

5.1 SHORT TEST CORRELATIONS WITH CUEDCS

The CUEDCs are intended as a tool for diesel vehicle inventory development, policy guidance and program monitoring. The results presented and analysed in Section 3.1 indicate they would be up to that task. Additional vehicle data will need to be added to the data bank, either on a project or continuing basis, to ensure the data are sufficiently representative of the fleet and sufficiently robust for the purpose.

On the other hand, the candidate short tests are being evaluated as an IM tool. For optimal effectiveness, the selected test should have good correlation with the CUEDCs. Also, a well-correlated short test would provide a mechanism to accumulate data that would usefully supplement the CUEDC-based inventory database.

Given a short test that correlates well with the CUEDCs in a laboratory environment, there is no doubt that gas measuring instruments are available that maintain that good correlation in an IM workshop environment. The purpose of this Section of the report is to show that it is also practical to measure diesel particulate in an IM workshop while maintaining correlation with the laboratory reference method.

5.1.1 Significance of the Correlations

For the successful application of a short test for diesel vehicles it is essential that:

(a) Low-cost, simple and rugged instrumentation is available to measure particulate matter. The previous Section has confirmed that laser light scattering photometry (LLSP) equipment meets all of these criteria and is readily available on the commercial market.

(b) The test reliably identifies those vehicles with excessively high emissions of particulates, NOx and smoke. For these criteria to be met, the selected test must have a high degree of correlation with "real-world" emission levels. Correlation with the Composite Urban Emissions Drive Cycle (CUEDC) is a measure of a test's capability in this area.

5.1.2 What Should be Correlated?

The most direct correlation is simply to plot short test results for a number of vehicles against the CUEDC results for the same vehicles, and statistically analyse their relationship. This is most commonly performed through regression analysis that determines a trend line (line of best fit) through the data points to show the overall relationship, and also measure the degree of fit between the trend line and the data by calculating the correlation coefficient (R^2).

5.1.3 Statistical Correlations with CUEDCs

This assessment is done in two parts: (a) correlations between the short test and the total CUEDC results, and (b) correlations between the short test and individual CUEDC segments (for the highest rating tests). Correlations for all other short test by CUEDC segment are presented in Appendix 7.

5.1.3.1 Correlations with Total CUEDC

Table 5-1 summarises each short test’s correlation with the weighted full CUEDC cycles.

Table 5-1 Coefficients of determination (R^2) for short tests v CUEDCs for all vehicles)

	Correlation Coefficient ($R^{2)}$					
Short Tests	Average NOx (g/s)	Average HC (g/s)	Average PM (LLSP) (mg/s)	PM (Filter) (mg)	Average Opacity (%)	Maximum Opacity (%)
AC5080	0.95	0.92	0.70	0.71	0.87	0.80
DT80	0.90	0.85	0.63	0.58	0.68	0.81
2 speed torque	0.62	0.72	0.30	-	0.40	0.68
DT80 last 10s	0.80	0.74	-0.35	-	0.15	-0.21
Lug Down	0.60	0.68	0.22	-	0.26	0.68
2 speed power	0.55	0.36	0.12	-	0.15	0.17
D550	0.64	0.53	-0.18	-0.23	0.03	-0.23
Snap idle	0.47	0.23	-0.02	-	0.29	0.59

Evaluation of short test correlations can be conveniently split into three groups:

- Non-loaded (Snap Idle)
- Steady state (D550, Lug Down, 2-Speed, DT80 last 10secs); and
- Transient loaded (DT80, AC5080)

Snap Idle, the only non-dynamometer test, is closely linked to the SAE J1667 free acceleration test. It proved to be an extremely poor indicator of particulate levels, even though it provided a reasonable correlation with maximum CUEDC opacity levels. It's HC and NOx results recorded the lowest correlation with the CUEDC of all the tests evaluated.

The second group of steady state tests **(D550, Lug Down, 2-Speed, DT80 last 10secs)** did not prove to be good surrogates for the CUEDC. Traditionally, diesel vehicles have been considered to be most polluting when labouring up a gradient with a heavy load. The smoke that often accompanies this operational mode was seen as proof of the high pollution.

In fact the steady-state tests, in particular the D550 and the Lug-Down, which were designed to replicate this mode, proved to be generally poor indicators of particulate emissions, as can be seen in the above table. Their NOx and HC results provided a fair correlation with the CUEDC.

This group of tests were, nevertheless, very useful in highlighting a fundamental requirement for any in-service diesel test, that is the need to measure particulate emissions under **transient** engine loading conditions.

It is apparent from Table 5-1 above that the two transient tests (highlighted), the AC5080 and the DT50, are the best-performing tests, and warrant further investigation.

5.1.4 Taking Account of Vehicle Mass

In addition, the above table, while it provides an excellent foundation for measuring the fundamental relationship between each short test and the CUEDC in absolute terms, this may not be the best way of measuring the value of a short test in picking the true high-polluters. As a general rule, emissions increase with engine power. Given that the power needed to accelerate and propel a vehicle through any given driving pattern is primarily a function of vehicle mass, there should logically be a direct linkage between drive cycle emissions and vehicle mass.

Moreover, in identifying high-polluting vehicles, it would be erroneous to simply measure the total level of emissions from a test. Fully laden heavy vehicles with large, powerful engines will inevitably produce higher emission levels than smaller vehicles, all other things being equal. Conversely, a light-duty vehicle with a small payload and relatively small engine, should produce less emissions.

Failing a vehicle simply on the gross emissions number would produce an inequitable bias against heavy vehicles, and could allow light vehicles to deteriorate to abysmal levels before failing a test.

To take account of this, the data has been normalised, by dividing emission levels by the vehicle test mass, thereby giving an emission rate expressed in grams (or milligrams) per kilometer-tonne (g/km.t) - a much more realistic and equitable measure of performance.

The effect of this technique is to significantly improve the relationship between particulate results on the two primary short tests versus the CUEDC. The correlations for DT80 and AC5080 particulates are shown on the following charts and tabulated below in Table 5-2.

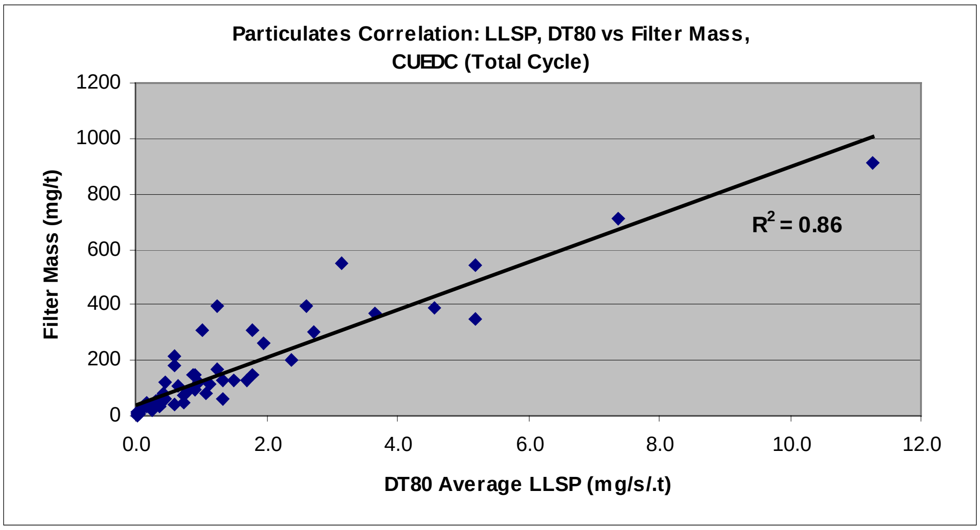
Table 5-2: Correlation Coefficients of Short Test Emissions vs CUEDC-Mass normalised

	***Correlation Coefficient (R^2) –** mass normalised*				
Short Tests	*Average NOx (g/s)*	*Average HC (g/s)*	*Average PM (LLSP) (mg/s)*	*PM (Filter) (mg)*	*PM (LLSP vs Filter **)*
AC5080	*0.68*	*0.68*	*0.88*	*0.84*	*0.84*
DT80	*0.84*	*0.76*	*0.84*	*0.86*	*0.85*
Lug Down	*0.33*	*0.54*	*0.61*	*-*	*0.70*
2 speed	*0.27*	*0.21*	*0.63*	*-*	*0.59*
D550	*0.24*	*0.26*	*0.23*	*0.49*	*0.34*
Snap Idle	*0.23*	*0.46*	*0.39*	*-*	*0.36*

The far right hand shaded column (LLSP vs Filter) in Table 5-2 contains the correlation values for the relationship between the CUEDC and short tests using the two different particulate measuring techniques (filter paper and LLSP). The correlations are derived from four variables (CUEDC using filter paper and DT80 using LLSP). This provides a an indication of the potential of the short test to be integrated with low cost LLSP equipment and used as an accurate and correlating IM test (see Section 6 for further discussion).

As shown by Figure 5-1 and Figure 5-2 below, mass normalising improves relationship with the trend line for the higher emitting vehicles. Without normalising for mass, there was an apparent loosening in the relationship as emissions increased. This additional analysis, better reflecting the criteria needed to be measured in a short test, also tightens the relationship for the high-emitters - the area where it is most important.

Figure 5-1*:* Mass-normalised particulates - DT80 LLSP vs CUEDC filter mass



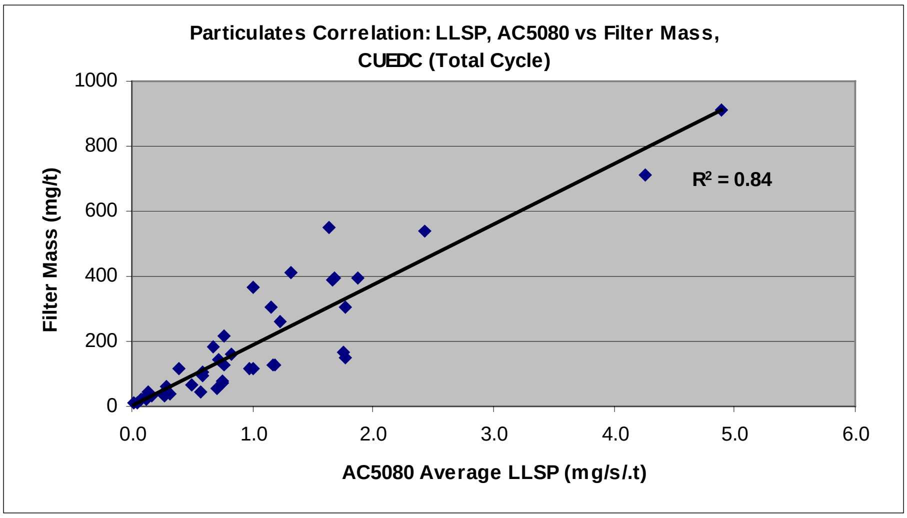


Figure 5-2*: Mass-normalised particulates -AC5080 LLSP vs CUEDC filter mass*

The same normalisation process can be applied to other pollutants whose emission levels are measured on a grams per kilometre basis, most importantly for measurement of NOx. The outcome for the NOx results is to actually reduce the degree of correlation, compared with the gross (non-normalised) results. Nevertheless, the NOx Figures are still excellent for the DT80 and actually help to differentiate which is the better of the two transient tests. Figure 5-3 and Figure 5-4 below show the NOx correlations for the DT80 and AC5080.

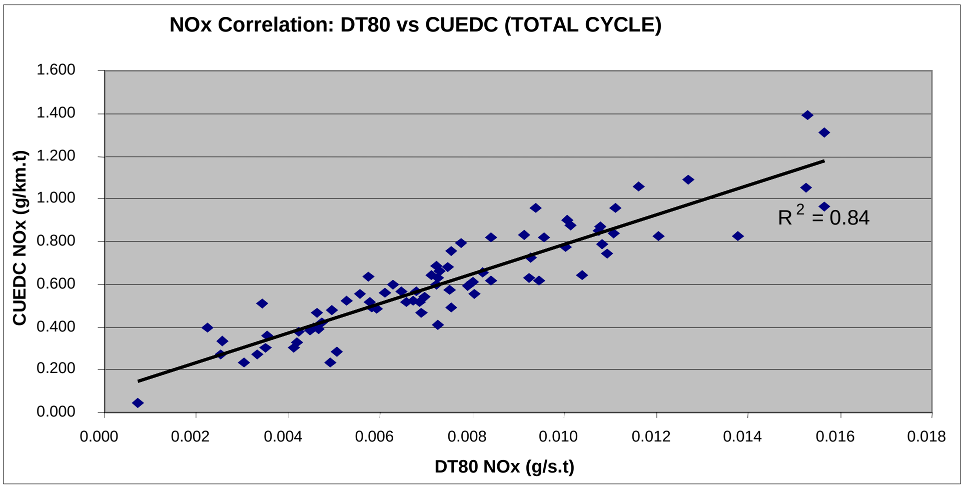


Figure 5-3*: Mass-normalised NOx correlation, DT80 vs CUEDC*

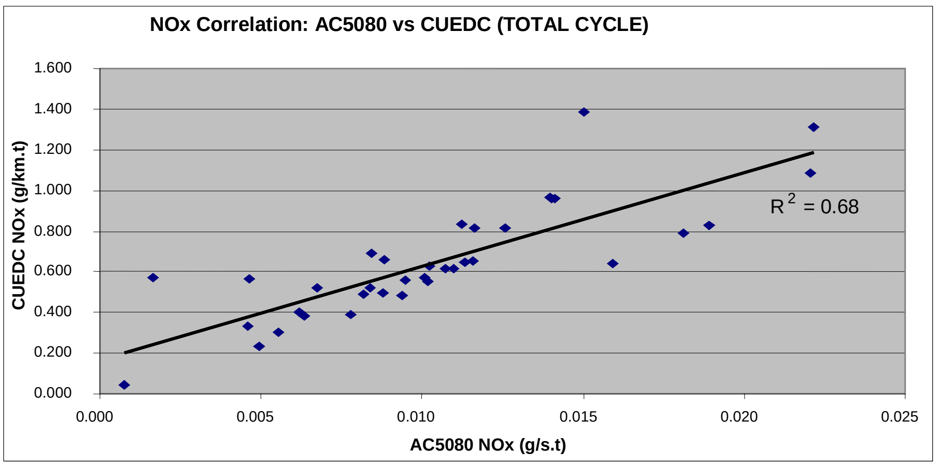


Figure 5-4*: Mass-normalised NOx correlation, AC5080 vs CUEDC*

Although the AC5080 test has a better correlation than the DT80 for the gross NOx emissions, the DT80 is superior when the data are normalised for mass.

5.1.5 Correlations by Road Flow Mode

The correlation data has been further broken down into individual road flow segments for each short test and tabulated in table 6.3. Appendix 6 provides a comprehensive statistical analysis of the short test correlations by individual ADR category.

This analysis was carried out to identify whether some tests actually performed better in specific road flow conditions than others i.e. if one of the lesser overall correlating tests such as the D550 performed better under specific road flow conditions. This would then potentially enable certain tests to be used in congested city areas and others in free flowing regional areas or where traffic flow and therefore vehicle operation was significantly different.

However, the data presented in Table 5-3 below clearly shows that apart from the two transient tests (DT80 and AC5080) the others don't correlate well in any of the road flow modes. In fact all other tests are generally around an R^2 of 0.2-0.3 with a few occasions reaching 0.5 but never greater than 0.6. In comparison the DT80 and AC5080 range from R^2 0.5 to 0.8 across all road flow segments.

Table 5-3: Short test correlations (R^2) by CUEDC road flow segment.

Short Tests vs CUEDC		R^2 values					
Short Test	Road Flow Segments	Average NOx (g/s)	Average HC (g/s)	Average LLSP (mg/s)	Filter mass (mg)	Average Opacity (%)	Maximum Opacity (%)
DT80	Congested	0.51	0.56	0.40	0.31	0.24	0.44
	Minor	0.69	0.68	0.77	0.74	0.58	0.72
	Arterial	0.72	0.70	0.79	0.79	0.62	0.67
	Highway	0.71	0.72	0.67	0.64	0.70	0.72
AC5080	Congested	0.52	0.67	0.49	0.40	0.58	0.47
	Minor	0.62	0.83	0.78	0.78	0.71	0.68
	Arterial	0.57	0.78	0.82	0.83	0.74	0.67
	Highway	0.51	0.65	0.53	0.55	0.57	0.64
2 Speed Torque	Congested	0.13	0.35	0.43		0.18	0.29
	Minor	0.20	0.47	0.50		0.34	0.48
	Arterial	0.22	0.47	0.50		0.34	0.52
	Highway	0.27	0.56	0.36		0.30	0.50
2 Speed Power	Congested	0.17	0.09	0.23		0.14	0.25
	Minor	0.22	0.20	0.40		0.24	0.40
	Arterial	0.23	0.16	0.42		0.27	0.37
	Highway	0.31	0.24	0.22		0.23	0.43
Lug Down	Congested	0.22	0.38	0.36		0.12	0.29
	Minor	0.27	0.46	0.55		0.33	0.53
	Arterial	0.29	0.47	0.60		0.36	0.57
	Highway	0.37	0.57	0.36		0.34	0.58
D550	Congested	0.10	0.00	0.09	0.11	0.05	0.13
	Minor	0.16	0.00	0.27	0.24	0.24	0.28
	Arterial	0.18	0.00	0.21	0.18	0.22	0.27
	Highway	0.25	0.00	0.17	0.15	0.27	0.33
Snap Idle	Congested	0.35	0.28	0.42		0.29	0.43
	Minor	0.29	0.32	0.42		0.35	0.54
	Arterial	0.21	0.25	0.37		0.34	0.50
	Highway	0.19	0.15	0.24		0.27	0.49

5.1.6 Exhaust Opacity

Because smoke (exhaust opacity) is not measured on a mass basis, but simply as a level of obscuration, it is independent of vehicle mass and the correlations already performed to compare the DT80 and the AC5080 continue to be valid. Again, the DT80 proved to be the better test, by a small margin.

The R^2 correlation coefficient for smoke opacity was 0.88 for the DT80, compared with 0.86 for the AC5080.

5.1.7 Summary

Only two tests, the DT80 and the AC5080, appear to have sufficient correlation with the CUEDC for them to be considered for use in an Inspection and Maintenance program.

When normalised for vehicle mass, and hence reflecting a true measure of emissions performance, the DT80 is shown to be better than the AC5080 in measuring both particulates and NOx, and, as will be seen in Table 5-6, in practical discrimination of vehicles with high particulate and NOx emissions. The DT80 also has marginally the best correlation with the CUEDC for smoke opacity.

5.2 Analyses of Results of On-Road Smoke Tests

Australia has national standards for the emission of on-road smoke. The standard states that vehicles should not emit continuous smoke for greater than 10 seconds. Most states have programs or strategies for identifying and rectifying smokey vehicles. In light of the poor correlations between exhaust opacity and emissions of NOx and fine particles presented earlier in this report it is of interest to examine how the emission of on-road ***observed*** smoke relates to emission performance on ***measured*** emission tests.

The following figures compare the time a vehicle was observed smoking on the road to the particulate matter and opacity measured during the DT80 short test i.e. the short test which best correlates with the CUEDC. Note those observed smoking for more than 10 seconds are not included in the figures. These are discussed in the next section.

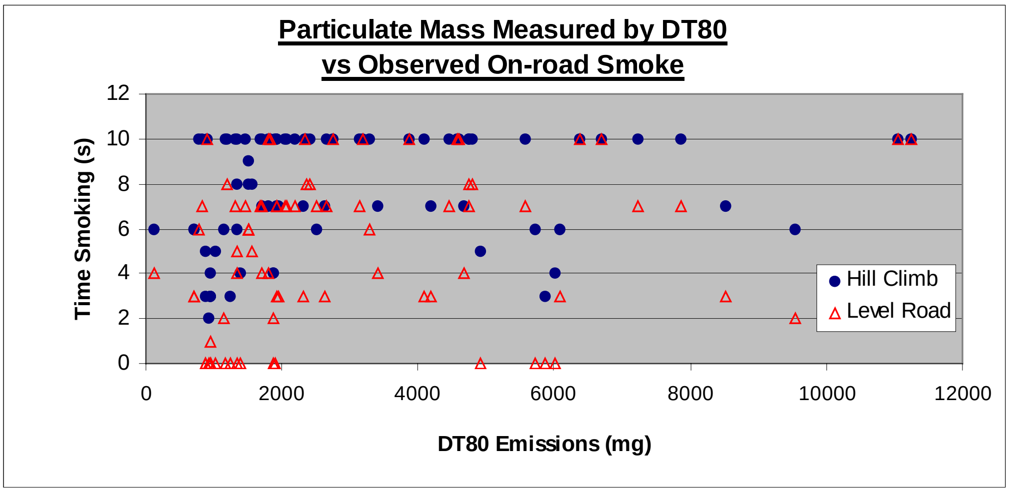


Figure 5-5: Observed on-road smoke vs DT80 particulate emissions

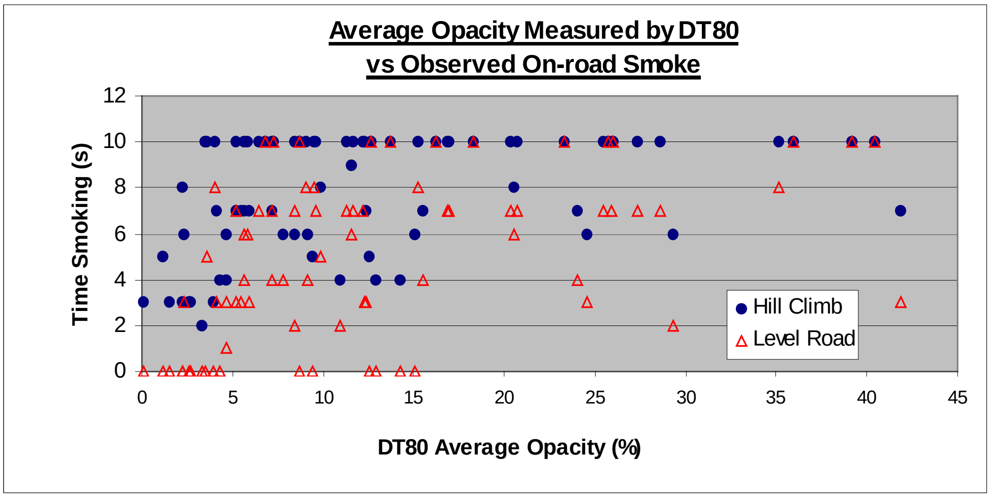


Figure 5-6: Observed on-road smoke vs DT80 average opacity

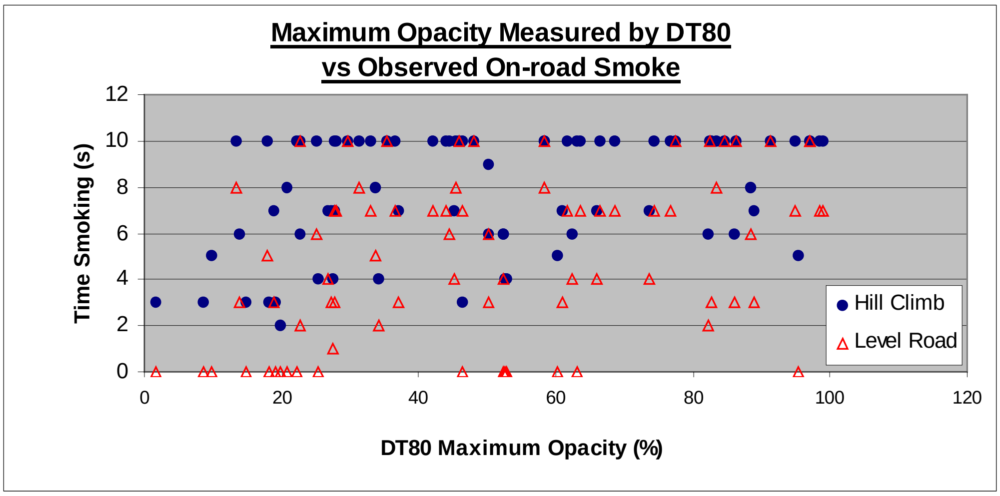


Figure 5-7: Observed On-road smoke vs DT80 maximum opacity

The great deal of scatter in the charts only confirms the previous statements made in relation to the poor correlation of smoke with particulate matter. It also raises questions as to the effectiveness of on-road observations as an IM measure of a vehicles emissions performance.

The data in Table 5-4 below provides an assessment of the potential pass and fail performance of the on-road smoke observation when compared to the measured particulate test results. The table compares the highest 20% of vehicles (16 of the 80 tested) measured for particulate emissions by the CUEDC and DT80 to the number of "high emitting" vehicles (41 on the hill and 12 on the level road) observed continuously smoking during the on-road test. Note for the purpose of this analysis "high emitters" have been classified as those vehicles observed smoking for more than 10-seconds during either the hill or level road test.

Table 5-4: On-road smoke observation vs measured particulate test results

	CUEDC Particulate Matter		DT80 Particulate Matter	
On-Road Smoke Test	**Hill**	**Level**	**Hill**	**Level**
On-road observations identified as smokey vehicles and as high emitters by the measured tests	32% (13/41)	50% (6/12)	24% (10/41)	50% (6/12)
On-road observations identified as smokey vehicles but as low emitters by the measured tests	68% (28/41)	50% (6/12)	76% (31/41)	33% (4/12)

Of those vehicles that failed the on-road smoke test 24 to 50% were also included in the upper 20% of high emitting vehicles measured by the CUEDC and DT80 tests as high emitters. At the same time 33 to 76% of vehicles observed as smoky vehicles were not identified as high emitters (upper 20%) by the measured tests.

The inference of this is that for the on-road smoke test to **correctly** identify 2 vehicles as high particulate emitters, 5 vehicles are also **incorrectly** identified and labelled as high emitters. Furthermore even though 50% are failed 20% still escaped being correctly identified as high particulate emitting vehicles.

This failure to correctly identify high emitting vehicles leads to what is commonly termed as false failure. In an in-service program this would relate to a vehicle wrongly judged as failing the test and having to be repaired when in fact the vehicle was compliant.

Also as expected due to the higher demands on the engine 51%(41) of the 80 vehicles tested exhibited visible smoke for 10 seconds or more under hill slope conditions while only 12 of 80 exhibited continuous smoke under level slope conditions.

Overall the on-road observation test generally classified a higher number of vehicles as high particulate emitters than either of the measured tests (CUEDC and DT80). This may be due largely to the fact that there is no degree of obscurity applied to observed smoke levels - if there is ***any*** visible smoke, no matter how faint, the vehicle is deemed to be an excessive polluter.

In summary, the detection of high particulate emitting vehicles using on-road smoke observations is unreliable at best and could not be used with any confidence as the only means of determining the emission performance of a vehicle. However, the on-road test has a role to play in minimising the damage to visual amenity from vehicles with excessive smoke levels and as such is a useful tool to complement an in-service program that focuses on NOx and PM reductions. It is also important because it is one of the primary indicators of vehicle pollution to the public at large.

5.3 Analyses of Results of 6-Point Inspection

The six features that the project brief required to be inspected did not provide a basis for assessing an individual vehicle's emission levels. Indeed, of the six inspection items, air filter condition was found to have more than a couple of negative inspection outcomes in the whole 80-vehicle test sample.

Comparing observed air filter condition with laboratory measured (CUEDC) emission levels failed to uncover any pattern or meaningful correlation. Comparing filter condition with smoke opacity, the four vehicles with highest measured smoke levels in the CUEDC test were recorded as having "clean" or "moderate" filter conditions, while a number of the lowest opacity vehicles had filters recorded as "need replacing".

For PM, NOx and HC the representation of "need replacing" filters was randomly distributed throughout the 80 vehicles tested and there was no apparent correlation between filter condition and measured emission levels.

Given that overseas research has shown that most high-polluting diesel vehicles' poor emissions performance can be attributed to injector or pump problems, neither of which can be assessed by external inspection, the value of a visual inspection is at best marginal.

5.4 COMPARATIVE ASSESSMENTS OF THE SHORT TESTS

Assessments of the short tests against the criteria specified in the Project Brief, together with their relative rankings, are shown in Table 5-6. These assessments are discussed below under each of the applicable headings.

5.4.1.1 Comparison with Light Duty Gasoline Test Correlations

It is perhaps useful to compare the degree of correlation found between other widely used short tests and their respective reference test. The Australian "National In-Service Emissions" (NISE) project completed in 1995 is similar to thie project. It studied emissions from petrol vehicles and the effectiveness of a number of short in-service petrol vehicle tests. Although a much larger sample (640 vehicles) were tested compared to the 80 in this project, the NISE project only focused on gaseous emissions rather than particulates.

The reference test for the NISE study was the ADR 37 (light duty petrol vehicle) certification test which, like the CUEDC, is a complex, transient test replicating urban traffic flows. There were also strong parallels in the types of short tests evaluated, with a transient, dynamometer test (IM240), two steady-state dynamometer tests (ASM and SS60) and two unloaded tests (idle and high idle at 2500rpm).

As for this project, the best correlations were with the loaded, transient test (IM240), which performed very significantly better for all gases measured (particulates were not regulated for petrol vehicles and so were not included in the evaluations).

The correlations are summarised in
Table 5-5 (note that correlations in the NISE report were recorded as R, and have been converted to R^2 in the following table to be consistent with the correlations in this diesel study).

Table 5-5: Correlations between Short Tests and ADR Results (Petrol Cars)

	ADR 27			ADR 37/00		
	HC	**CO**	**NOx**	**HC**	**CO**	**NOx**
IM240	0.64	0.86	0.83	0.88	0.81	0.81
ASM	0.27	0.50	0.48	0.41	0.61	0.46
SS60	0.38	0.64	0.55	0.64	0.71	0.52
Hi Idle	0.24	0.50	N / A	0.49	0.38	N / A
Idle	0.19	0.30	N / A	0.52	0.45	N / A

Note: ADR 27 applied to cars manufactured 1974-86, ADR 37/00 for vehicles manufactured 1986-97. The certification (reference) test was virtually identical for both ADRs, Comparing the above chart with the corresponding correlation summary for the diesel short tests shows a remarkable similarity. The transient IM240 petrol test, like the AC5080 and DT80 transient diesel tests, is clearly the most effective test, and as such has been widely adopted in petrol Inspection and Maintenance programs.

5.4.1.2 Correlations with Individual CUEDC Segments

The Tables in Appendix 6 of this report summarise correlations between individual segments of the CUEDC and the DT80 and AC5080 tests, respectively. The correlations are further desegregated into the six ADR vehicle categories.

Given the extremely small number of vehicles in each correlation group created by this desegregation, the tables show remarkably good agreement between the two short tests and most of the CUEDC road flow segments.

Only particulate measurements in Segment 1 (congested flow), were shown to have consistently lower correlation, which undoubtedly affected the overall particulate correlation numbers.

The reason for this disparity almost certainly lies in the fundamental difference in power profiles between the CUEDC congested flow and both of the short transient tests.

In the CUEDC congested flow, power demand is generally low, with only moderate acceleration rates and low maximum speeds. In addition, for a large proportion of the time, the vehicle is idling, at rest. Together, these operating modes result in the engine working for most of the time in very inefficient parts of its operating envelope, where emissions can be both high and inconsistent. Review of Segment 1 particulate data reveals that particulate emissions (via filter mass) are quite variable, with heavy vehicles tending towards very high particulate emissions (compared with Segment 2,3 and 4 emission levels), with the reverse being the case for light vehicles.

In contrast, both the DT80 and AC5080 have aggressive acceleration and cruise modes, at much higher speeds, and with very much higher average engine power demands. This type of operation is much more in keeping with CUEDC road flow segments 2, 3 and 4, with which the two short tests have much higher correlation.

Given the extreme difference in operating modes between the two transient short tests and the CUEDC congested flow segment, it is not surprising that the correlation between the two is not as good as for other modes.

5.4.1.3 Practical Effectiveness of the DT80 and AC5080 Tests

As noted above, only two short tests (the DT80 and the AC5080) appear to have sufficient statistical correlation with the CUEDC results to warrant serious consideration for use in an I/M program.

Another, very basic but nevertheless extremely important measure of the potential value of a short test is whether it identifies the same high-polluting vehicles as the CUEDC.

This inherent discrimination, for both the DT80 and the AC5080 tests, was explored in the following manner for the three diesel pollutants of greatest concern, *viz* oxides of nitrogen (NOx), particulate matter (PM) and exhaust smoke opacity:

(a) The test results database was normalised on a mass basis for all gaseous and particulate emissions by dividing each vehicle's g/km emissions by the vehicle's test mass (i.e. the mass of the vehicle when carrying half its maximum payload). This reflects the general rule that emissions over any drive cycle are a function of power consumed, which in turn is largely a function of vehicle mass;

(b) The database was then sorted, for each pollutant, to rank the top 20% emitting vehicles as identified, in turn, by the "reference" CUEDC test and the two candidate short tests. As the vehicle population sample contained 80 vehicles, this resulted in a "high emitter" list of 16 vehicles for each of the tests;

(c) For each pollutant, the "high emitter" list for each of the short tests was compared with the equivalent list derived from the CUEDC results. The number of vehicles that appeared in both the CUEDC and the respective short test's list was recorded.

(d) To gain a feel for the number of "near misses", i.e. vehicles identified by the short test as being in the top 20%, but which were actually only in the CUEDC's top 30% emitters, a second group of vehicles was identified. These vehicles were those in the top 20% of a short test's list, but which were ranked between 17th and 25th in the CUEDC results for a particular pollutant.

(e) Any remaining vehicles were classified as "not selected" vehicles.

The outcomes of this empirical analysis, based on mass normalised emission results, are as follows:

Table 5-6*: Effectiveness of DT80 test to pick highest CUEDC emitters*

Pollutant	No of highest 20% CUEDC emitters (16) selected in top 20% (16) DT80 emitters		No of highest 30% CUEDC emitters (25) selected in top 20% (16) DT80 emitters	
	Selected by DT80	Not selected by DT80	Selected by DT80	Not selected by DT80
PM	11	5	14	2
NOx	13	3	15	1
Smoke Opacity	11	5	14	2

Table 5-7*: Effectiveness of AC5080 test to pick highest CUEDC emitters*

Pollutant	No of highest 20% CUEDC emitters (16) selected in top 20% (16) AC5080 emitters		No of highest 30% CUEDC emitters (25) selected in top 20% (16) AC5080 emitters	
	Selected by AC5080	Not selected by AC5080	Selected by AC5080	Not selected by AC5080
PM	11	5	14	2
NOx	9	7	12	4
Smoke Opacity	13	3	15	1

As can be seen in the tables, both tests performed well, except for the AC5080 in respect of NOx emissions. Although this test had a very high degree of correlation with the CUEDC (around 0.95) using the gross emissions data, when the data was normalised for mass the relationship became a little looser than the DT80.

Overall, both the AC5080 and the DT80 discriminated well in selecting high emitting vehicles, and either would be suitable for use in a periodic vehicle-testing program.

5.4.2 Sensitivity of the test to reflect changes in emission performance.

Perhaps the best means of testing for this would have been to test vehicles over the CUEDCs and the short tests, both before and after adjustment and/or maintenance. This was beyond the scope of the Project specified in the Project Brief, but could be included as a possible extension to Project 7, which includes some repair effectiveness studies.

However, if one were to postulate that the sensitivity of a test to changes in the emissions performance of an individual vehicle can be inferred from the degree to which that test correlated with CUEDC results, then it could be concluded that the AC50/80 and the DT80 tests are superior to all others, with the DT80 being slightly better than the AC5080.

While such a proposition may prove to be correct, there is no way of directly validating it from the data amassed in this project. Consideration should be given to performing this sensitivity analysis in future projects.

5.4.3 Ability to identify reasons for poor emissions.

Overseas studies have identified fuel injector problems and injector pump maladjustment as the source of most excessive pollutants in diesel vehicles. Other service items, such as air and fuel filter condition, have been shown to be much less prevalent as a cause of high pollution.

The transient mixed-mode nature of the DT80 and the AC5080 provides potential for information on which to base judgements of the reasons for poor emissions, assuming real time emissions integrated over each mode are recorded. Both tests would give similar diagnostic guidance on fuel injection system condition and adjustment, governor adjustment, boost control, and air filter condition. The steady state full load tests would give some diagnostic guidance on fuel injection system condition and adjustment and air filter condition. The snap idle and D550 test would give little diagnostic information.

5.4.4 Safety of application

In any test that involves operating a vehicle and/or rotating equipment, there are potential risks to personnel, vehicles and equipment. However, the use of dynamometers for vehicle testing is a well-established procedure and safety precautions have been developed to minimise any danger to operations personnel and vehicle occupants. Potential risks can be minimised through rigorous attention to vehicle condition prior to test, test facility design, equipment maintenance, and operating procedures.

In particular, minimising the number of personnel in a lane, and segregating the drivers and other vehicle occupants from lane operations is of paramount importance.

Because it does not involve the use of a dynamometer, the snap idle test poses the lowest safety risk of the tests evaluated, but experience overseas has shown that there is some risk of engine damage, particularly if the engine is in poor condition or the engine speed governor is incorrectly adjusted.

There is always potential for a defective tyre to blow during a long, heavily loaded dynamometer test. The very short duration of I/M tests, coupled with a rigorous check prior to testing, greatly diminishes the likelihood of this occurring. From testing experience on the rare occasion that extended high speed, high load testing results in a tyre failure no serious consequential damage is likely.

5.4.5 Suitability for use across the range of vehicles tested

The snap idle test is unsuitable for some vehicles with electronic engine management systems that limit free acceleration.

All the dynamometer tests can be used across the full range of vehicles tested. However, care should be taken when specifying the dynamometer to ensure that the rotating masses and parasitic losses are not so great as to affect the accuracy of measurement when testing light-duty vehicles.

5.4.6 Ease of Use

The snap idle test is by far the easiest to use, requiring only a suitable opacimeter and no dynamometer.

The D550 is the easiest of the dynamometer tests to perform as it requires only driving at a constant speed, with the dynamometer pre-set to a fixed retardation load.

Transient tests, such as the AC5080 and the DT80 require the driver to follow on-screen instructions or a moving "drivers aid" trace. This is a skill readily learned by most people with average hand / foot / eye coordination skills.

The lug-down and 2-speed tests are more complex, as they are done in two stages; the first to determine the vehicle's maximum power and torque, and the speeds at which they occur; the second to drive the vehicle at these speeds, or some multiple of them, at full throttle. Unless this procedure is fully automated, it involves some calculations and decision-making on the part of the driver / operator.

5.4.7 Time requirements for test

The snap idle test can be completed in less than three minutes. The dynamometer-based tests each require a total time of around 15 minutes for safety inspection, set-up, and test.

Actual lane throughput would be much faster if the test sequence is broken into 2 or more stages. That is, Stage 1 would be registration and safety checks, Stage 2 would be the test component, Stage 3 would be visual inspection of filters, pumps, etc and issuing of test results to driver. In this case, a stream of vehicles would complete the test at a rate of around 6 to 8 per hour.

5.4.8 Resource requirements for test

The snap idle test requires just a relatively inexpensive (~$12,000) opacimeter and a relatively small open area. The test can be conducted by a single technician having minimal training.

The steady-state tests (D550, full load / 2-speed, and lug-down) require a relatively simple dynamometer, gas sampling equipment, instrumentation and computing equipment, with an estimated purchase price of up to $350,000.

The transient tests (the AC50 / 80 and DT 80) require more sophisticated and expensive dynamometer, gas sampling equipment, instrumentation and data logging / processing equipment, at an estimated cost of up to $450,000.

(Note that for light-duty vehicles, the same dynamometer could be used for testing both spark-ignition and diesel vehicles, provided it could be readily switched between the different drive cycles required. Only the measuring equipment would need to differ, at a cost of probably $AUS 80,000)

The above costs are based on a single driving axle (or a differential lock that allows one pair of wheels to rotate on idle rollers without diminishing power delivery to the other axle). Virtually every twin drive axle truck has this capability.

Note that the above costs are for the test equipment only. Facility costs will vary considerably, depending on whether existing facilities are utilised / adapted, and on the way asset values (land and buildings) are attributed.

The dynamometer tests would require a team of at least two lane technicians.

Depending on the test facility location, consideration also needs to be given to avoiding excessive noise levels.

5.4.9 Suitability for Use in Large Scale Testing Programs

The transient tests (AC50/80 and DT80) are most suited to dedicated test-only facilities that are most likely to be used in large-scale testing programs, where their high resource requirements (test cell, dynamometer, instrumentation, etc) can be justified by their greater effectiveness and high utilisation rates.

The snap idle test (used in many overseas countries) has much superficial attraction due to its low cost and simplicity. However, its lack of correlation with on-road emissions is leading many overseas researchers (particularly in North America and Europe) to search for an alternative.

We assess the steady-state dynamometer tests (the D550, full-load/2-speed, and lug-down) as unsuitable for large-scale in-service testing programs due mainly to their poor correlation with on-road emissions replicated in the CUEDCs.

5.4.10 Correlation with 6-Point Inspection and 10-Second Smoke Rule

We have found no significant correlation between the results of the 6-point inspection and any of the short tests. We therefore provide no score for this procedure.

In respect of the 10-second on-road smoke test, the Ringleman Scale used for visually estimating smoke opacity from vehicles during on-road use, is a very coarse measure, graded 0 (clear) to 3 (dense black smoke). As a result, it is difficult to do a meaningful statistical analysis. Comparing the observed Ringleman numbers with corresponding CUEDC opacity readings, it was apparent, nevertheless, that vehicles with low opacity readings in the laboratory tended also to rate as low on the Ringleman scale. Conversely, vehicles with a high-observed Ringleman number were all measured to have at least 30% opacity in laboratory tests.

Given that there is little correlation between smoke and any of the other pollutants of concern, on-road 10-second smoke observations are not suitable for an emissions program focusing on particulates and NOx. Visual observations are, nevertheless, a useful adjunct to a dynamometer-based program in helping to identify vehicles that may not receive adequate maintenance, and diverting them to a test centre for an instrumented test.

5.5 OVERALL TEST RANKING

Table 6.6 overleaf provides a ranking of 1 to 10 for all aspects of the tests referred to above. A ranking of 10 is the highest or best.

The AC50/80 and DT80 rate quite closely as best and second best on the quantitative and qualitative assessments above. These are followed by the snap idle test. The last three are quite close in the assessment, and (in order) are the lug-down test, the 2-speed test and lastly the D550.

In finally differentiating between the top two rated tests, the following additional points should be considered -

- AC5080 is not as aggressive as DT80, placing lesser demands on equipment and vehicle. It would likely cause less concern from vehicle owners that damage to the vehicle may be caused through testing.
- The AC50/80's acceleration to 50 km/hr and subsequent acceleration to 80 km/hr are more common in "real world" driving than the DT80's acceleration direct to 80 km. This is evident in the CUEDC's.
- The DT80's three acceleration phases provide potential for 'fast pass' criteria to be set.
- Equipment, operation and labour costs are very much the same for the AC50/80 and the DT80 cycles.

Based on these (non-correlation) aspects, we consider the AC50/80 and the DT80 to rank equally in cost, safety, personnel requirements and other operational issues. The DT80's superior performance in identifying high polluters makes it the better choice of test, but not by a wide margin. Nevertheless, we consider there is scope to further refine both tests, to reduce throughput times and possibly improve performance through better simulation of congested traffic operations. The effects of pre-conditioning in improving the consistency of measurements should also be explored.

Table 5-8*: Evaluation of Short Tests*

(10 = highest potential value, 1 = no value)

Criterion		AC50/80	DT80	Full Load 2-speed	Lugdown	Snap Idle*	D550
Correlation with CUEDCs	**NOx**	7	9	6	6	5	6
	PM	7	8	2	2	0	0
	Opacity	8	8	2	2	2	0
	HC	9	8	2	6	5	2
Sensitivity to reflect changes in emissions over the CUEDC		8	8	3	4	3	2
Ability to identify reasons for poor emissions		6	6	4	4	2	2
Safety of application		8	8	8	8	9	8
Suitability for use across the range of vehicles tested		8	9	7	7	9	8
Ease of use		7	7	4	4	9	8
Time requirements		5	5	5	5	8	5
Resource requirements		5	5	7	7	10	7

Criterion	AC50/80	DT80	Full Load 2-speed	Lugdown	Snap Idle*	D550
Suitability for wide use in large scale in-service vehicle testing program	8	7	7	7	9	2
Correlation with 10-second Rule						
Correlation with 6-point inspection						
Overall Rating (sum above)	86	88	57	62	64	46

Note: *Snap idle is unsuitable for vehicles with electronic engine management that limits free acceleration.

6. COMPARISON OF PARTICULATE MEASUREMENT TECHNIQUES

6.1 COMPARISONS OVER THE CUEDCs

Comparisons of the results of all particulate and opacity measurements using the various instruments discussed above have been made, and correlation coefficients derived for all vehicles across the CUEDCs. These are summarised below in Table 6-2.

Table 6-1: Particulate Measurement Correlation over the CUEDCs

Measurement Comparison	Correlation (R^2)
Filter v APS PM10	0.98
Filter v TEOM	0.96
Filter v LLSP	0.92
TEOM v LLSP	0.90
LLSP v APS PM10	0.88
LLSP v Average Opacity	0.39
Filter v Average Opacity	0.38
TEOM V Average Opacity	0.38
APS PM1, PM2.5, PM10 v Average Opacity	0.27/0.26/0.26
Filter v Maximum Opacity	0.05

The scatter plots, from which these correlations were derived, are shown in Figure 6-1 to Figure 6-12. The Figures illustrate the effectiveness of each instrument with reference to filter mass and smoke opacity.

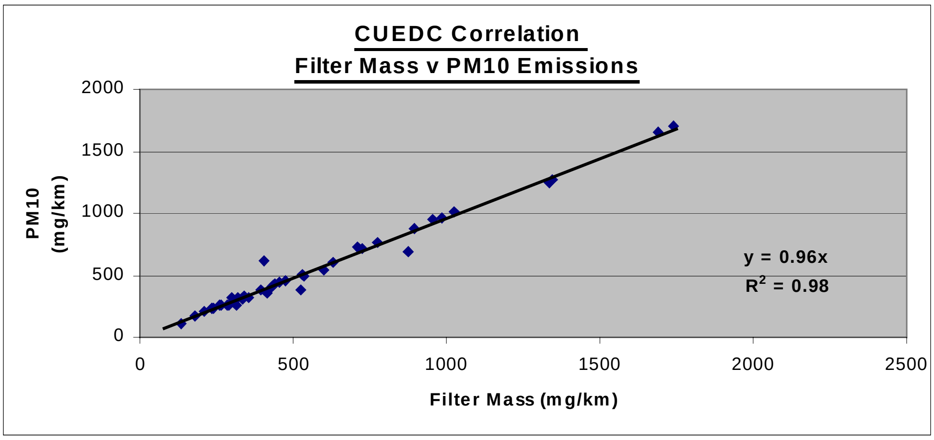


Figure 6-1: Filter v PM10 over CUEDCs

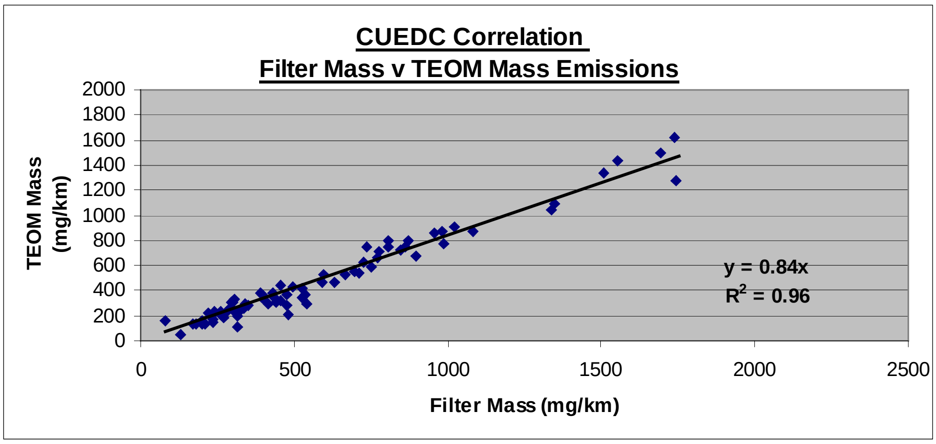


Figure 6-2: Filter v TEOM over CUEDCs

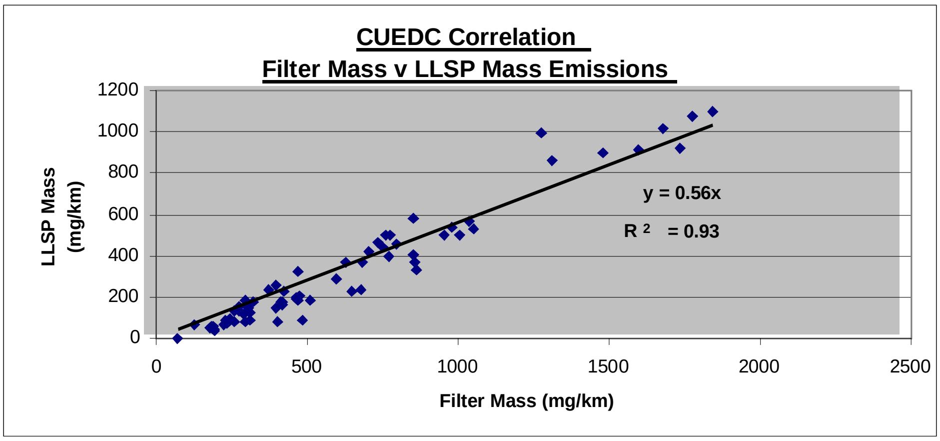


Figure 6-3: Filter v LLSP over CUEDCs

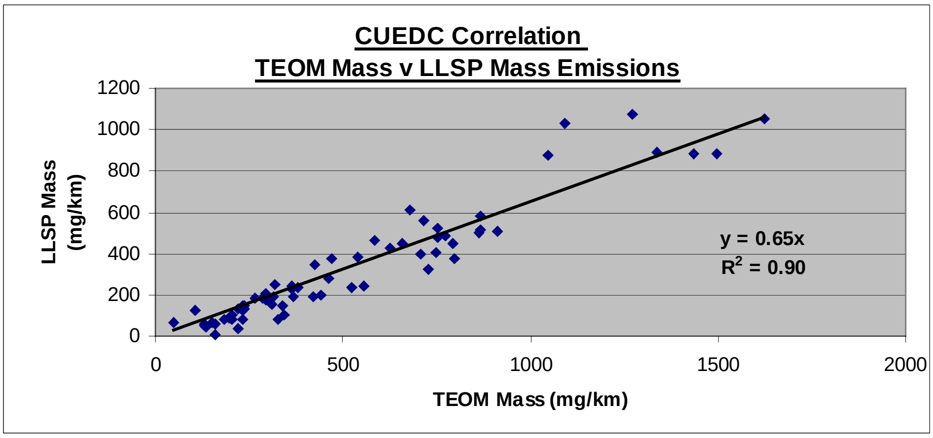


Figure 6-4: TEOM v LLSP over CUEDCs

As illustrated in
Figure 6-2 to Figure 6-4 the TEOM (laboratory grade instrument) is in good agreement with the filter (Figure 5.1) but surprisingly, given its low cost, so is the LLSP. Only 4 percentage points separate the instruments in terms of correlation (R^2). However, the values reported from both instruments are lower than the reference filter. A reason for this is provided in the discussion below Figure 6-6.

The very highly correlated APS instrument (measuring all particles below 10µm) as illustrated in Figure 6-1 is shown below against the LLSP. Again the LLSP reports a lower value but it also maintains a high correlation (R^2 0.88) in line with the other particulate measuring techniques. Figure 6-6 compares the three instruments (TEOM, LLSP, and APS) against filter.

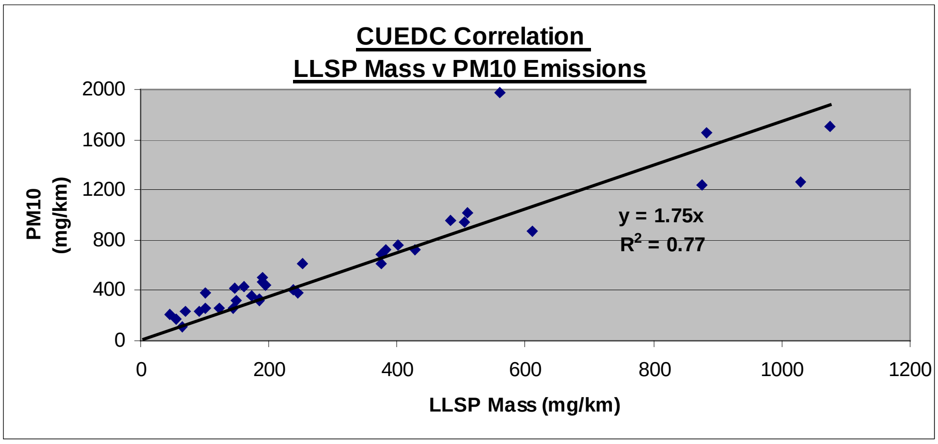


Figure 6-5: LLSP v PM10 over CUEDCs

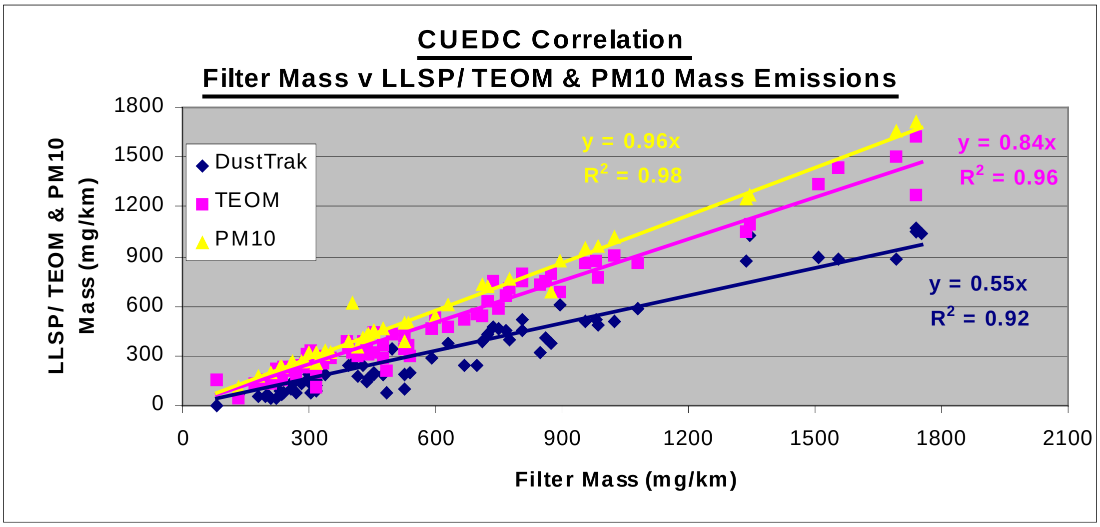


Figure 6-6: Filter v LLSP, TEOM and PM10 over the CUEDCs

The TEOM, LLSP and APS (Pm10) have excellent correlations (R^2 0.96, 0.92 and 0.93 respectively) with the filter paper mass. However, as already briefly mention all instruments report lower values (in descending order of APS, TEOM and LLSP) than the filter. This is evidenced by the equations of the respective regression lines (y=0.96x, 0.84x and 0.55x) noted on the graph.

The lower values reported for the TEOM are accounted for by the slightly higher operating temperature (55 deg. C) of the instrument which causes more of the soluble organic fractions (SOF's) normally stuck to the extremities of carbon core of particles to be driven off. In comparison, the sample collected by the filter paper is maintained well below 51.7 deg. C and so less of the SOF's are driven off, resulting in a higher total particulate mass.

The LLSP while not new to measuring particles, its application as a diesel vehicle exhaust measuring instrument is and as such calibration data for transient test conditions such as the CUEDCs is limited to this project. Supplementing the existing calibration data used to initially "set up" the instrument with the data collected during this project will deliver a finer calibration scale.

However, the situation changes dramatically when smoke opacity vs filter, TEOM, LLSP or APS (Pm1, 2.5 and 10) is evaluated. Average opacity reported across the cycle is used as the measure of smoke.

As smoke opacity has historically been used to assess diesel vehicle particulate emissions we have drilled into many areas of the database and compared a number of instruments in an effort to uncover relationships that would support and sustain this approach. However, as we travel from Figure 6.7 through to 6.15 it is clear that smoke is not a good determinate of a vehicle emissions status nor does it correlate well with proven particulate measuring instruments or hold any potential (through calibration or correction) to become so.

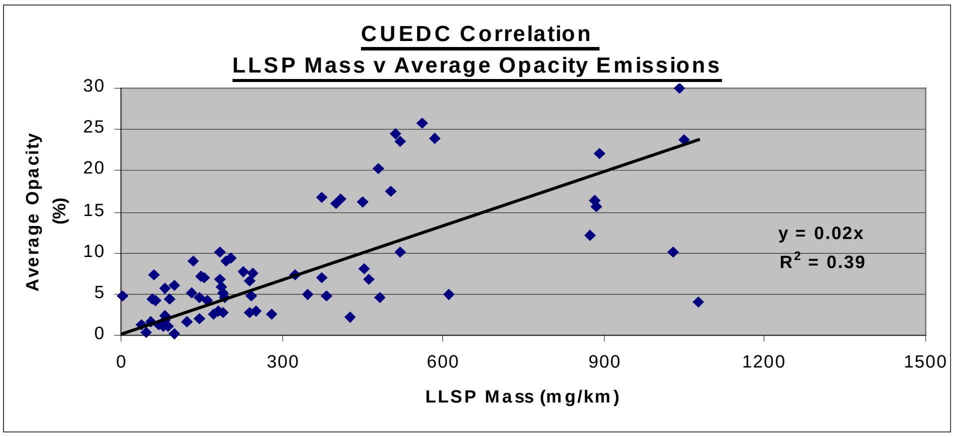


Figure 6-7: LLSP v Average Opacity over CUEDCs

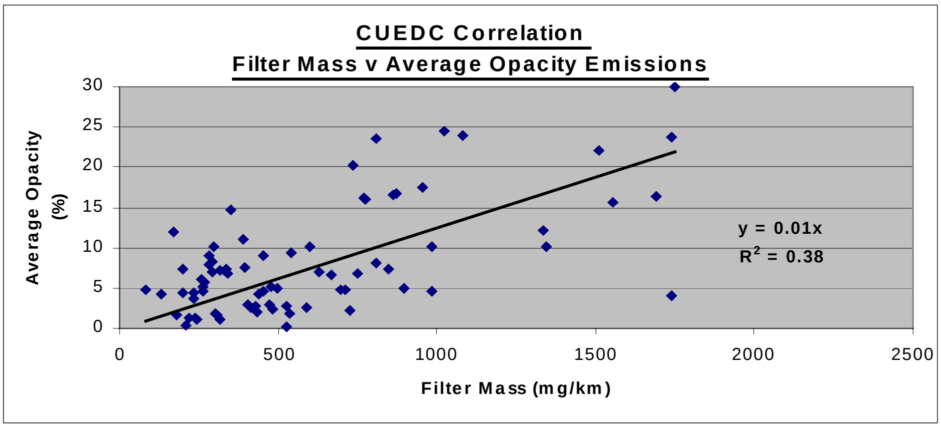


Figure 6-8: Filter v Average Opacity over CUEDCs

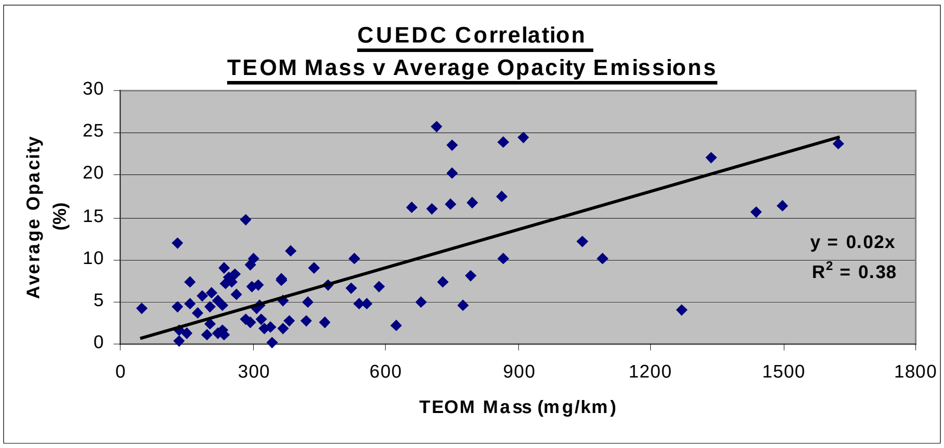


Figure 6-9: TEOM v Average Opacity over CUEDCs

Figure 6-7 to Figure 6-9 as expected all show similar low correlation values of R^2 0.38 for all three particulate mass measuring instruments (TEOM, LLSP and Filter). The APS instrument is correlated slightly lower at R^2 0.27 for all size ranges in Figure 6-10 to Figure 6-12 below.

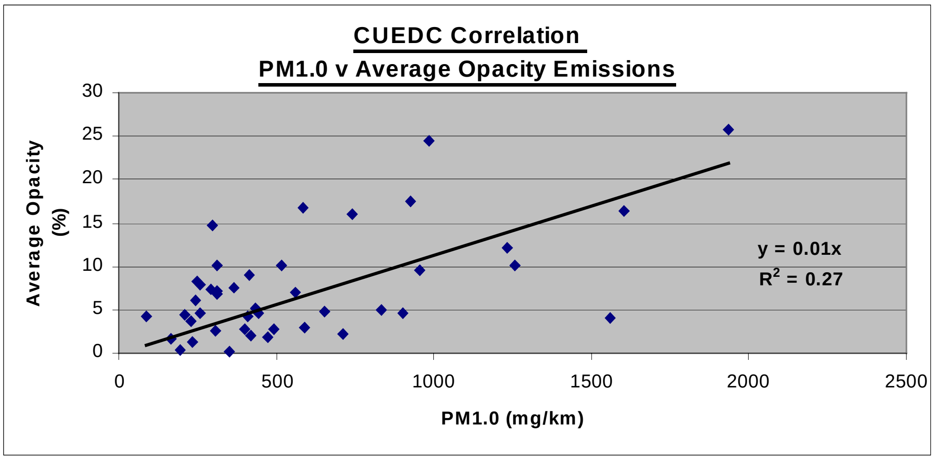


Figure 6-10: APS PM1 v Average Opacity over CUEDCs

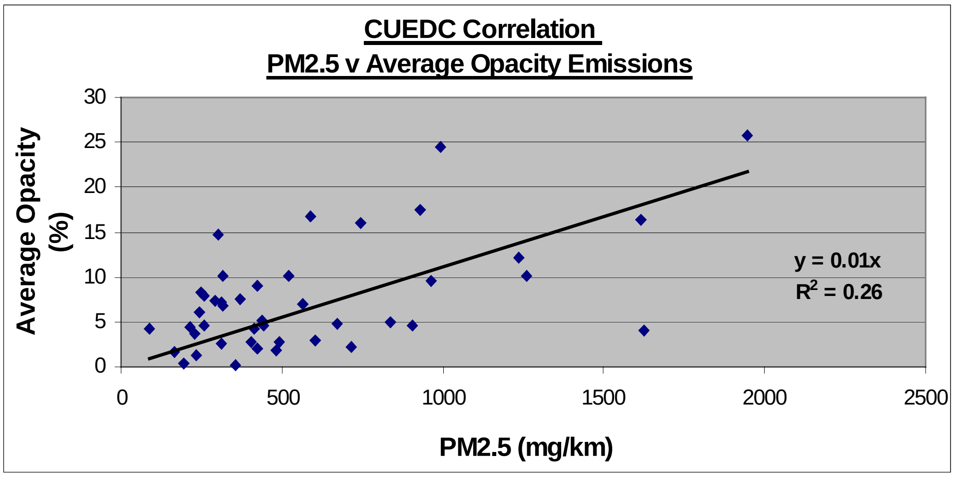


Figure 6-11: APS PM2.5 v Average Opacity over CUEDCs

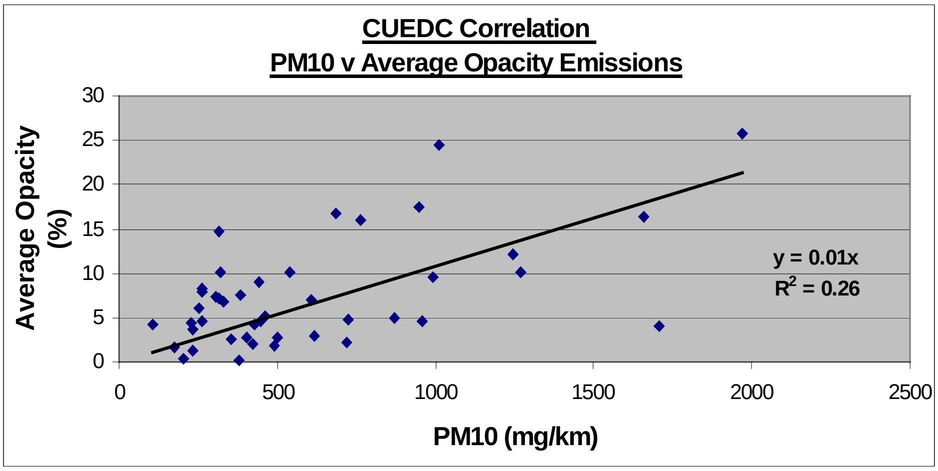


Figure 6-12: APS PM10 v Average Opacity over CUEDCs

The next two Figures (Figure 6-13 and Figure 6-14) are refinements of the previous APS data that investigates the relationship of the % mass of particles in a specific size range.

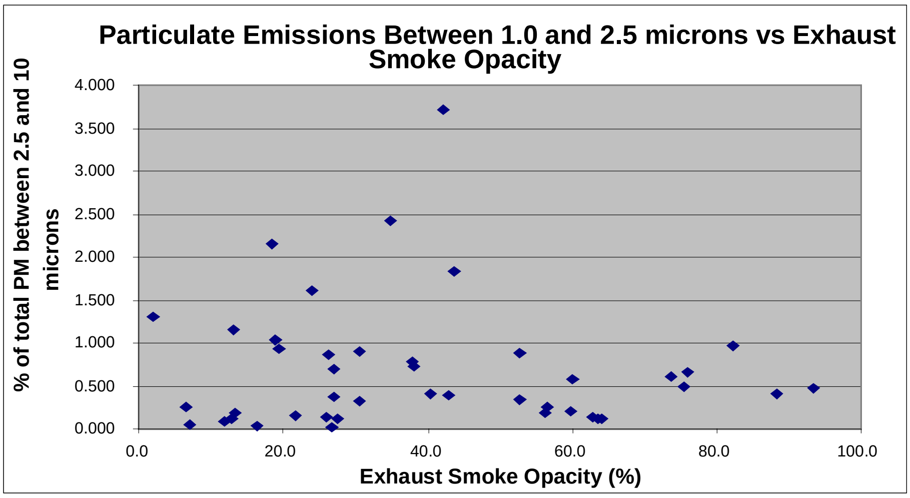


Figure 6-13: % of APS Pm (>1.0 < 2.5) v Smoke Opacity over the CUEDC

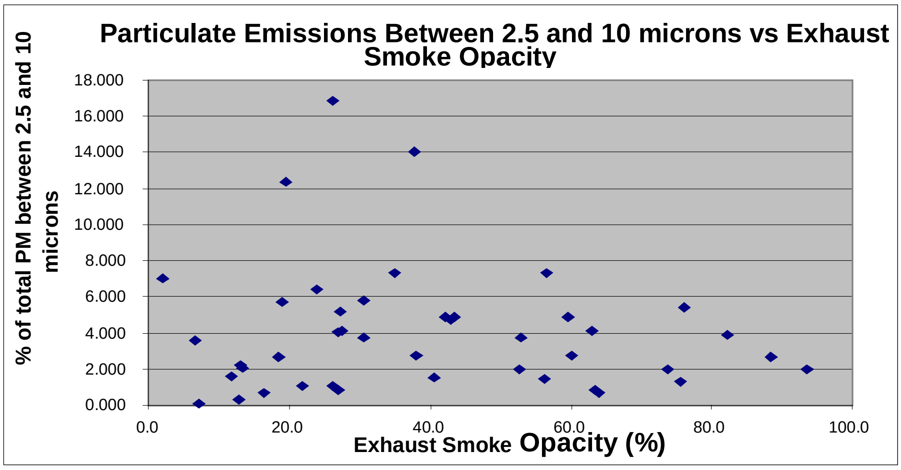


Figure 6-14: % of APS Pm (>2.5 < 10) v Smoke Opacity over CUEDC

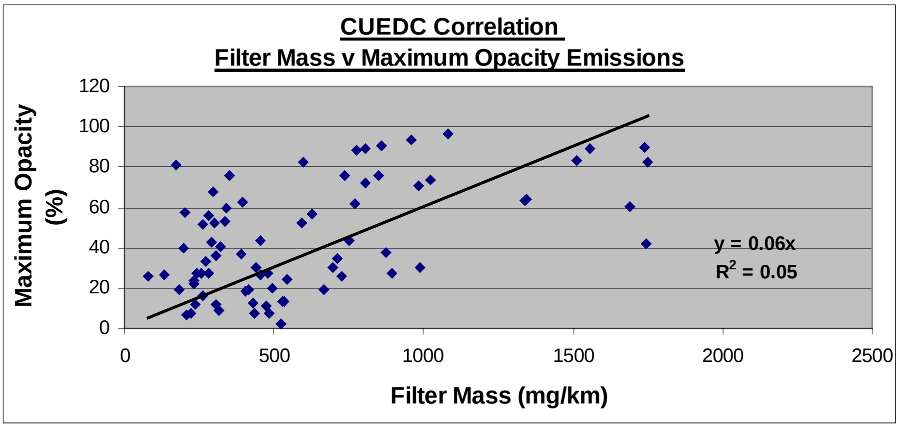


Figure 6-15: Filter Mass v Maximum Opacity over CUEDCs

Figure 6-15 compares maximum rather than average smoke opacity with filter mass. Again there is no correlation (R^2 0.05). The other instruments have also been compared with maximum opacity. However as they also exhibit poor correlations there is no value in presenting a further series of graphs.

6.2 COMPARISONS OVER THE SHORT TESTS

Comparisons of the particulate mass results from the filter paper measurement, against LLSP and Opacimeter results over the D550, DT80 and AC50/80 tests are presented in appendix 4 and here as Figure 6-16 and Figure 6-17.

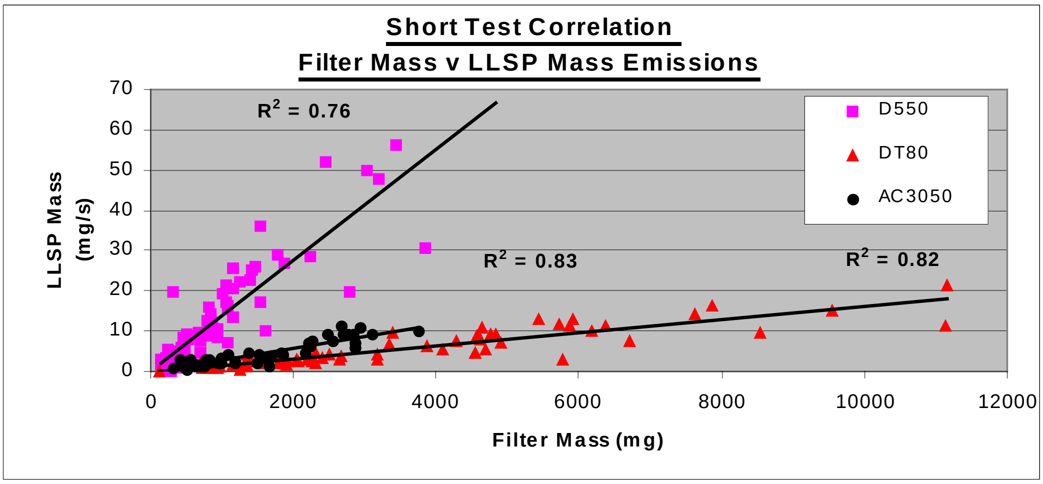


Figure 6-16: Particle Filter Mass v LLSP over DT80, AC50/80 and D550

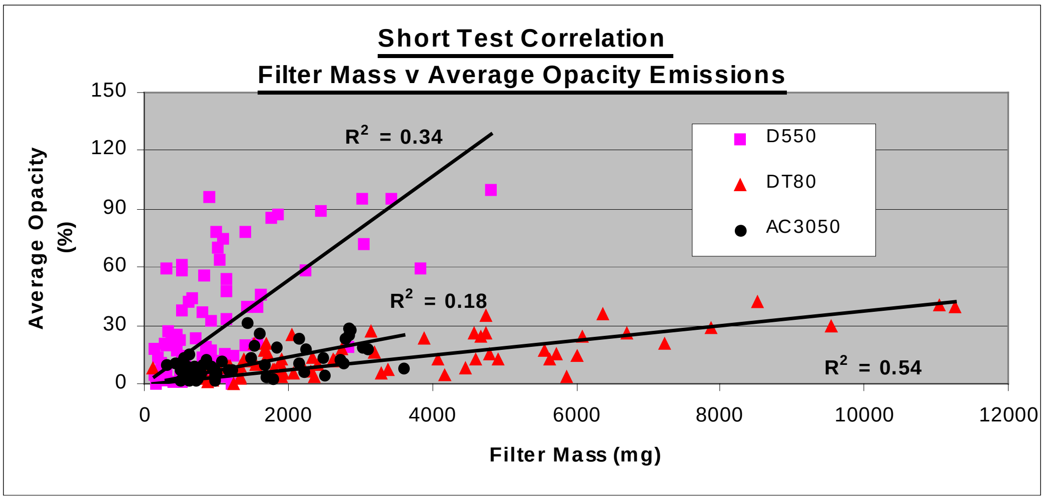


Figure 6-17: Particle Filter Mass v Average Opacity over DT80, AC50/80 and D550

These correlations are summarised in Table 6-2. It should again be stated that the AC5080 and DT80 are transient tests while the D550 is a steady state test.

Table 6-2: Particle Filter Mass v LLSP and Average Opacity over Short Tests

	Correlation (R^2)	
Short Test	**Filter v LLSP**	**Filter v Ave Opacity**
AC50/80	0.83	0.18
DT80	0.82	0.54
D550	0.76	0.34

The slightly better correlations achieved for the transient tests is encouraging as it gives added confidence in the LLSP's ability to perform during the relative harsher "real world" transient conditions as well as the more stable steady state conditions of the D550. It is also worth noting that the short tests are ~2 minutes in duration compared to the CUEDC of ~30 minutes, however the LLSP performs well under both sampling conditions.

The data also shows the similarities in the data of the two inertia loaded transient tests compared to the higher loaded D550. The DT80 being more aggressive (accelerating to 80km/hr three times) than the AC5080 generates ~3 times as much particulate which can be problematic for IM test applications if sample handling systems become effected by the high particulate loadings generated by rapid acceleration to high speeds.

Smoke opacity does not correlate well although it is noticeable that the R^2 for the DT80 is higher (0.54) than the previously reported values. However, similar poor values are reported for the other two tests. This again demonstrates that even during a simple short test, smoke opacity is not a good measure of a vehicles particulate emissions status.

6.3 Summary

The Filter, APS, TEOM and LLSP have all shown to be in excellent agreement with each other. This provides further confidence in the measuring techniques employed by all the instruments used to measure particulates.

In terms of operational practicality, the LLSP proved to be far superior than the other laboratory grade instruments. It is a very robust, compact and a simple instrument to operate that is suited for workshop environments. Coupled with its demonstrated repeatability and accuracy it is also suitable for widespread integration into gaseous measuring systems and use as a means of measuring particulate matter in vehicle inspection and maintenance programs.

As a huge bonus, the LLSP costs at least an order of magnitude less than any of the other instruments currently available to measure diesel particulate emissions.

Smoke opacity (average or maximum values) did not correlate with any of the particulate instruments used. This leads to the conclusion that opacity cannot satisfactorily be used as a surrogate for particulate mass measurement. However, this in no way undermines the value of opacity measurement in assessment of **visible** smoke (public annoyance and perceptions of pollution).

7. CONCLUSIONS

As mentioned earlier readers should note that, from this sample size (80 vehicles), relationships that are based on data from <u>all</u> the vehicles tested, should be fairly robust. On the other hand, some of the age/category groups contain only a very small number of vehicles and so it may not be appropriate do draw any firm inferences, at this stage.

Based on the results obtained the following conclusions are made under the two main headings: ***Inventory and Inspection & Maintenance:***

7.1 INVENTORY

1. The diesel vehicle fleet displays a highly variable emission profile, unlike the petrol fleet where a more consistent profile is evident.
2. In the main areas of concern (NOx and Particulates), new engine technologies are delivering lower Particulate emissions. However, there has been little if any overall reduction in average NOx emissions over the last two decades.
3. No single road flow condition of the 6 CUEDC's is dominant in terms of grams emitted per kilometer travelled. The proportion of emissions generated in each road flow category can vary, depending on the mass of the vehicle tested.
4. Approximately 90% (by mass) of all diesel Particulate emissions have a size of less than 1 micron.
5. Smoke opacity is not a surrogate for particulate emission levels. It should only be referred as a measure of visual amenity. As such, smoke density cannot be used in isolation to determine the emission performance of a vehicle. Particulate emission levels can only be reliably determined by directly measuring the particles.

7.2 INSPECTION & MAINTENANCE

The short test evaluation has shown that:

1. Dynamometer-based short tests with transient acceleration segments perform much better than unloaded or steady state tests in estimating "real world" emissions of all regulated pollutants.
2. There is a very poor correlation between smoke opacity and particulate emissions. Smoke opacity is a measure of visual amenity only.

3. Of all the short tests evaluated in this project, the DT80 and AC5080 are by far the most suitable tests for determining if a vehicle is a high emitter. These tests have excellent correlation with CUEDC emission levels, for all pollutants.
4. The DT80 performs somewhat better than the AC5080 in regard to practicality and suitability for IM program application.
5. The 6-point inspection did not provide a clear indication of a vehicle's state of tune or its emissions performance.
6. The On-Road smoke test also did not correlate well with the CUEDC and was onerous and impractical as an IM test. On-road smoke observations may, nevertheless, have some use as a supplementary tool to support a loaded test IM program.
7. Laser light-scattering photometry, in conjunction with effective sample pre-conditioning techniques, can be an accurate, robust and reliable method of measuring particulate mass and has strong potential as an effective, low cost IM tool.