Analysis of Australian
In-service Vehicle Emissions Data

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Executive Summary

The data from in-service emissions testing of 523 Australian vehicles has been analysed to determine the effects on emissions of repairs to these vehicles and to compare six types of emissions tests. The results are preliminary due to some minor inconsistancies in the data. Key results are:

- The worst-polluting vehicles produce a disproportionate amount of the total emissions. For example, the worst 10% of post 86 vehicles were responsible for more than 30% of total emissions of CO and HC from post 86 vehicles.
- Repairs to all vehicles led to an overall reduction in emissions ranging from 10% (NOx) to 27% (CO). The cost of repairs averaged $152 per vehicle, including a labour cost of $70 per vehicle. Assuming the repairs last 2 years the cost is $76 per vehicle per year. In a number of cases repairs increased some emissions by small amount - this was generally confined to the latest year models tested.
- A program which targets high-emitters for repairs can be more effective in terms of emission reductions. For example, repairing the worst 20% of HC emitters produced 81% of the total reductions in HC due to repairs and repairing the worst 20% of NOx emitters produced 74% of the total reductions in NOx due to repairs.
- Fuel consumption savings due to repairs were highly variable but averaged $24 per vehicle per year. Taking into account fuel consumption savings, the net cost effectiveness for repair of all vehicles was $4,300 per tonne of HC saved and $5,800 per tonne of NOx saved. These compare favourably with other pollution control measures evaluated by the NSW EPA. These results are based on the assumption that no testing is conducted and all vehicles are repaired.
- When the results of the shorter, cheaper tests are compared with those of ADR37 tests there is a relatively high proportion of false-failures and false-passes. False failures should be avoided because they indicate that repairs are less likely to be effective in reducing emissions (and in a few cases, may increase emissions). Correlation co-efficients derived from comparing short test results with ADR37 results support this observation. Only the more complex IM240 test had reasonable correlation with ADR37.
- Targeted repairs (such as requiring the worst 10% of vehicles to be repaired) can lead to a substantial improvement in net cost effectiveness (including fuel savings but not test costs). In some cases there is a net saving to the vehicle owner because fuel savings exceed repair costs.
- For the short tests, the cost of performing emissions testing is of the same order as repair costs and therefore inclusion of test costs has a strong influence on the cost effectiveness calculation. A test which is used to target vehicles for repair must be relatively cheap otherwise the costs become prohibitive. For example, at a 5% failure rate, on average 20 vehicles must be tested to detect one failure. The cheapest tests are more likely to result in false failures and therefore less effective repairs but the overall cost effectiveness is still estimated to be better than more expensive tests.
- The overall cost effectiveness of repairing all vehicles, without conducting any screening test, is similar to that of a program which includes a short test for targeted repairs. This is due to the relatively high costs of the short tests evaluated in the study.
- Tentative results indicate that the onset of noticeable deterioration in the performance of catalytic converters occurs in the odometer range 100,000km to 150,000km but there are several confounding factors in the analysis. The number of cases where the catalyst was replaced is too

small for reliable analysis but the results for eleven vehicles suggest that there might be merit in targeting this type of repair.

1. Introduction

During 1994/5 the Federal Government funded an in-service emissions study. The NRMA supplied tune-up and repair services and technical advice. Details about the study and its findings are reported elsewhere. The purpose of this report is to set out the results of some additional data processing which was undertaken by Vehicle Design and Research Pty Limited for the NRMA.

These are preliminary results and are intended to give guidance on ways in which the data might be further analysed. At the time of writing some minor inconsistencies in the data had been identified but revised data were not available in time to incorporate in the report. It is therefore possible that subsequent analysis will arrive at slightly different results.

2. Background

About 600 vehicles were selected randomly from private owners. The selection was 200 vehicles manufactured between 1980 and 1985 inclusive ("Pre-86") and 400 manufactured between 1986 and 1991 inclusive ("Post-86"). This break point marks the implementation of Australian Design Rule 37/00 (ADR37) which saw the introduction of unleaded petrol and catalytic converters.

For a variety of reasons not all selected vehicles were tested. Valid ADR37 test results were obtained for 172 Pre-86 vehicles and 351 Post-86 vehicles.

Testing was undertaken at three laboratories: 196 tests were conducted by Ford Motor Company, 180 by the NSW EPA and 147 by the EPA of Victoria.

3. Types of Emissions Tests Conducted

Where possible, each vehicle was subjected to the following tests.

1. **ADR37** - Australian Design Rule 37/00

   An exhaust emissions test cycle which is applicable to passenger cars and other light vehicles manufactured on or after 1 January 1986 and fuelled by petrol. Note that pre-86 vehicles were also subjected to this procedure.

The test involves use of a chassis dynamometer for a driving cycle intended to simulate a range of driving conditions, with speed varying between zero and 94 km/h over a total distance of about 12km. Emissions are determined from the concentration of pollutants collected over the entire test cycle and the results are converted to grams per vehicle kilometre. The ADR37 limits for passenger cars are:

Hydrocarbons (HC)	0.93 g/km
Carbon Monoxide (CO)	9.3 g/km
Oxides of Nitrogen (NOx)	1.93 g/km

About one third of vehicles were also subjected to the evaporative emissions test of ADR37. In this case the vehicle is enclosed in a "Sealed Housing for Evaporative Determination" (SHED) under prescribed conditions, including the heating of fuel in the fuel tank. The ADR37 limit for passenger cars is 2 grams of HC per test.

2. **SS60** - Steady State Loaded 60km/h

   The vehicle is driven on a chassis dynamometer at a constant 60km/h. The emissions are collected by constant volume sampling (CVS) and the results are converted to grams per kilometre. HC, CO and NOx are measured.

3. **ASM** - Accelerated Simulation Mode Test Procedure (ASM2525)

   The vehicle is driven on a chassis dynamometer at a speed of 40km/h (manual vehicles in 2nd gear). Concentrations of raw exhaust emissions are sampled using infra-red analysers or equivalent. The results are in parts per million (ppm) for HC and NOx and % volume (%vol) for CO.

4. **IDLE** - Steady State Idle Test Procedure

   With the engine running at idle speed (accelerator not depressed) the concentrations of raw exhaust emissions are measured for CO (%vol) and HC (ppm)

5. **HI-IDLE** - Steady State High Idle Test Procedure

   With the engine running at a speed of 2500 rpm the concentrations of raw exhaust emissions are measured for CO (%vol) and HC (ppm)

6. **IM240** - Modified IM240 (Inspection & Maintenance) Test Procedure

   This is based on the test prescribed by the US EPA for vehicle inspection and maintenance programs. The test involves a short driving cycle which is similar to the start of the ADR37 cycle but only covers about 2km total distance. Emissions are collected by CVS and results are converted to grams per kilometre. HC, CO and NOx. are measured.

Vehicles were tested in the condition in which they were received. After the first series of tests (1 to 6 above) they underwent tune-up and repairs and were re-tested. The effects of repairs on emissions and fuel consumption could then be established.

For the purpose of data processing the test results were divided into pre-86 and post-86 vehicles due to the significant change in emissions standards applying from 1 January 1986. Most of the following results are based on these two groups.

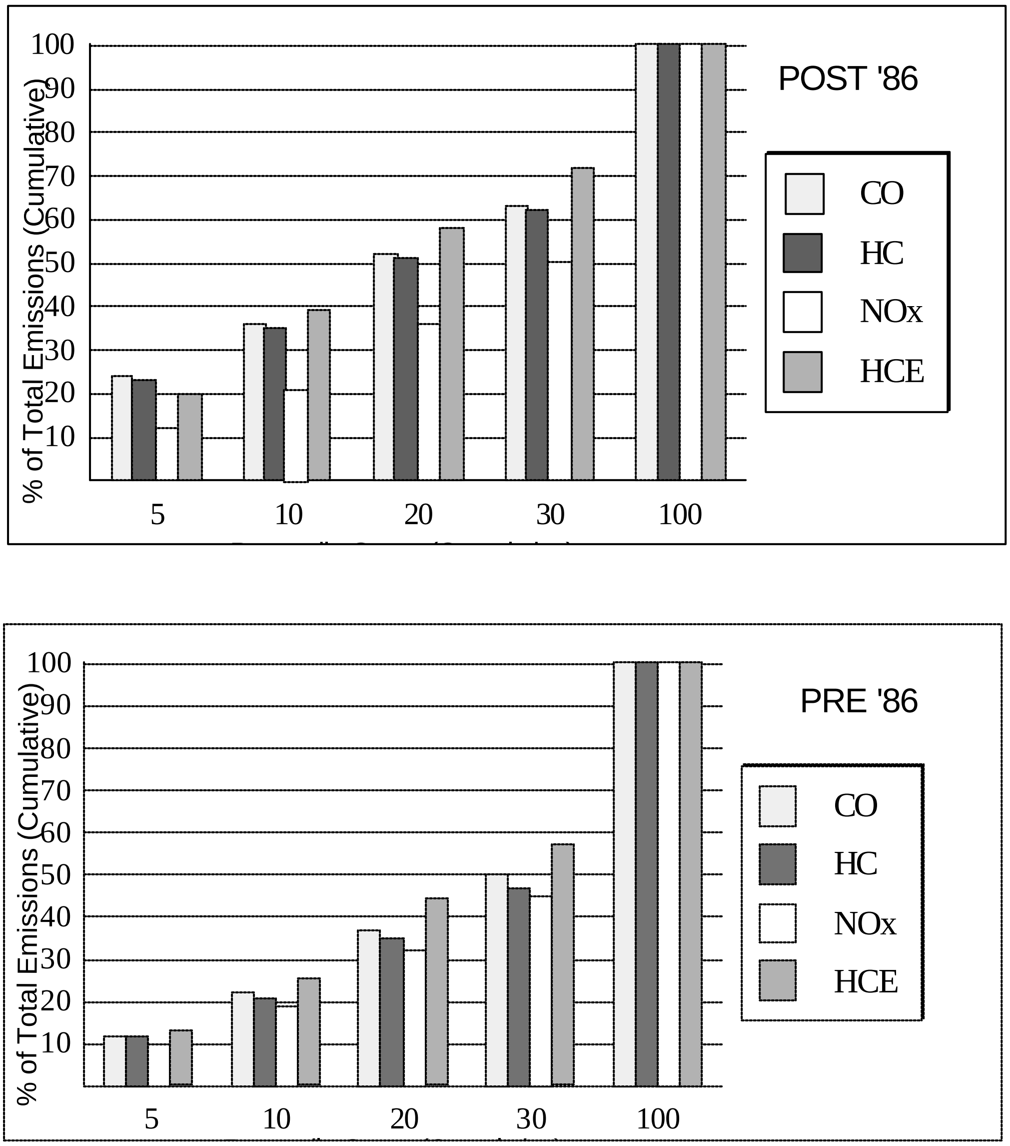
4. Overall Emissions and Percentile Groups

Test results for HC, CO, NOx and Evaporative HCs (HCE) were analysed to identify the ranking of vehicles. Each vehicle was assigned a percentile value within its group for each type pollutant. That is, if a vehicle ranked 20th out of 351 Post-86 vehicles for emission of NOx then it was assigned a percentile value of 5.7% (100 x 20 / 351) for that test and compound. It was then possible to determine the percentage of total emissions for each percentile range. Results for HC, CO and NOx are summarised in Figure 1 and detailed in Appendix A. For example, in the case of pre-86 vehicles, the worst 10% of vehicles caused 21% of total HC emissions for this group and in the case of post-86 vehicles, the worst 10% of vehicles caused 35% of total HC emissions for this group.

Figure 1

% Overall Emissions by Percentile Groups

ADR37 Test Results (Prior to Repairs)



5. Reduction in Emissions Due to Repair/Tune-up

After repairs the vehicles were retested. The difference in emissions for ADR37 tests gives an indication of the effects of repairs/tune-ups. These are summarised below in terms of total emissions to the air shed:

Table 1. Effect of repairs on emissions
Estimated % reduction per year
(taking into account estimated annual vehicle kilometres travelled)

Year of Manuf.	CO	HC	NOx	HCE
Pre-86	27%	14%	10%	19%
Post-86	24%	22%	8%	20%

For vehicles comprising the lowest 10% of emitters prior to repair (percentile value 90% or higher), the repairs generally led to a small *increase* in pollution but this increase was negligible (<1%) compared with the overall improvement. However, this does show a disadvantage of false failures under a targeted repair program - sometimes a "clean" vehicle can be made worse by repairs/tune-up.

6. Cost of Repairs and Cost Effectiveness of Emissions Reductions

In order to analyse the cost-effectiveness of repairs, estimates were made of annual emission reductions based on the grams per kilometre savings measured in the tests and Australian Bureau of Statistics (ABS) data for annual vehicle kilometres travelled by year of manufacture. The latter adjustment was necessary because the oldest vehicles in the analysis (1980) typically travel about half of the annual kilometres of the newest vehicles (1990). The ABS data were obtained by the NRMA and are included in Appendix B.

The term "cost of repairs" requires clarification. The raw data included an item "Total cost of parts $". Labour costs for repairs of individual vehicles were not available from the data but the overall time spent on repairs meant an average of $70 per vehicle. This value was added to the cost of parts to derive a total cost of repairs. In general the repairs can be expected to last more than one year. For the analysis it was assumed that the cost of repairs was spread over two years. The *annual* cost of repairs was therefore (cost of parts + $70) / 2.

In order to derive the cost effectiveness of repairs it is necessary to allocate the annual cost of repairs between the pollutants being evaluated. For the purpose of the analysis this cost was simply split fours ways - that is, for each pollutant the cost was assumed to be one quarter of the annual cost of repairs. The database used for data analysis has provision for recording this ratio so that other scenarios may be tested.

Appendix B sets out details of the cost-effectiveness analysis. Table 2 presents key results. It should be noted that there is considerable variation in both cost of repairs and amount of pollutants emitted from year to year (of vehicle manufacture) and this could indicate that the results are sensitive to relatively small sample sizes and some extreme results within these groups. Also, the costs of emissions testing are not included. Unless such tests are extremely cheap (less than about $2 per test) these costs will significantly increase the overall costs of a program (see Section 10).

Table 2
Summary of Cost Effectiveness Analysis

Year of Manuf.	No. Tested	Repairs per Veh $	HC Saved kg/yr	NOx Saved kg/yr	HC $ per tonne	NOx $ per tonne
80	26	$81	105	102	$5,000	$5,200
81	28	$76	270	153	$2,000	$3,500
82	30	$80	106	30	$5,700	$20,000
83	29	$66	79	89	$6,100	$5,400
84	20	$104	-12	30	-	$17,300
85	39	$69	165	94	$4,000	$7,100
86	59	$84	144	346	$8,600	$3,600
87	56	$78	629	218	$1,700	$5,000
88	59	$77	79	51	$14,300	$22,200
89	62	$68	88	-3	$12,000	-
90	59	$76	100	102	$11,200	$11,000
91	58	$66	30	86	$32,100	$11,200

For comparison, the NSW EPA in its publication "The Cost-Effectiveness of Motor Vehicle Emission Controls" (1992), estimates the cost effectiveness of HC controls at :

US 1992 new vehicle emissions standards	$1,400 to $8,600 per tonne
US Style Inspection/Maint. Programs (including test costs)	$3,000 to $12,000 per tonne
Vehicle Scrappage Schemes	$4,000 to $14,000 per tonne

7. Fuel Consumption

The overall average reduction in fuel consumption as a result of repairs/tune-ups was 0.2 litres/100km. This is only a 2% improvement but when typical annual kilometres are taken into account this translates to an average saving of $23.50 per vehicle per year, compared with an average repair cost of $81.30 per vehicle. Fuel consumption savings can therefore influence the cost-effectiveness calculation. Fuel consumption results are included in Appendix B and the key results are set out in Table 3. The precautions identified for Table 2 also apply to Table 3.

Table 3
Cost Effectiveness Taking Into Account Fuel Consumption Savings

Year of Manuf.	No. Tested	Repairs per Veh $	Fuel Saved $/yr/ Veh	Net Repair $/yr/ Veh	Net HC $ per tonne	Net NOx $ per tonne
80	26	$81	$11	$82	$4,400	$4,500
81	28	$76	$55	$24	$500	$1,000
82	30	$80	$7	$83	$5,200	$18,300
83	29	$66	$34	$29	$3,000	$2,600
84	20	$104	$19	$118	-	$14,100
85	39	$69	$34	$34	$2,100	$3,600
86	59	$84	$17	$81	$6,800	$2,800
87	56	$78	$69	$14	$200	$600
88	59	$77	$4	$76	$13,600	$21,100
89	62	$68	$16	$53	$9,100	-
90	59	$76	$23	$62	$7,800	$7,700
91	58	$66	$0	$62	$32,100	$11,200
All	519	$76	$23	$53	$3,900	$5,300

8. Effectiveness of Short Tests Compared with ADR37 Test

One of the aims of the current analysis was to determine whether a cheap, quick test could be used for in-service testing and targeting vehicles for repair. The ADR37 test procedure is intended primarily for use by manufacturers in establishing compliance of new vehicle models and not for in-service testing.

One method of assessing the effectiveness of the "short" tests is to examine pass/fail trends. In essence, a desirable outcome is that all the vehicles which pass a short test also pass the ADR37 test and all the vehicles which fail a short test also fail the ADR37 test. Undesirable outcomes are false failures (fail short test and pass ADR37 test- i.e. a low-polluting vehicle on the road is incorrectly failed) and, to a lesser extent, false passes (pass short test but fail ADR37 test). In this analysis, we evaluate what might happen in an operational scheme where the pass/fail criteria are based on percentiles within a group for *either HC or NOx* (except in the case of IDLE and HI-IDLE tests). For example, a 10% failure rate for a test indicates that the pre-repair value of either HC or NOx fell into the worst 10% for that group (pre-86 or post-86). For IDLE and HI-IDLE tests absolute failure values were used (for pre-86 vehicles HC>1000ppm and CO > 4.5%vol, for post-86 vehicles HC> 150ppm and CO>2%vol).

Due to the combination of HC & NOx failures, the ratios in the tables will not necessarily match the "failure rate". The NOx failures are generally different populations to the HC failures. Therefore a 5% failure rate will target up to 10% of all vehicles.

Table 4
Pass/Fail Comparison of Short Tests with ADR37

Test	**Group**	**Sample**	**Failure rate %** (Both tests, for HC or NOx)	**Pass ADR**		**Fail ADR**	
				Pass ASM (true pass)	**Fail ASM** (false fail)	**Pass ASM** (false pass)	**Fail ASM** (true fail)
ASM	Pre 86	171	5%	150 (97%)	5 (3%*)	13 (81%#)	3 (19%@)
			10%	126 (91%)	12 (9%)	26 (79%)	7 (21%)
			20%	88 (82%)	19 (18%)	45 (70%)	19 (30%)
	Post 86	303	5%	265 (97%)	7 (3%)	22 (71%)	9 (29%)
			10%	235 (95%)	12 (5%)	35 (62%)	21 (38%)
			20%	178 (89%)	22 (11%)	57 (57%)	46 (46%)

Test	**Group**	**Sample**	**Failure rate %** (Both tests for HC or NOx)	**Pass ADR**		**Fail ADR**	
				Pass SS60 (true pass)	**Fail SS60** (false fail)	**Pass SS60** (false pass)	**Fail SS60** (true fail)
SS60	Pre 86	170	5%	146 (95%)	8 (5%)	13 (81%)	3 (19%)
			10%	125 (91%)	12 (9%)	17 (52%)	16 (48%)
			20%	84 (39%)	22 (21%)	27 (42%)	37 (58%)
	Post 86	347	5%	309 (98%)	7 (2%)	8 (26%)	23 (74%)
			10%	268 (92%)	22 (8%)	17 (30%)	40 (70%)

Test	**Group**	**Sample**	**Failure rate %** (Both tests for HC or NOx)	**Pass ADR**		**Fail ADR**	
				Pass IM240 (true pass)	**Fail IM240** (false fail)	**Pass IM240** (false pass)	**Fail IM240** (true fail)
IM240	Pre 86	170	5%	149 (97%)	5 (3%)	8 (50%)	8 (50%)
			10%	131 (96%)	6 (4%)	8 (24%)	25 (76%)
			20%	94 (88%)	13 (12%)	12 (19%)	51 (81%)
	Post 86	348	5%	311 (98%)	6 (2%)	9 (29%)	22 (61%)
			10%	273 (94%)	16 (6%)	21 (36%)	38 (64%)
			20%	220 (91%)	21 (9%)	22 (21%)	85 (79%)

* Percentage which passed ADR criteria but failed the short test criteria (false fail).

Percentage which failed ADR criteria but passed short test (false pass)

@ Percentage which failed both tests (true fail)

Test	Group	Sample	Failure rate % (ADR Only for HC or NOx)	Pass ADR		Fail ADR	
				Pass IDLE (true pass)	**Fail IDLE** (false fail)	**Pass IDLE** (false pass)	**Fail IDLE** (true fail)
IDLE	Pre 86	172	5%	114 (73%)	42 (27%)	9 (56%)	7 (44%)
			10%	104 (75%)	35 (25%)	19 (58%)	14 (42%)
			20%	87 (81%)	21 (19%)	36 (56%)	28 (44%)
	Post 86	333	5%	245 (81%)	57 (19%)	13 (42%)	18 (58%)
			10%	233 (85%)	41 (15%)	25 (42%)	34 (58%)
			20%	196 (86%)	31 (14%)	62 (58%)	44 (42%)

Test	Group	Sample	Failure rate % (ADR Only for HC or NOx)	Pass ADR		Fail ADR	
				Pass HI-IDLE (true pass)	**Fail HI-IDLE** (false fail)	**Pass HI-IDLE** (false pass)	**Fail HI-IDLE** (true fail)
HI-IDLE	Pre 86	172	5%	143 (92%)	13 (8%*)	13 (81%#)	3 (19%@)
			10%	129 (93%)	10 (7%)	27 (82%)	6 (18%)
			20%	101 (94%)	7 (6%)	55 (86%)	9 (14%)
	Post 86	321	5%	269 (92%)	24 (8%)	11 (39%)	17 (61%)
			10%	252 (95%)	14 (5%)	28 (51%)	27 (49%)
			20%	213 (96%)	9 (4%)	67 (67%)	32 (32%)

* Percentage which passed ADR criteria but failed the short test criteria (false fail).

Percentage which failed ADR criteria but passed short test (false pass)

@ Percentage which failed both tests (true fail)

These results indicate that the cheapest, quickest tests generally have relatively high false-pass/false-fail rates. In particular, in the case of the IDLE test a large proportion of vehicles which passed the ADR37 criteria (worst 5%, 10% or 20%) failed the short test (in this case, absolute values). An emissions testing program which falsely failed such a high proportion of good vehicles would quickly lose credibility. The HI-IDLE test had a relatively low false-fail rate, comparable with some of the more complex tests, but this could be a manifestation of the low overall failure rate for this test, which was based on absolute values rather than percentile groups - the false-pass rate for HI-IDLE tends to be much higher than that for the complex tests.

The ASM test procedure, although less complex than the other chassis dynamometer tests, had a relatively good pass/fail effectiveness.

The short test failure rates shown in Table 4 have been included in the graphs associated with the correlation analysis, described in the next section.

9. Correlation Between Short Tests and ADR37 Test

An alternative method of comparing short test results with ADR37 results is to calculate the correlation between the two sets of results. This is illustrated in the graphs contained in Appendix C and summarised in Table 5. Note that several outliers have been excluded from the analysis, pending clarification of actual test results.

Table 5
Correlation Analysis

TEST	COMPOUND	GROUP	MATCHED PAIRS	CORR. CO-EFF.
ASM	CO	Pre-86	176	0.61
		Post-86	278	0.78
		All	448	0.71
	HC	Pre-86	169	0.48
		Post-86	302	0.56
		All	448	0.71
	NOx	Pre-86	37	0.52
		Post-86	72	0.6
		All	109	0.71

TEST	COMPOUND	GROUP	MATCHED PAIRS	CORR. CO-EFF.
SS60	CO	Pre-86	172	0.47
		Post-86	335	0.81
		All	507	0.82
	HC	Pre-86	170	0.59
		Post-86	348	0.67
		All	518	0.75
	NOx	Pre-86	170	0.47
		Post-86	348	0.7
		All	518	0.65

TEST	COMPOUND	GROUP	MATCHED PAIRS	CORR. CO-EFF.
IM240	CO	Pre-86	171	0.89
		Post-86	350	0.89
		All	521	0.91
	HC	Pre-86	170	0.85
		Post-86	348	0.77
		All	518	0.88
	NOx	Pre-86	169	0.76
		Post-86	349	0.83
		All	518	0.84

TEST	COMPOUND	GROUP	MATCHED PAIRS	CORR. CO-EFF.
IDLE	CO	Pre-86	171	0.57
		Post-86	285	0.67
		All	456	0.71
	HC	Pre-86	171	0.52
		Post-86	318	0.62
		All	489	0.65

TEST	COMPOUND	GROUP	MATCHED PAIRS	CORR. CO-EFF.
HI-IDLE	CO	Pre-86	172	0.68
		Post-86	286	0.62
		All	458	0.72
	HC	Pre-86	169	0.5
		Post-86	279	0.57
		All	448	0.6

On the basis of minimising false-failures and false-passes, a correlation co-efficient of at least 0.8 is considered desirable for this type of analysis. Only the IM240 tests had reasonably good correlation with the ADR37 test results - this reflects the derivation of the IM240 test from the ADR37 cycle. It should be noted, however, that a good overall correlation (covering all points - including many near zero) does not necessarily mean that the correlation is acceptable for the cases in the worst percentile bands. This is more evident in the graphs presented in Appendix C, where false-fail/false-pass envelopes have been included for three failure rates: 20%, 10% and 5%.

10. Targeted Repairs

Cost effectiveness can be improved by targeting the vehicles required to undergo repairs. Appendix D sets out the results of an analysis of targeted repairs. Note that sample sizes for some of the tables in Appendix D are small.

The method involves selecting only those vehicles falling within the nominated failure rate for a particular test (for example the worst 10% of pre-86 vehicles for the ASM HC test). The actual emission savings (based on ADR37 values for the same vehicle), cost of repairs and estimated fuel consumption savings are calculated for the selected vehicles and a net cost effectiveness is obtained (taking into account estimated fuel savings).

In general repairs to the worst vehicles result in a large reduction in emissions. This means that the net cost effectiveness tends to be greatly improved, particularly for CO and HC tests. For example, the net cost effectiveness of targeting the worst 5% of pre-86 vehicles in the ADR37 CO test is only $40 per tonne (4c/kg) compared with $150 per tonne if all vehicles are "repaired". In the case of HC emissions the effect is even more pronounced because the fuel savings exceed repair costs and there is a net saving to owner of a vehicle in the worst 5% of ADR37 HC tests, compared with a net cost of $3,400 per tonne of HC if all vehicles are repaired.

Table 5
Net Cost Effectiveness of Targeted Repairs $/tonne
Pre-86 Vehicles (Includes fuel savings but not test costs)

Compound	Test Type	Failure rate at which repairs are required				
		5%	10%	20%	30%	100%
CO	ADR37	$40	$0	$10	$50	$150
	ASM	$170	$70	$60	$70	$150
	HI-IDLE	$50	$40	$50	$40	$150
	IDLE	$70	$70	$60	$80	$150
	IM240	$40	$0	$30	$40	$150
	SS60	($10)	$50	$40	$40	$150
HC	ADR37	($30)	$170	$380	$620	$3400
	ASM	$710	$1200	$1700	$1200	$3400
	HI-IDLE	$550	$430	$640	$860	$3400
	IDLE	$310	$690	$1600	$2200	$3400
	IM240	$130	$460	$870	$820	$3400
	SS60	$1100	$510	$670	$710	$3300

NOx	ADR37	$250	$910	$1100	$1400	$4900
	ASM	$480 *	$2500	$1300	$3400	$5900 *
	IM240	$1900	$2000	$2500	$1700	$4700
	SS60	$1400	$1200	$1200	$1300	$4700

* Small sample size may affect reliability ( ) indicates net saving to vehicle owner

Post 86 Vehicles

Compound	Test Type	Failure rate at which repairs are required				
		5%	10%	20%	30%	100%
CO	ADR37	($10)	$10	$50	$80	$310
	ASM	$0	$30	$60	$70	$280
	HI-IDLE	$40	$50	$80	$130	$310
	IDLE	($10)	$10	$90	$140	$320
	IM240	($10)	$30	$70	$80	$300
	SS60	($10)	$30	$50	$90	$280
HC	ADR37	$10	$470	$1300	$1800	$4700
	ASM	$90	$760	$1200	$1600	$4000
	HI-IDLE	($90)	$220	$1700	$3000	$4400
	IDLE	$470	$870	$1200	$1700	$4300
	IM240	$90	$1000	$2000	$2500	$4600
	SS60	($10)	$690	$1900	$2300	$4800
NOx	ADR37	$890	$1400	$2000	$2300	$6500
	ASM	$2000	$4200	$5800	$6200	$6700
	IM240	$1600	$1800	$2400	$3000	$6500
	SS60	$1300	$1700	$3600	$3600	$7500

( ) indicates net saving to vehicle owner

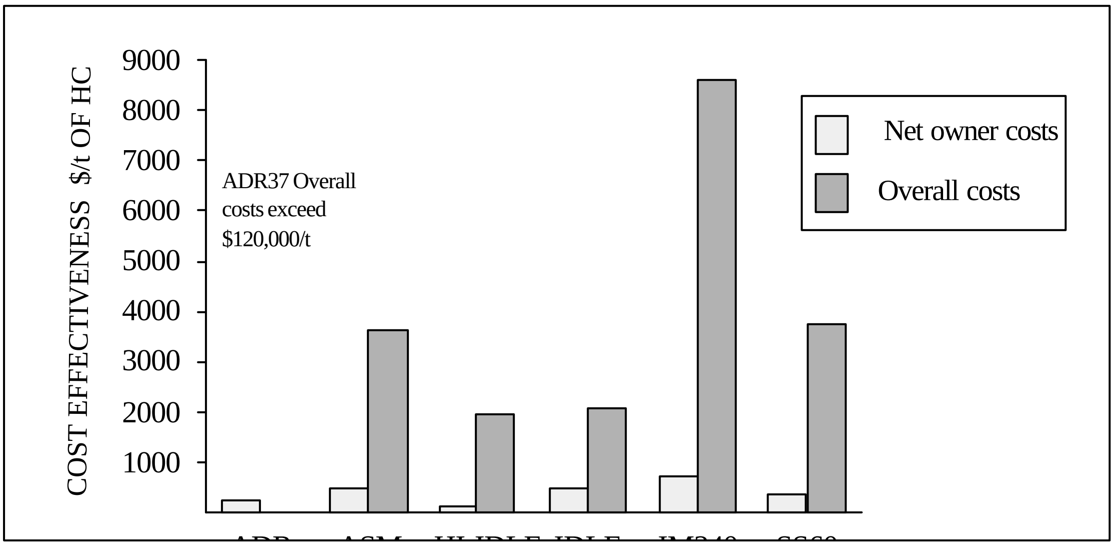
Inclusion of testing costs

The cost effectiveness values derived in Tables 2, 3 & 5 do not include allowance for the cost of testing. Estimates have been made of the costs for each type of test, based on preparation and testing time and overheads for facilities and equipment:

ADR37	$1000/vehicle
ASM	$20/vehicle
HI-IDLE	$10/vehicle
IDLE	$10/vehicle
IM240	$50/vehicle
SS60	$20/vehicle

It is evident that testing costs are similar to (or in the case of ADR37, much higher than) the cost of repairs and fuel savings therefore test costs can be expected to have a strong influence on the outcome of the cost effectiveness analysis. The tables in Appendix D include the results of this analysis. It is assumed that the test concerned is used for identifying vehicles requiring repair. This methodology tends to favour the cheaper tests because, at low failure rates the testing costs tend to swamp the repair costs and fuel savings. For example, if the failure rate is set at 5% then, on average, 20 vehicles must be tested in order to detect one that requires repair. In the case of ADR37 the total testing cost per "failure" (at 5% failure rate) would be $20,000. Assuming that all vehicles are tested, the effect of a high test cost leads to the paradoxical situation where a high failure rate, such as 30% can lead to the best overall cost effectiveness, in terms of $/tonne saved, even though the overall costs are highest and many of the repairs are relatively unproductive. Figure 3 shows the effect of including test costs for a 10% failure rate for HC emissions with post-86 vehicles (see Appendix D for derivation of values).

Figure 2 - Example of Inclusion of Testing Costs in Cost Effectiveness Analysis 10% Failure Rate for HC Emissions with Post 86 Vehicles



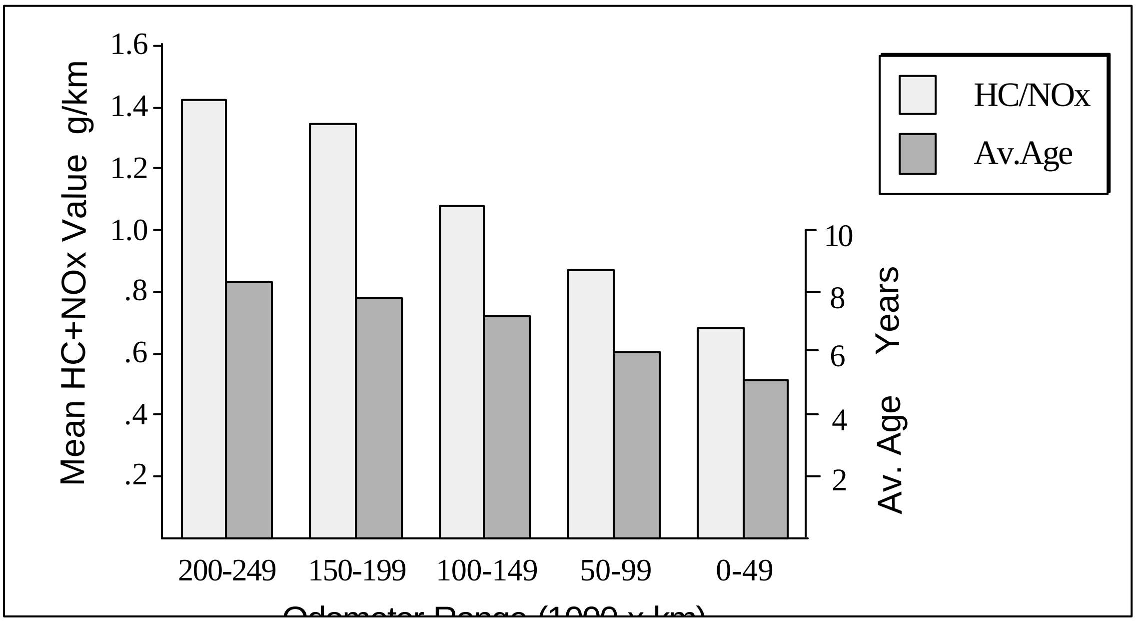
In effect, this methodology takes into account false-failure cases because vehicles which are low-polluting in the ADR37 test and high polluting in the short test tend to reduce the calculated average emissions saved through repair of the selected vehicles (based on the ADR results). The cost effectiveness for the test is therefore made worse (increased $/kg). On the basis of the results set out in Appendix D, this compensating effect is not sufficient to push the cost effectiveness of the HI-IDLE and IDLE tests beyond that of the cheaper chassis dynamometer tests (ASM & SS60), even though the false failure rate of HI-IDLE and IDLE tests tend to be high. Note that use of these tests to select vehicles for repair still results in an overall saving in emissions but, in general, the savings are about half of those resulting from the selection of the same number of vehicles with an ADR37 test.

11. Estimated Life of Catalytic Converters

The emission performance of Post-86 vehicles depends crucially on the effective operation of the catalytic converter. The data were therefore analysed to look for trends in deterioration of the catalytic converter. One method is to examine the emissions by odometer reading (distance travelled since the vehicle was new). It can be expected that, if gradual deterioration of the catalytic converter due to normal usage occurs, this will be related to odometer reading rather than vehicle age.

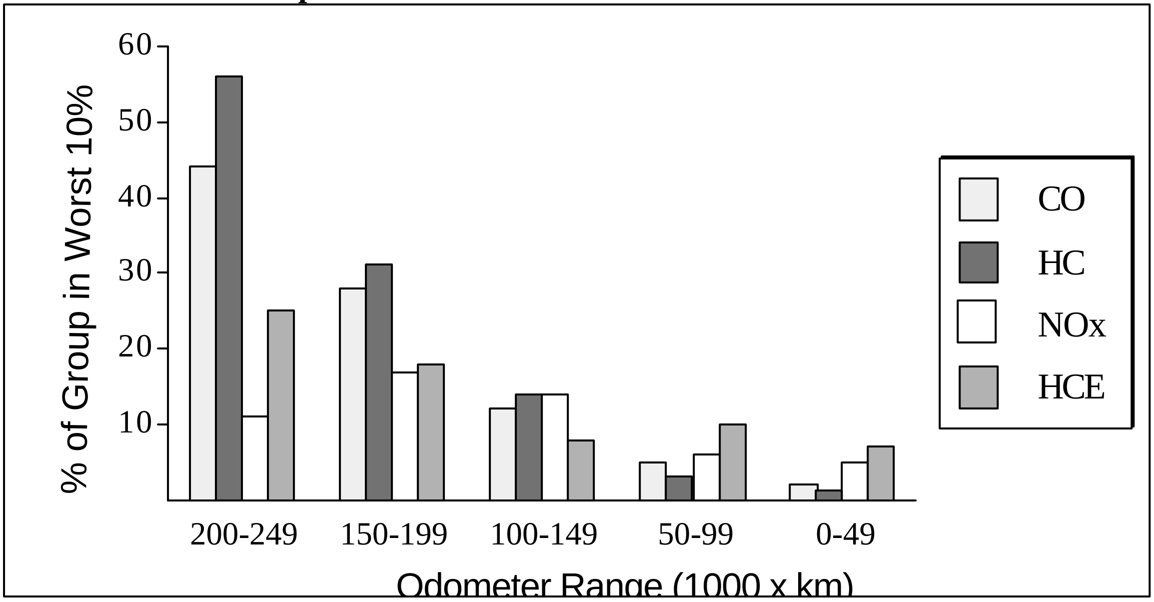
The emissions by odometer readings have been analysed in two ways. The first involved taking the average of all HC and NOx results for ADR37 tests. Figure 3 presents the results of this analysis.

Figure 3
Relationship between Odometer Reading and HC+NOx Emissions
Post 86 Vehicles



The above analysis indicates a gradual increase in emissions as kilometres build up and also, as expected, suggests a link between age and odometer reading. There do not appear to be any step changes which might indicate a sudden deterioration in catalyst performance. In order to derive a better indication of catalytic converter failures the data were also analysed to examine the proportion of vehicles within each odometer range which fell into the worst 10% of all Post-86 vehicles. This has been divided into compounds (CO, HC & NOx). HCE results have been included as a control group because evaporative emissions are unaffected by catalyst performance. Figure 4 presents the results of this analysis.

Figure 4
Relationship between Odometer Reading and
Proportion in the Worst 10% of Post 86 Vehicles



These results are likely to be confounded by the link between age and odometer reading and care should be taken in interpreting the results, particularly since the oldest vehicles in the group represent early experience with catalytic converter technology in Australia. Subject to this reservation, there is a relatively large jump in the CO, HC & NOx results at 100,000km. This is not apparent in the HCE results until 150,000km is reached. There are also substantial jumps in CO & HC results for the 150,000km and 200,000km ranges. These results are tentative but they suggest the onset of catalytic converter deterioration occurs in the range 100,000km to 149,000km.

Due to cost and time limitations very few of the post-86 vehicles had catalysts replaced therefore the effects of this type of repair cannot be reliably obtained from the data. Subject to this reservation, for 11 vehicles which had a catalyst replaced the avearge saving was 22 kg of HC per vehicle per year and 23 kg of NOx per vehicle per year. Table 6 compares these results with overall and "worst 5%" results.

Table 6
Catalyst Replacements Compared with Other Results

Caution: Very small sample size for catalyst replacements

Compound	Group	Sample Size	Savings kg/yr /veh	Repairs $/yr/veh	Fuel saved $/yr/veh	Net Cost Effect. $/tonne
HC	Catalyst Replace.	11	21.8	$166	$26	$1,600*
	All Post-86	347	3.1	$75	$22	$4,300
	Worst 5% (Post 86)	17	32.5	$99	$116	($130)*
NOx	Catalyst Replace.	11	22.6	$166	$26	$1,600*
	All Post-86	347	2.2	$75	$22	$6,000
	Worst 5% (Post 86)	17	14.8	$78	$32	$760*

* Does not include test costs.

Note that the worst 5% of HC emitters are not necessarily the same vehicles as the worst 5% of NOx emitters.

12. Discussion - selection of vehicles for repair using a short test

There are several factors which need to be considered in selecting a short test for a program to target high-polluting vehicles for repairs:

1. Will the tests be confined to specialised testing laboratories or will they be conducted by automotive repair workshop or roadside testing stations?
2. What is an acceptable failure rate?
3. What is an acceptable false failure rate (i.e. unnecessary repairs) and will false failures matter if there is no simple way to determine individual cases?
4. Should emphasis be given to certain pollutants such as HC and NOx?

On the assumption testing will be conducted by automotive repair workshops with access to simple (constant speed) chassis dynamometers and four-gas analysers, and that priority is given to reducing HC and NOx, then the results of the analysis suggest that either ASM (constant 40km/h) or simplified SS60 (constant 60km/h but raw exhaust sampling the same as ASM) testing should be considered. Although IDLE and HI-IDLE tests generally produce the best overall cost effectiveness (including test costs), they have high false-failure/false pass rates and give no measure of NOx emissions.

Due to relatively high test costs and the assumption that all vehicles will need to be tested (i.e. no simple screening method is available), overall cost effectiveness does not vary greatly at different failure rates for the same test. Other factors appear more important for choosing an appropriate failure rate. For ASM and SS60 tests the false-failure rate appears to be optimum at a 10% failure rate (although false-passes are relatively high). At this failure rate it can be expected than about one in ten "failed" vehicles would undergo less effective repairs although, generally, emissions would still be reduced with these repairs.

A scenario which should not be discarded at this stage is compulsory maintenance of all vehicles. That is, no emissions tests are conducted but all vehicles are required to undergo tune-ups/repairs. This would result in overall emissions reductions as set out in Table 1 for a similar overall cost effectiveness to programs based on the short tests, when used to target vehicles for repair. About 30% of vehicles which underwent repairs experienced a small increase in emissions (this amounted to less than 1% of overall emissions) and about 40% of vehicles experienced a small increase in fuel consumption (average increase less than 0.4 l/100km). Nevertheless, the overall savings in emissions and fuel consumption through tune-up/repair of all the vehicles were substantial: for the 523 vehicles tested this amounted to 33 tonnes of CO, 2 tonnes of HC (including evaporative emissions), 1.2 tonnes of NOx and fuel savings of $12,200 per year.

13. Conclusions

The data from in-service emissions testing of 523 Australian vehicles has been analysed to determine the effects on emissions of repairs to these vehicles and to compare six types of emissions tests. Key results are:

- The worst-polluting vehicles produce a disproportionate amount of the total emissions. For example, the worst 10% of post 86 vehicles were responsible for more than 30% of total emissions of CO and HC from post 86 vehicles.
- Repairs to all vehicles led to an overall reduction in emissions ranging from 10% (NOx) to 27% (CO). The cost of repairs averaged $152 per vehicle, including a labour cost of $70 per vehicle. Assuming the repairs last 2 years the cost is $76 per vehicle per year. In a number of cases repairs increased some emissions by small amount - this was generally confined to the latest year models tested.
- A program which targets high-emitters for repairs can be more effective in terms of emission reductions. For example, repairing the worst 20% of HC emitters produced 81% of the total reductions in HC due to repairs and repairing the worst 20% of NOx emitters produced 74% of the total reductions in NOx due to repairs.

- Fuel consumption savings due to repairs were highly variable but averaged $24 per vehicle per year.
- Taking into account fuel consumption savings, the net cost effectiveness for repair of all vehicles was $4,300 per tonne of HC saved and $5,800 per tonne of NOx saved. These compare favourably with other pollution control measures evaluated by the NSW EPA. These results are based on the assumption that no testing is conducted and all vehicles are repaired.
- When the results of the shorter, cheaper tests are compared with those of ADR37 tests there is a relatively high proportion of false-failures and false-passes. False failures should be avoided because they indicate that repairs are less likely to be effective in reducing emissions (and in a few cases, may increase emissions). Correlation co-efficients derived from comparing short test results with ADR37 results support this observation. Only the more complex IM240 test had reasonable correlation with ADR37.
- Targeted repairs (such as requiring the worst 10% of vehicles to be repaired) can lead to a substantial improvement in net cost effectiveness (including fuel savings but not test costs). In some cases there is a net saving to the vehicle owner because fuel savings exceed repair costs.
- For the short tests, the cost of performing emissions testing is of the same order as repair costs and therefore inclusion of test costs has a strong influence on the cost effectiveness calculation. A test which is used to target vehicles for repair must be relatively cheap otherwise the costs become prohibitive. For example, at a 5% failure rate, on average 20 vehicles must be tested to detect one failure. This causes a dilemma because the cheapest tests are more likely to result in false failures and therefore less effective repairs but the overall cost effectiveness is still better than more expensive tests.
- The overall cost effectiveness of repairing all vehicles, without conducting any screening test, is similar to that of a program which includes a short test for targeted repairs. This is due to the relatively high costs of the short tests evaluated in the study.
- Tentative results indicate that the onset of noticeable deterioration in the performance of catalytic converters occurs in the odometer range 100,000km to 150,000km but there are several confounding factors in the analysis. The number of cases where the catalyst was replaced is too small for reliable analysis but the results for eleven vehicles suggest that there might be merit in targeting this type of repair.

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Appendix A -Percentile Groups

Test results were ranked by pre-repair values and assigned to percentile groups. The contribution of the total emissions of a percentile group to overall emissions was then established and a cumulative % of total emissions was calculated. Percentile values were rounded up to the nearest integer so, for example, 5.1 becomes "6".

Pre-86 Vehicles

Percentile Group	CO		HC		NOx		HCE	
	Total g	Cum. %	Total g	Cum. %	Total g	Cum. %	Total g	Cum. %
0-5	535	12%	45	12%	38	10%	179	13%
6-10	456	22%	32	21%	30	19%	165	25%
11-20	690	37%	50	35%	49	32%	268	44%
21-30	579	50%	43	47%	46	45%	178	57%
31-40	479	-	37	-	40	-	154	-
41-50	422	-	34	-	36	-	115	-
51-60	378	-	32	-	35	-	111	-
61-70	318	-	27	-	30	-	87	-
71-80	268	-	25	-	27	-	56	-
81-90	229	-	24	-	22	-	50	-
91-100	131	-	17	-	12	-	24	-
All	4484	100%	365	100%	364	100%	1388	100%

Post-86 Vehicles

Percentile Group	CO		HC		NOx		HCE	
	Total g	Cum. %	Total g	Cum. %	Total g	Cum. %	Total g	Cum. %
0-5	825	22%	57	23%	52	12%	308	12%
6-10	475	36%	28	35%	41	21%	205	39%
11-20	588	52%	39	51%	67	36%	248	58%
21-30	406	63%	27	62%	60	50%	189	72%
31-40	305	-	22	-	50	-	129	-
41-50	263	-	18	-	46	-	92	-
51-60	221	-	15	-	39	-	70	-
61-70	215	-	13	-	33	-	37	-
71-80	154	-	11	-	26	-	22	-
81-90	121	-	9	-	20	-	13	-
91-100	63	-	5	-	11	-	6	-

All	3634	100%	246	100%	444	100%	1319	100%

Appendix B - Cost Effectiveness Analysis

Results of the cost effectiveness analysis are set out on the following pages. The method was, for each compound, to calculate the difference between pre and post repair emissions. This is used to derive the total emissions saved per kilometre for the year model. This is multiplied by the estimated annual vehicle kilometres travelled (VKT) to obtain total emissions saved per year for the year model. One quarter of the total cost of repairs divided by the emissions per year gives the cost effectiveness, in dollars per kg of emissions saved.

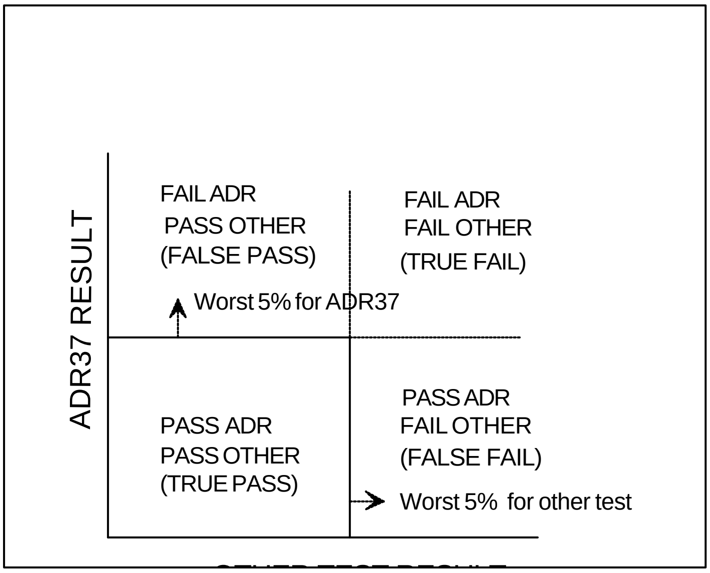
Appendix C

Correlation Between Short Tests & ADR37

The following graphs illustrate the relationship between the results of the short tests (ASM, IDLE, HI-IDLE, IM240 & SS60) and those of ADR37. Results for individual vehicles are plotted in the form of scatter graphs, with the horizontal axis being the short test result and the vertical axis being the ADR37 result.

Also plotted are failure rate envelopes. For example the right-most vertical line shows the 5% failure rate for the short test - any points to the right of this line were in the worst 5% of the short test results. Similarly the top-most horizontal line shows the 5% failure rate for the ADR37 test - any points above this line were in the worst 5% of ADR37 results. The true-pass cases set out in Table 4 are below the horizontal line and to the left of the vertical line. The other cases (false-fail, false-pass and true fail) can be found by extrapolating the lines to form the remaining three quadrants as illustrated below.

For reference, ADR37 limits for new vehicles are approximately 1 g/km for HC,
9 g/km for CO and 2 g/km for NOx.. These are not intended to apply to in-service tests.



Appendix D

Overall Cost Effectiveness
Including Estimated Test Costs

The following tables show the effects of failure rate on the cost effectiveness for each type of test. Column H includes the cost of testing, which in the case of ADR37 is very high.

Results of the analysis of grouped by pollutant (CO, HC, NOx or HCE) so that the performance of each type of test can be compared. The effectiveness of a particular test in targeting high-polluting vehicles is indicated in column B ("Saving kg/year/vehicle"). These vary from test to test because the vehicles in the sample are usually different (e.g. the 17 vehicles which were in the worst 10% of ADR37 HC results were not the same as the 16 vehicles in the worst 10% of ASM HC results). The optimum value in this column is the ADR37 result, although sample sizes and ineffective repairs (in terms of pollution savings) can cause unusual results, such as the case with ASM NOx for post 86 vehicles at a 5% failure rate.

In some cases annual fuel savings exceed the cost of repairs - a net gain for the vehicle owner and a negative net cost effectiveness (Column F).

The testing cost per "failure" increases as the failure rate decreases (Column G). This assumes that the only pollution-control benefit arising from testing is the repair of "failed" vehicles. For a 5% failure rate 20 vehicles must be tested to identify one failure. Column H shows the effect of including this testing cost in the cost effectiveness calculation. Due to the relatively high costs of testing, the effect is to negate the advantages of targeting high-polluting vehicles. There is relatively little difference in overall cost effectiveness between a 5% failure rate and a 30% failure rate. In fact, the net cost effectiveness of requiring all vehicles to be repaired and *not conducting any tests* (Column F of the 100% failure rate table) is similar to the scenarios for conducting testing at different failure rates.

Appendix C

Correlation Between Short Tests & ADR37

The following graphs illustrate the relationship between the results of the short tests (ASM, IDLE, HI-IDLE, IM240 & SS60) and those of ADR37. Results for individual vehicles are plotted for each compound in the form of scatter graphs, with the horizontal axis being the short test result and the vertical axis being the ADR37 result.

Also plotted are failure rate envelopes. For example the right-most vertical line shows the 5% failure rate for the short test - any points to the right of this line were in the worst 5% of the short test results. The horizontal line indicates a nominal ADR failure level which is 25% higher than the limit applying to *new* vehicles under the relevant ADR (ADR37 for Post 86 vehicles and ADR27 for pre 86 vehicles). Any points above this line exceed the relevant ADR by more than 25%.

"True-pass" cases are below the horizontal line and to the left of the relevant vertical line. The other cases (false-fail, false-pass and true fail) can be found in the remaining three quadrants as illustrated below. These cases are not the same as those set out in Table 4 because that table is based on a combination of HC and NOx results. Also, in Table 4, the ADR failure rate is varied with the short test failure rate.

For reference, ADR37 limits for new vehicles are 0.93 g/km for HC, 9.3 g/km for CO and 1.93 g/km for NOx. ADR27 limits for new vehicles are 2.1 g/km for HC,
24.2 g/km for CO and 1.9 g/km for NOx.