BC Clean Air Research Fund

Collection of PM Emission Data

from

In-Use Light-Duty

Diesel and Gasoline Vehicles

Final Report

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CONTENTS

SUMMARY

There is very little available data relating to the PM emissions from in-use light-duty vehicles. In 1999 a project was undertaken by Environment Canada at the AirCare Research Centre, to collect PM emissions data from in-use gasoline vehicles. It used the established gravimetric method of collecting PM samples on filter papers. A total of 62 light-duty vehicles were tested. Since then, we are not aware of any further work aimed at characterising the PM emissions of the BC in-use fleet.

For this project the AirCare Research Centre used its unique ability to solicit appropriate volunteer vehicles, together with its in-house chassis dynamometer/CVS emissions testing system to develop a way to collect PM mass emission data from in-use light-duty gasoline and diesel vehicles. The PM measurements were obtained using a MAHA MPM4 light-scattering analyser that gives a continuous measurement of exhaust PM concentration (mg/m^3). The purpose of this project was to collect PM emissions data from a sample group of light-duty diesel and gasoline vehicles in order to characterise the PM emissions of the in-use fleet. The resulting data will be used for emission factor development; in developing mitigation strategies; and to support evaluation of the effectiveness of mitigation strategies.

The inconvenience of gravimetric PM measurement has created a situation where new vehicle PM emissions are regulated in units of grams of PM per km or per bhp-hr, but in-use inspections have been limited to measuring opacity. Although opacity remains a reliable and affordable way of identifying diesel vehicles that are in need of repair, it is not a surrogate for PM measurement. Opacity is more of a qualitative test and the correlation between opacity measurements and PM measurements is poor. This means that opacity data cannot be used to develop a picture of the PM emissions of the in-use fleet, or to help develop emission factors for inventory purposes.

The MAHA MPM4 is a light-scattering PM analyser, and is intended for routine vehicle emission inspection. This means that it is more affordable, and more convenient to use, than equipment intended for a purely research environment. Measurements were made in real time at a frequency of 1Hz, which is enough to track the effects of transient vehicle operation. So, as well as delivering overall mg/km measurements over a set driving cycle, the data also indicates which driving modes produce more PM, and any transient relationships between PM, NOx and other emissions. This is something that is impossible with filter collection methods.

The results presented in this report for gasoline vehicles are comparable to those obtained by Environment Canada in 1999. However, they also include diesels, which were not included in the EC work, and also include vehicles up to model year 2010, reflecting advances in emission control technology. The data also highlight the range of emissions from old and new vehicles and the effect of oil-burning on the rate of PM emissions.

The project has confirmed the suitability of the MAHA analyser for routine PM data collection, and has verified the methodology developed to combine the PM concentration measurements with CVS modal data in order to derive PM mass emission factors in units of mg/km.

Although this report marks the end of this specific project, the work of data collection will continue, and the next phase is to deploy an analyser in an inspection lane where it will be used for every vehicle brought through for regular inspection. This approach has already been used for NOx measurement of diesels: A Horiba diesel NOx analyser was first used in the CVS lab and then moved out to Lane #1 at

the Abbotsford inspection centre. This lane tests about 100 diesels per month as well as many more gasoline vehicles. The PM analyser will be deployed to the same lane.

VEHICLE RECRUITMENT

Some diesel and gasoline vehicles were recruited directly from PVTT and ETC staff , from AirCare Repair Facilities, and from vehicles undergoing their regular inspection. These sources were most useful for the newer gasoline vehicles. Owners were incentified by the provision of gasoline coupons.

The older gasoline vehicles came mainly from those being tested in support of the BC Scrap-it Program and the national Retire-Your-Ride program. These vehicles are a good cross section of those in use, but it is important to remember that in every case there was a reason that the owner believed it was time to retire it permanently. This can mean that the vehicles might have more problems than those of the same age and mileage that remain in use. Having said that, their overall emissions do not appear excessive in comparison.

Some diesels were vehicles we were testing for other reasons. These included ambulances and smaller handydart buses. We also arranged to borrow a number of service vehicles from Cummins Western Canada. Overall, the diesels were the most difficult to recruit, because most diesels are commercial vehicles and are simply not readily available for testing. We also rented a small number of diesel vehicles.

VEHICLES TESTED

Diesel Vehicles

Table 8 in the Appendix gives a full list of the vehicles. They range in model year from 1981 to 2009, and in size from small passenger vehicles up to 1 ton trucks.. Their makes were: Mercedes: 4, Ford: 12, Dodge: 10, GMC: 2, and VW: 6.

Gasoline Vehicles

Tables 9 and 10 in the Appendix give full lists of the vehicles tested. They range from model year 1985 to 2010, and across all common makes. Most vehicles are passenger vehicles of various sizes, but there are a number of SUVs, and some pickup trucks.

DATA COLLECTION AND PROCESSING

The MAHA MPM4 Light-Scattering PM Analyser

Light propagation can be attenuated by absorption, reflection or scattering. The mechanism used by an opacity meter is absorption. This can work well for black carbon particles typical of the visible smoke that is commonly associated with old diesel engines, but many particles are not black, and an opacity meter can not detect them. Scattering of light or other electromagnetic radiation is the deflection of rays in random directions by irregularities in a propagation medium, or at a surface or interface between two media. Most objects that one sees are visible due to light scattering from their surfaces. Indeed, this is our primary mechanism of physical observation. Scattering of light depends on the wavelength or frequency of the light being scattered. Since visible light has wavelength on the order of a micron, objects much smaller than this cannot be seen, even with the aid of a microscope. Mie scattering is a broad class of scattering of light by spherical particles of any diameter. The scattering intensity is generally not strongly dependent on the wavelength, but is sensitive to the particle size. So light scattering is a technique that can measure the intensity of scattered light to obtain the average size of suspended particles.

Polarized light scattering has been developed to determine the composition of undiluted diesel exhaust since about 1999. An instrument was first created at Lawrence Berkeley National Laboratory and then development was transferred Oak Ridge. [1]

We understand that the MAHA instrument was developed independently. [2] It is specifically intended for measuring particle mass concentration in exhaust streams, in a non-laboratory environment. Its output includes all particles up to 10 microns, and a cyclone in the sampling system would be necessary if the desire was to limit the range to a smaller size, such as $PM_{2.5.}$ However, in the context of the exhaust from diesel or gasoline engines this expense and complication is not justified or necessary, because such exhaust contains almost exclusively only particles less than 2.5 microns. So there is no practical difference between measuring PM_{10} and $PM_{2.5,}$ in this context.

The Hot 505 Transient Driving Cycle

All the testing presented in this report is from hot-start tests which equate to the third phase of the standard EPA75 test known as the Federal Test Procedure (FTP). Hot-start testing does not require the vehicle to be cold-soaked overnight before the test, and is therefore much more easily arranged when vehicle recruitment is an issue. Phase 3 of the FTP starts with a fully warmed up engine, and comprises 505 seconds of transient driving for 5.7km. It includes a number of short idles, and peak speeds up to 92 kmh. The speed trace is shown in Fig 1 .

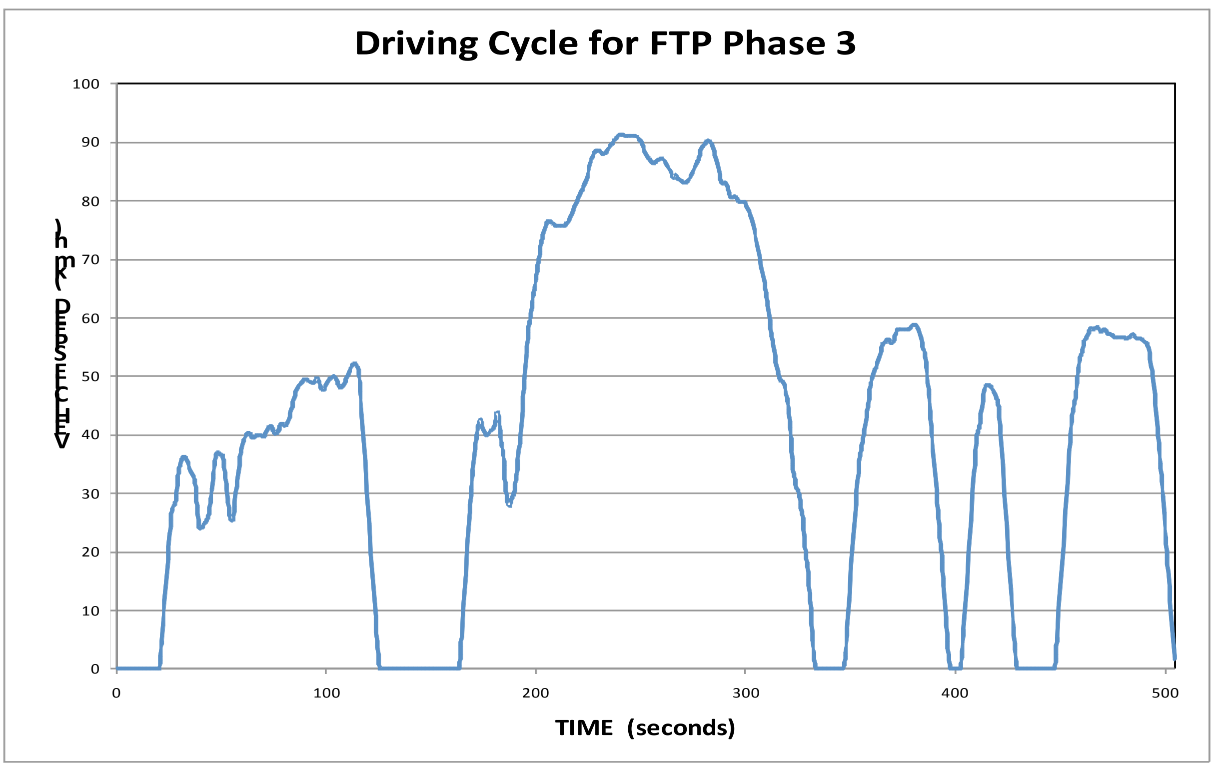


Fig 1.

[1] ***Modeling Light Scattering from Diesel Soot Particles*** Patricia Hull, Ian Shepherd, and Arlon Hunt http://escholarship.org/uc/item/6m61f82q , 2002

[2] ***MPM-4 Real-Time Particle Analyzer Principles of Operation*** MAHA GmbH&Co.KG Rev3 November 2009

Continuous PM Concentration Measurement

The MAHA analyser measures PM concentration continuously, and logs results at a frequency of up to 10 times per second. For all the tests reported here the frequency was one record per second, and each record is the average over the one second sampling period. This frequency was chosen to match with the frequency of the CVS modal data, and the driving cycle definition. Fig 2 graphs a typical test record. For this particular test the peak values appear to correspond to the acceleration events during the transient driving test.

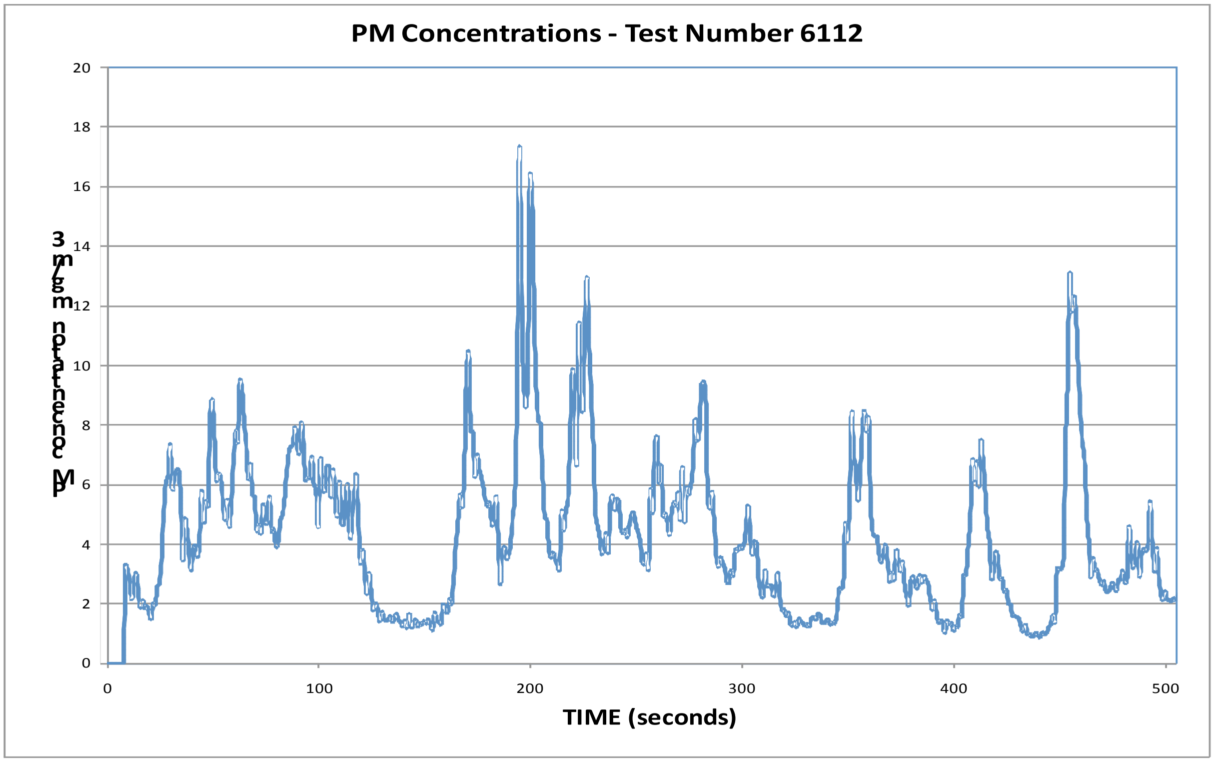


Fig 2.

CVS Modal Data

In Constant Volume Sampling (CVS) testing the vehicles exhaust flow is diluted by make-up air in order to maintain a constant flow rate through a critical flow venturi. The dilution rate depends on the instantaneous exhaust flow rate. For a vehicle using a fuel of known carbon, hydrogen and oxygen mass fractions, the dilution ratio can be calculated using carbon balance from the measured dilute exhaust concentrations of CO_2, CO and HC. The dilution ratio can then be applied to each dilute measurement to derive the tailpipe concentrations.

Fig 3 shows typical dilute gas concentrations, measured during the same test as Fig 2. The green CO_2 line is a clear indicator of the relative rates of fuel burn through the test. During steady-state operations the tailpipe CO_2 concentration for virtually any gasoline catalyst-equipped vehicle will be about 15%. The peak dilute values of CO_2 are around 2% when running at high speed, and this indicates a dilution ratio of about 7.5. During the idle periods, the dilute CO_2 concentration is around 0.3% which suggests a dilution ratio of about 45.

For vehicle emissions diagnostics these dilute data can be converted to show actual tailpipe concentrations, and a consideration of all four gases simultaneously is the first step in diagnosing whether the engine and its emission controls are all operating correctly.

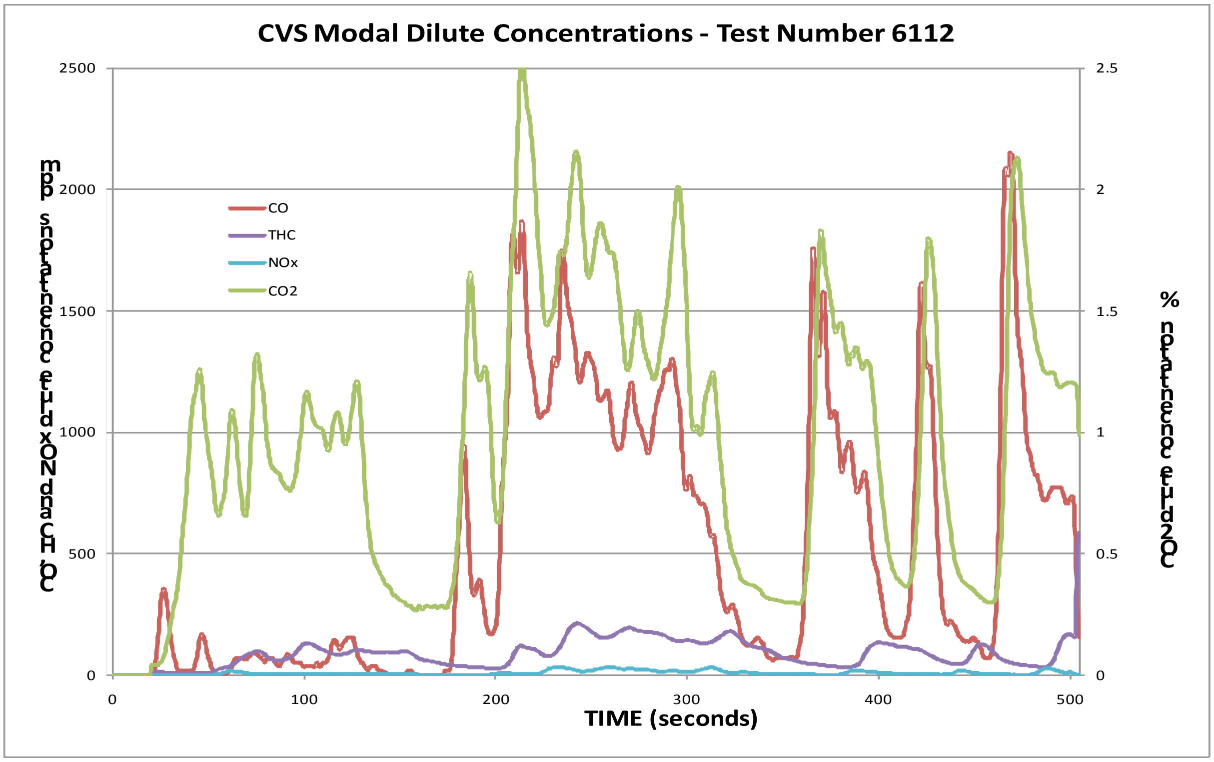


Fig 3.

PM Data Aggregation

For PM testing, instead of using the CVS dilute data to calculate tailpipe gas concentrations, we instead use it to derive instantaneous tailpipe flow rates. This is necessary because the PM concentration measurements are taken from the raw tailpipe exhaust, before the CVS dilution air is introduced. By combining the calculated tailpipe flow rate with the measured PM concentration we can derive the instantaneous emission rate for PM. The summation over the complete test, divided by the distance driven, results in a mass emission factor in units of mg/km. Other vehicle mass emission factors are usually stated in units of g/km.

PM ANALYSER COMPARISON TESTING

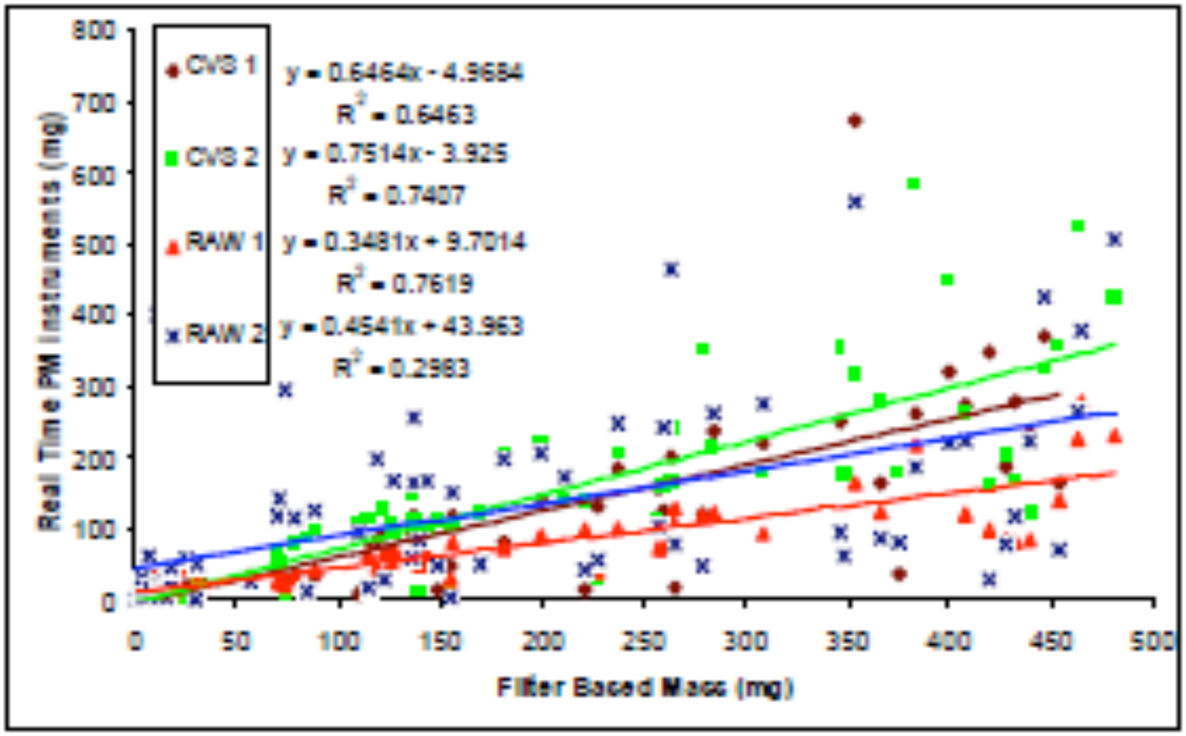
This aspect of the project did not generate results capable of confirming the absolute correlation of the MAHA measurements with other, more conventional, PM measurements. It is an aspect that will need more work in future. We present some correlation results from the Air Resources Board in California, and from the manufacturers themselves. Both indicate encouraging values of R^2, but in neither case is the gradient =1. It is our intention to acquire our own gravimetric PM measurement capability once funds are available, and the future of the AirCare lab is more certain. This will enable our own assessment of the issue.

Environment Canada

In February the MAHA analyser was shipped to Environment Canadas emission lab in Ottawa. The plan was to acquire continuous PM concentration data in parallel with volume flow rates, and while also using filter-based gravimetric measurements as a reference. This depended on piggy-backing onto other testing already being conducted at EC. They were to select a suitable vehicle or engine that was already scheduled for testing, and to simply add the MAHA analyser to the test arrangements. This all went as planned, however the engines and vehicles currently being tested by EC are mostly quite new. This meant that the subject engine had very low PM emissions – so low as to be barely detectable using filter collection, and right at the low end of the MAHA usable range. The two sets of results did indicate the same order of magnitude, but their actual values were so low as to not satisfy the intended purpose of the testing.

California Air Resources Board

CARB has also been evaluating various continuous PM analysers, in comparison to, and as a possible alternative to the filter-based reference method. Their testing set-up and measurements were essentially what we had hoped to do with EC, and their results are more relevant than what was accomplished at EC. Fig 4 is from a 2009 presentation[3].



Correlation between real-time instruments measured PM mass vs filter based PM mass. Fig 4.

It compares the total mass of PM derived from the continuous analysers (vertical axis) to that measured by filters (horizontal axis). The red points and line are for the MAHA analyser, and show R^2=0.7619. At high PM concentrations the MAHA agreed well with the filter based method. The range of values shown is comparable to our own tests.

MAHA

The manufacturers have, of course, performed many tests to establish their performance claims.
Fig 5 is from a 2009 presentation[4]. It presents the same type of information as Fig 4 , except that the scales are mg/km and extend to much higher values. For this range of emission rates the correlation is shown as R^2= 0.95

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[3] Zhang Mang et al. ***COMPARISONS OF REAL-TIME PM INSTRUMENTS AND GRAVIMETRIC MEASUREMENT ON LIGHT DUTY GASOLINE VEHICLES*** , 19th CRC On-Road Vehicle Emissions Workshop, Hyatt Regency Mission Bay, San Diego, California, USA March 23-25, 2009

[4] Antonio Multari, ***Clean Air Conference*** Estes Park Colorado September 2009

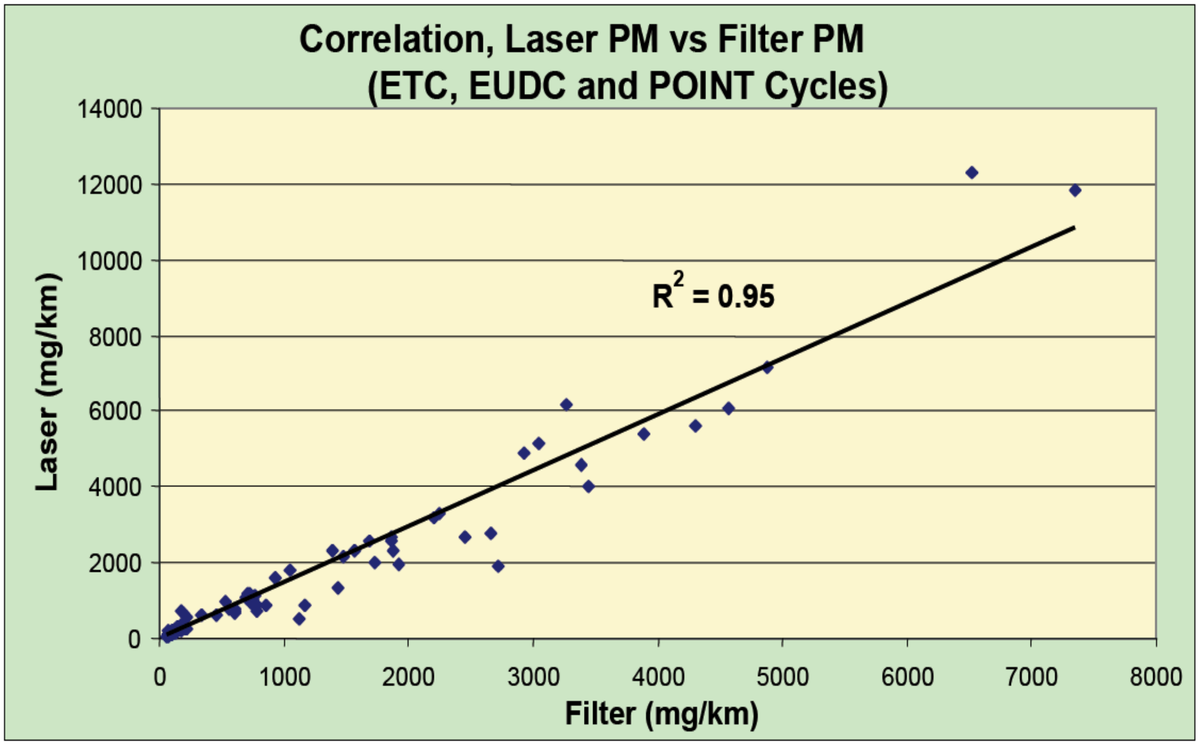
Correlation, Laser PM vs Filter PM
(ETC, EUDC and POINT Cycles)
14000
12000
10000
8000
6000
4000
2000
0
Laser (mg/km)
$R^2 = 0.95$
0
1000
2000
3000
4000
5000
6000
7000
8000
Filter (mg/km)

Fig 5.

SUMMARY OF RESULTS

Correlation of PM to Other Data

The essential function of the CVS system in this project was to provide a means to derive values for instantaneous tailpipe exhaust flow-rates. This is what enabled us to transform simple tailpipe PM concentrations (mg/m^3) into the much more useful and meaningful mg/km mass emission factors. However, the process necessarily involves measuring the vehicle's CO, HC and NOx emissions, so for each vehicle tested we also have mass emission factors for these gases as well as for PM.

The tables in the Appendix that list all the tested vehicles, also show the emission factor results for PM and for HC, CO and NOx.

We also have some vehicle characteristics information, and it is natural to look at how the PM emissions might relate to the other emissions, or to the vehicle characteristics. This can sometimes suggest how one measurement or characteristic might serve as a surrogate for another, and can usually at least indicate how the data might be grouped and summarized. The following scatter plots plot PM emission rates against other data. The first of each pair is for the diesel vehicles, and the second for gasoline. All the vertical axes have the same scale of 0 to 100 mg/km of PM. One of the diesel vehicles (1991 Jetta) is not plotted, because its PM emissions were more than twice the maximum value shown on the scale. Two of the gasoline vehicles (1990 Civic and 1991 Civic) had PM emissions almost twice as high as the maximum scale value, and a 1993 caravan was 37% off scale – so these are not plotted either.

Figs 6 and 7 relate PM to vehicle model year. There are no old diesels with low PM emissions. The only ones that are low are vehicles up to about five years old. But age is not an adequate indicator of low PM emissions for diesels, because there are also many vehicles in this newer age range that do have high PM. The data suggest that all old diesels have high PM, and that newer diesels might also have high PM. This means that the average PM from newer diesels is significantly lower than from older. The situation for gasoline vehicles is quite different. The vast majority have very low PM, even when they are old. It appears that only vehicles over about 15 years old are liable to develop high PM emissions. Since high PM from gasoline vehicles is most probably associated with engine wear and oil consumption, it is reasonably not expected to happen until the vehicle has reached a certain age or mileage. However, most of the older gasoline vehicles still have very low PM.

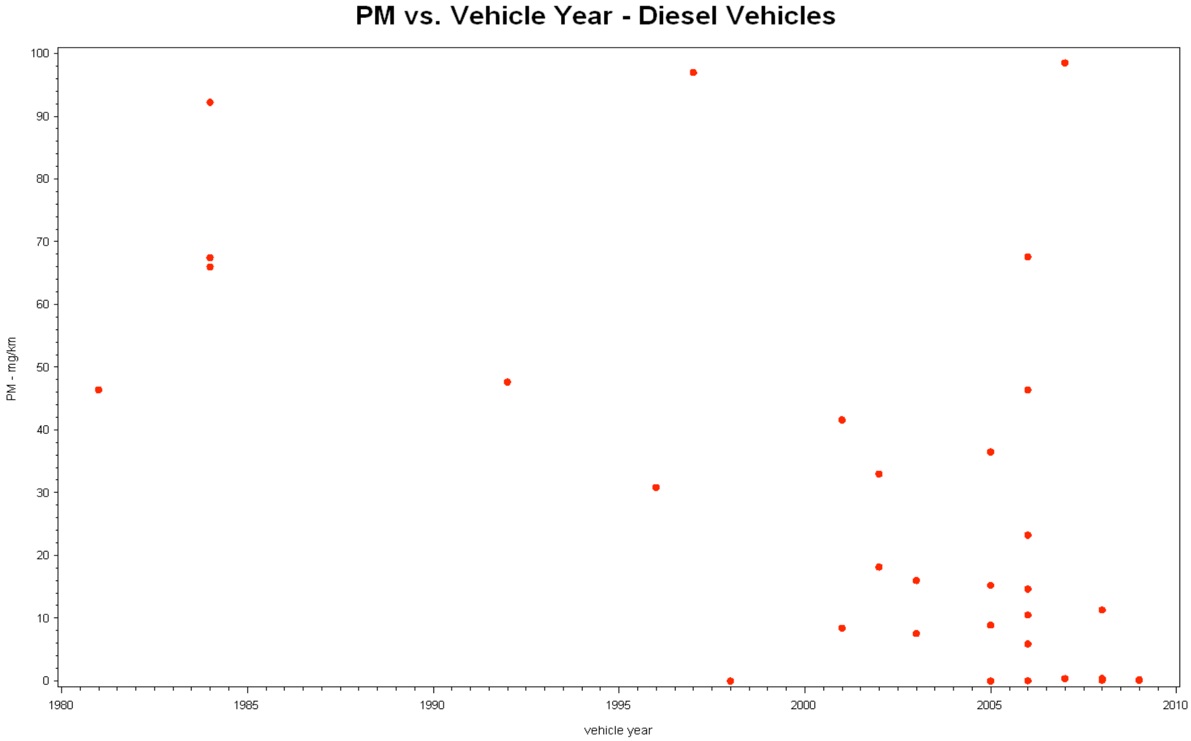
PM vs. Vehicle Year - Diesel Vehicles
PM - mg/km
vehicle year
0
10
20
30
40
50
60
70
80
90
100
1980
1985
1990
1995
2000
2005
2010

Fig 6.

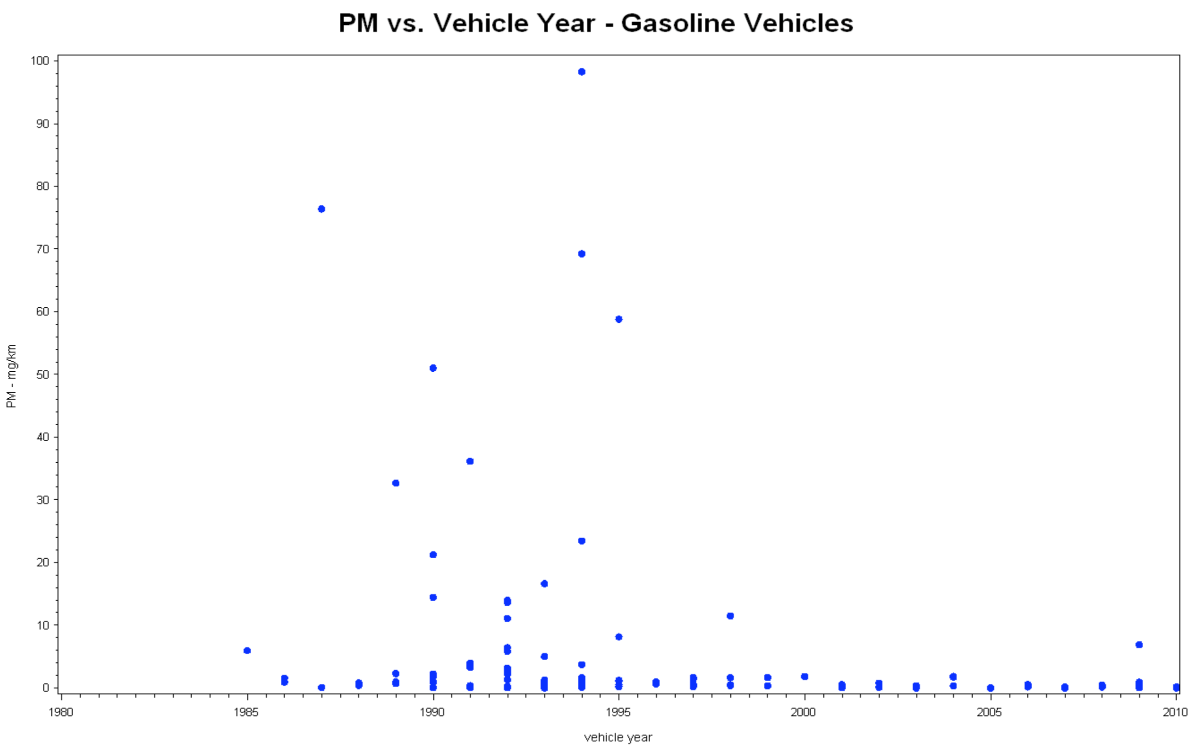
PM vs. Vehicle Year - Gasoline Vehicles
PM - mg/km
vehicle year
0
10
20
30
40
50
60
70
80
90
100
1980
1985
1990
1995
2000
2005
2010

Fig 7.

Figs 8 and 9 plot PM against vehicle test weight. The diesels range from small VW cars to 1 ton pickup trucks, ambulances and handydart buses. There appears to be no relation between vehicle weight and PM. Most of the gasoline vehicles are smaller, and for these vehicles there again appears to be no relation between weight and PM. At the higher weights it does seem that PM is typically lower, but these heavier vehicles do not include any old, high mileage vehicles.

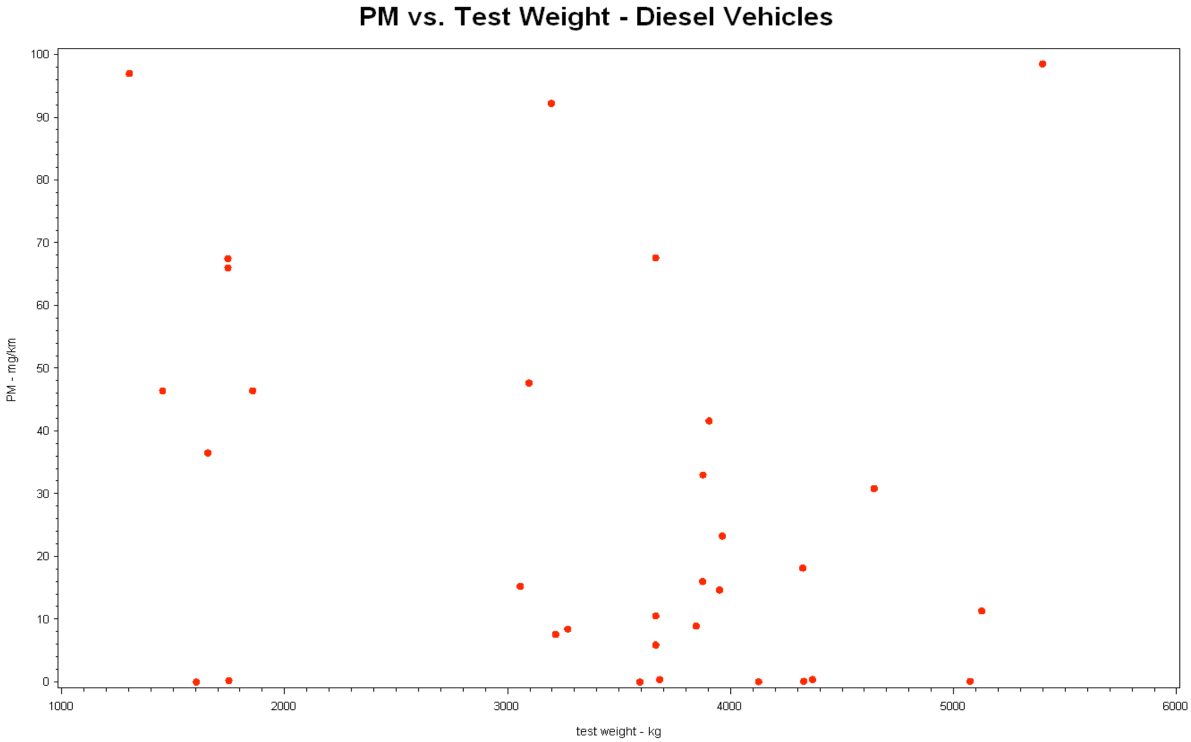

Fig 8.

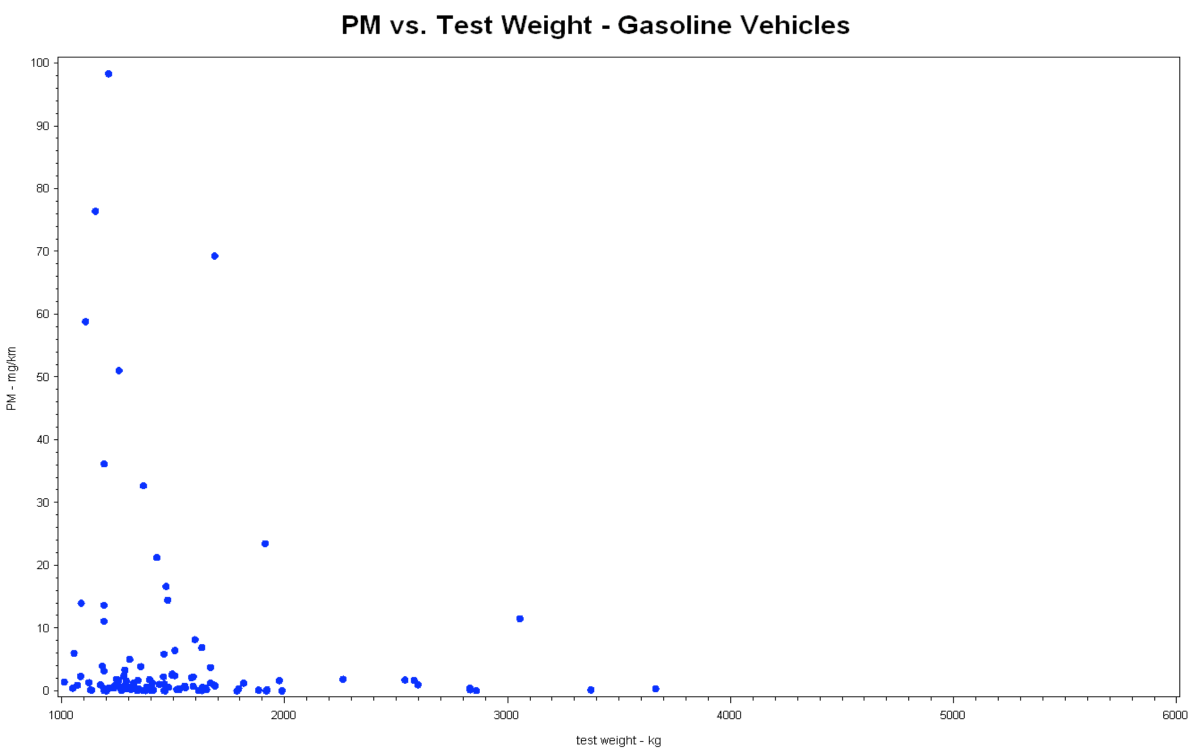

Fig 9.

Figs 10 and 11 plot PM against engine displacement. For both fuels, there is no more relation of PM to engine size than there is to vehicle weight.

PM vs. Engine Size - Diesel Vehicles

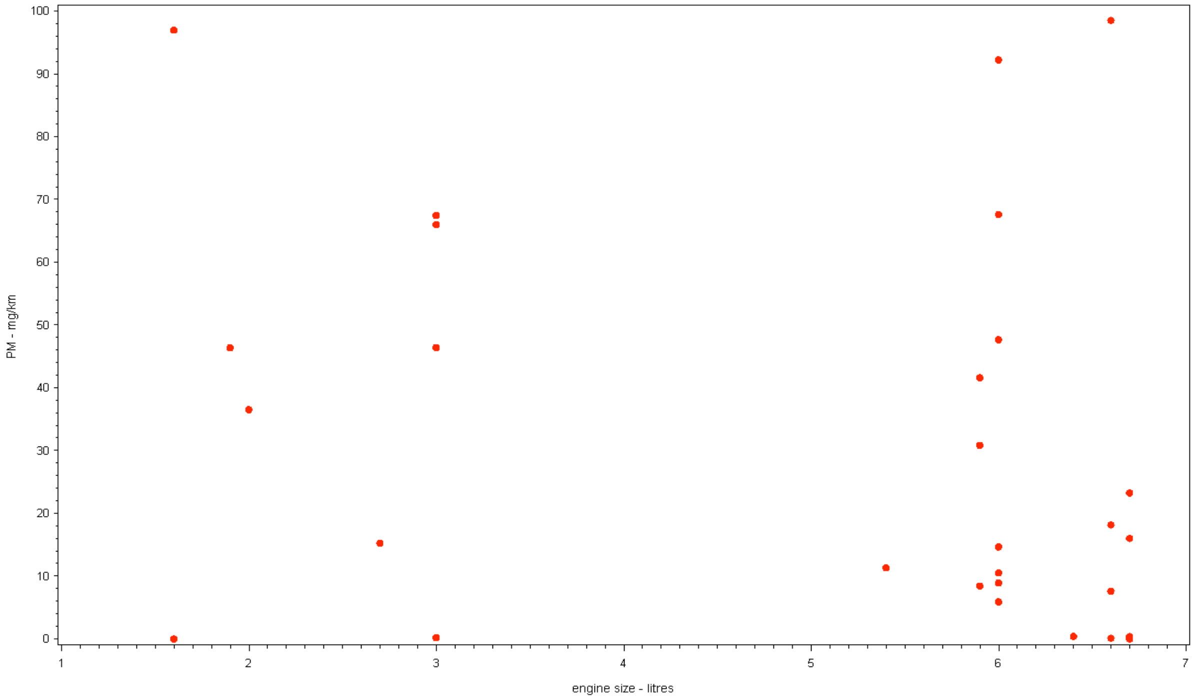

Fig 10.

PM vs. Engine Size - Gasoline Vehicles

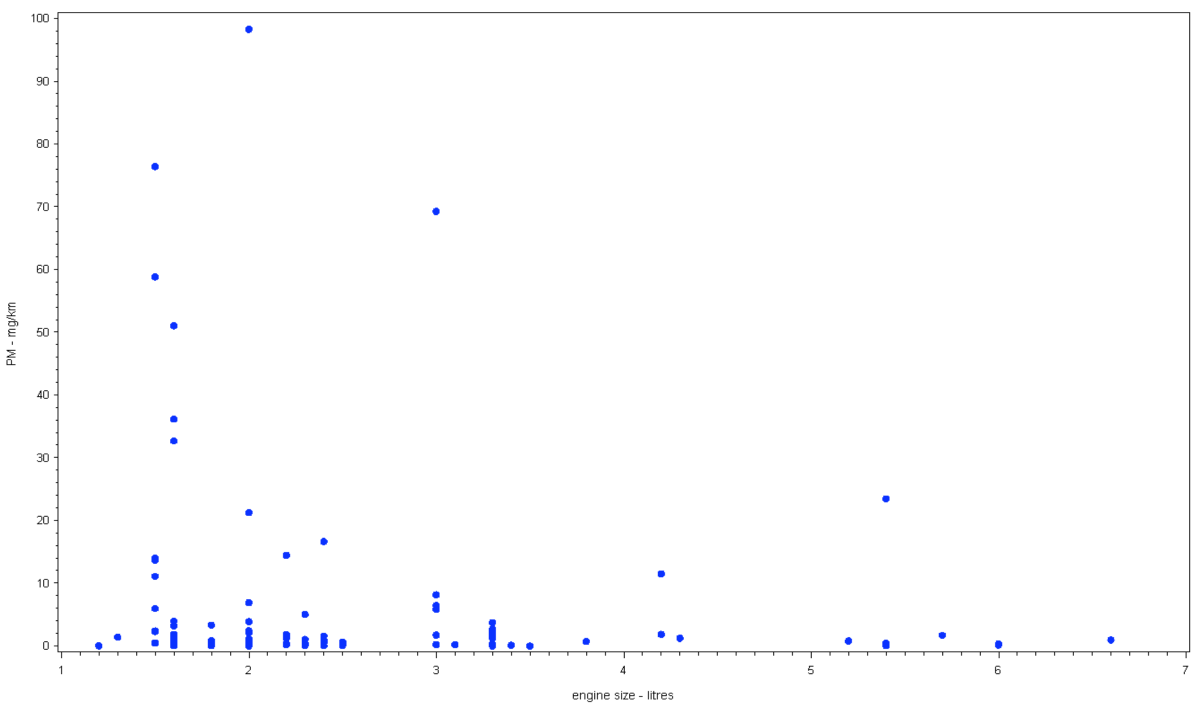

Fig 11.

Figs 12 and 13 plot PM against HC emissions. The diesels all have very low HC, but some of the gasoline vehicles have much higher HC. However, in both cases there is no relation to PM.

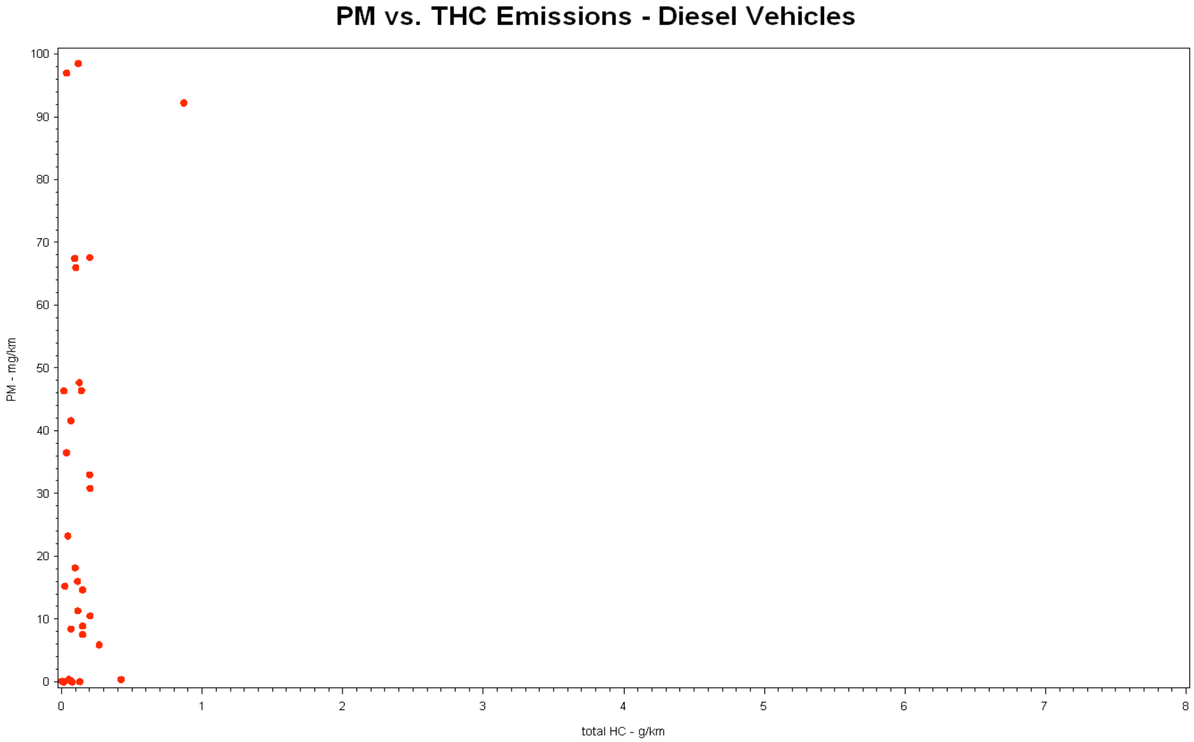

Fig 12.

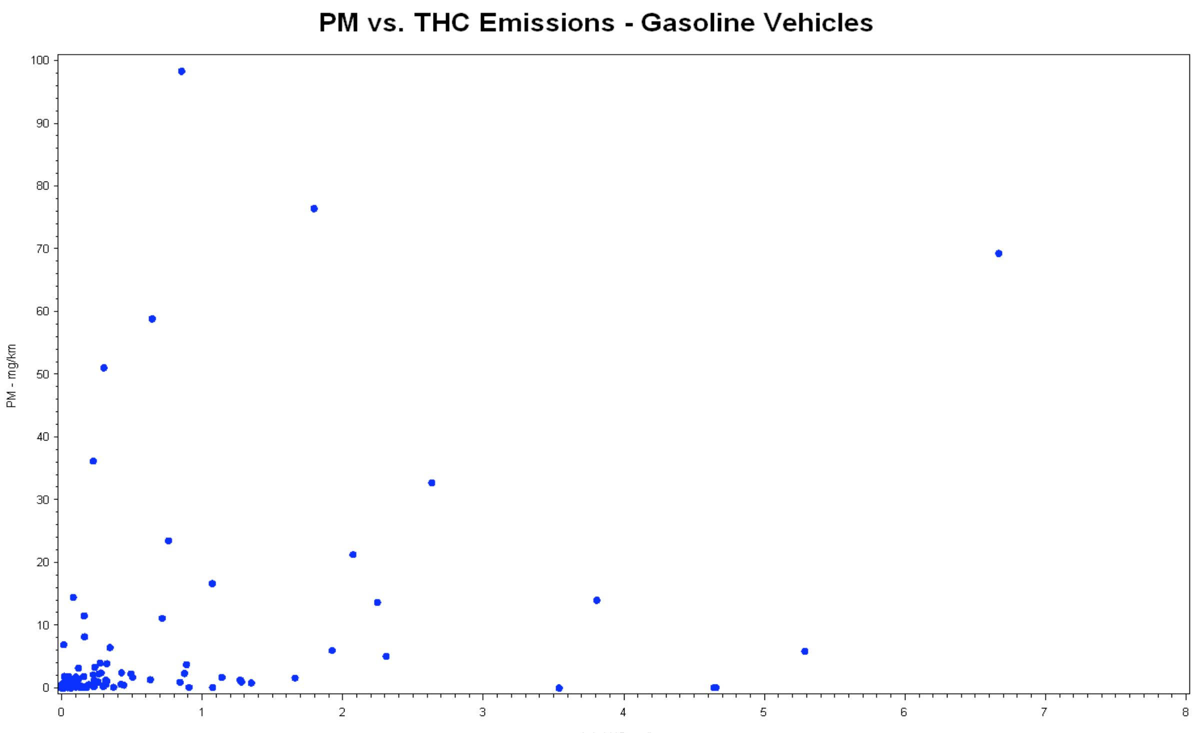

Fig 13.

Figs 14 and 15 plot PM against CO emissions. The range of CO values for gasoline vehicles is much greater than for diesel, but in both cases there is no relation to PM.

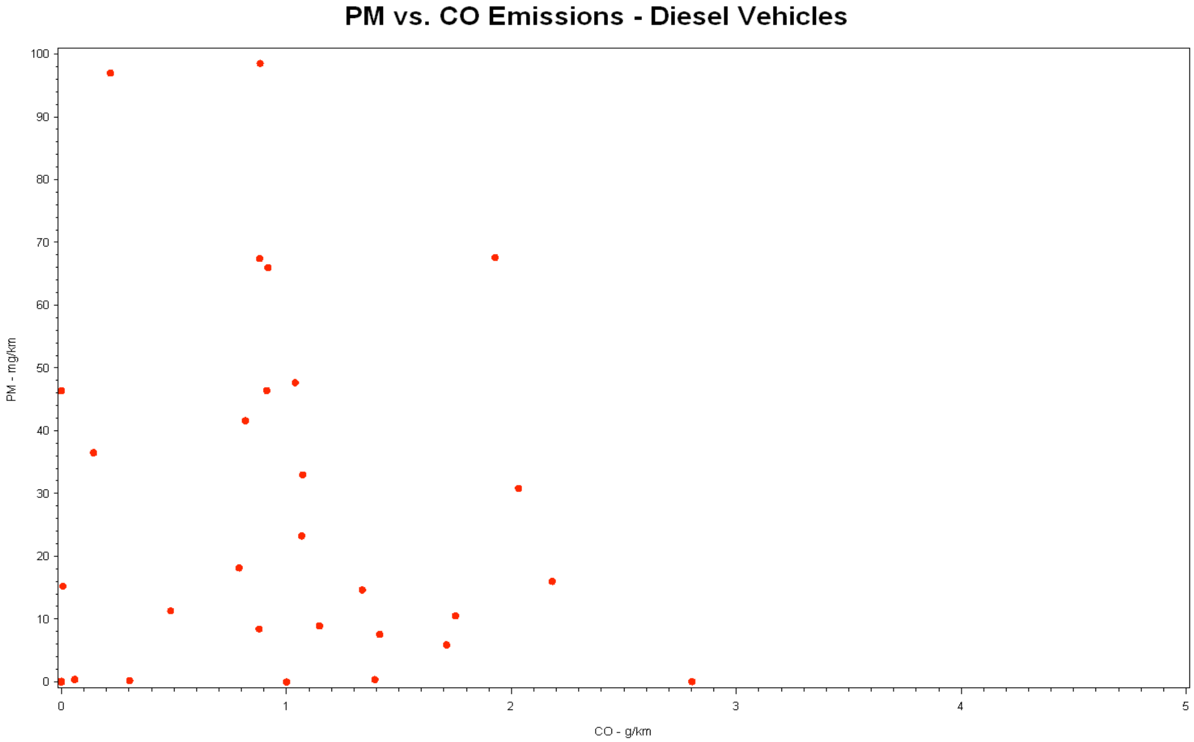

Fig 14.

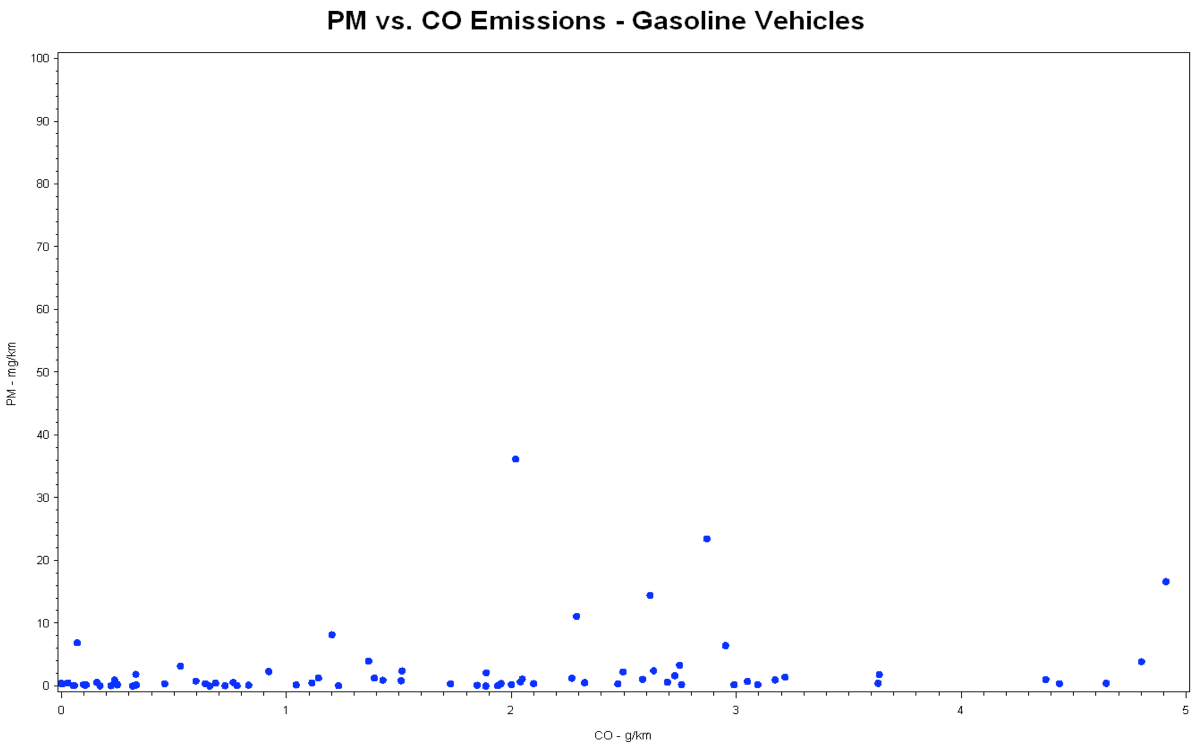

Fig 15.

Figs 16 and 17 plot PM against NOx emissions. The diesel NOx emissions are spread across the whole extent of the range plotted, but the gasoline NOx emissions are mostly at the lowest end of the range. In both cases there is no relation of PM to NOx.

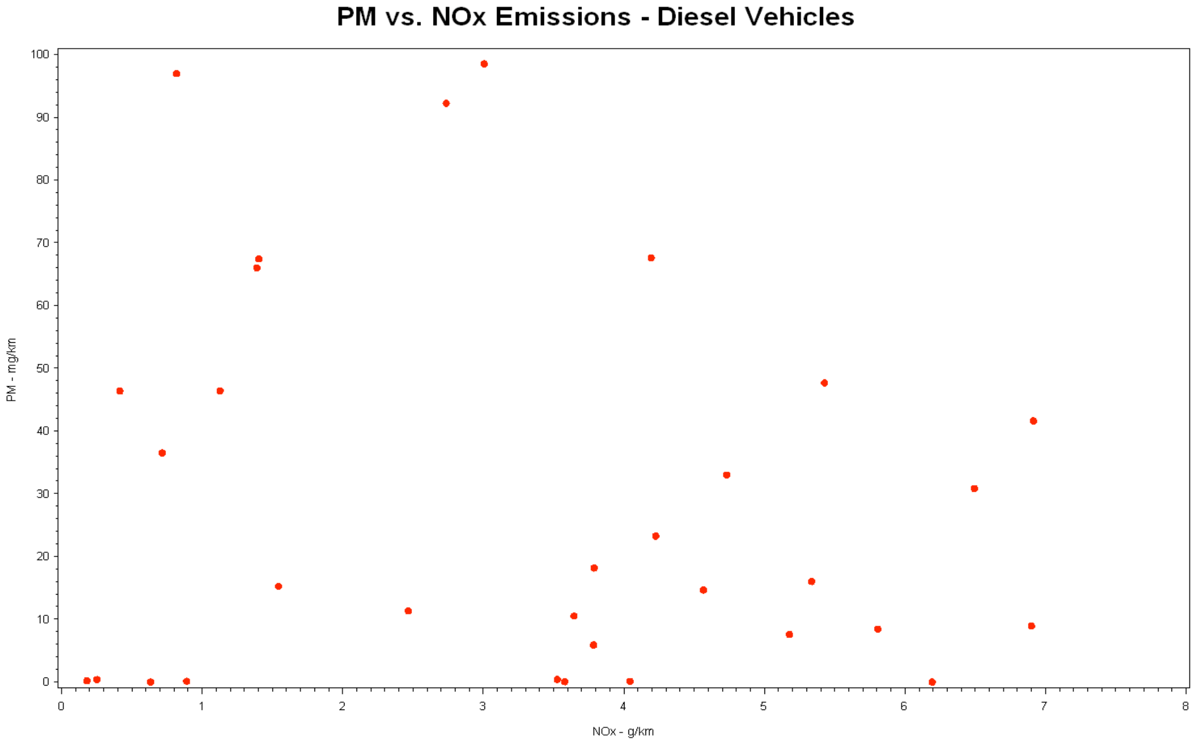

Fig 16.

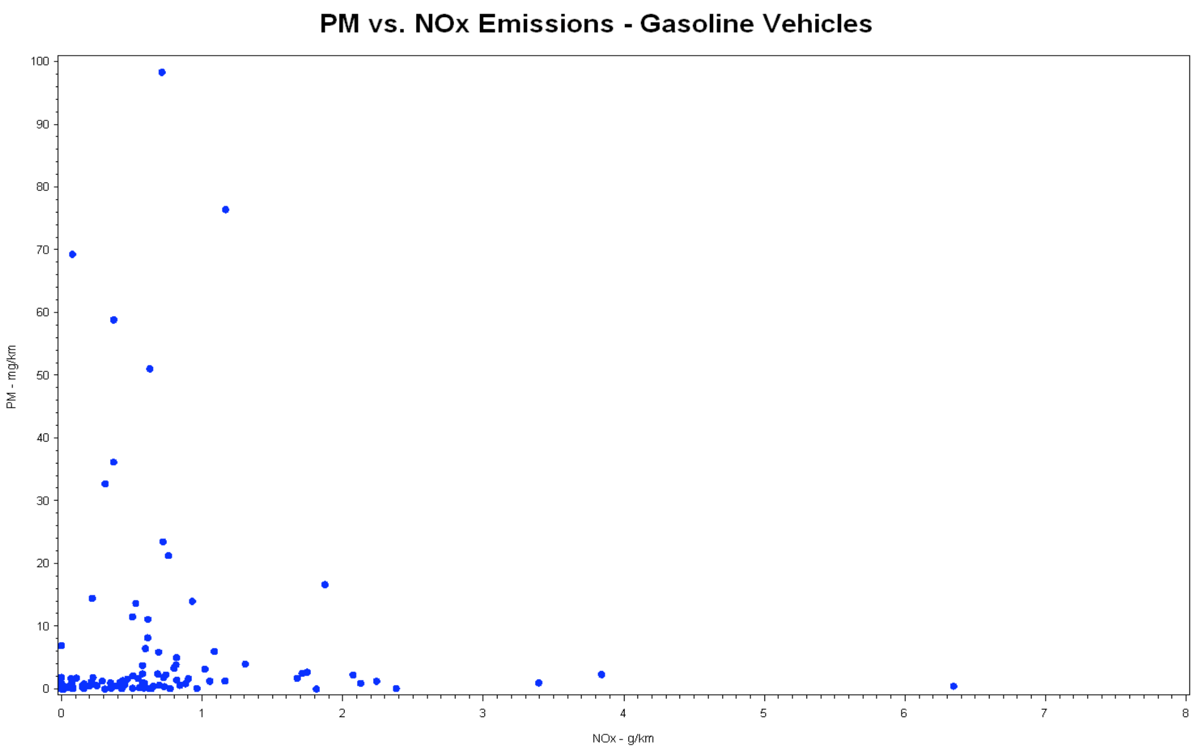

Fig 17.

Figs 18 and 19 plot PM against odometer readings. The results are essentially a reflection of those in Figs 1 and 2, because odometer reading always increase as vehicles get older. So diesels with high odometer readings are unlikely to have low PM, while those with low odometer readings might have either low or high PM. Gasoline vehicles simply do not develop high PM below 120,000km, and even at values as high as 300,000km, most still have low PM. It seems that only those vehicles that have suffered serious engine wear are likely to produce significant PM emissions. As mentioned earlier, there are three gasoline vehicles and one diesel that are not plotted, because their PM emissions are off-scale. All support the suggestion that high mileage can mean high PM. The 1991 Jetta had 764,971 km and PM of 235 mg/km. The two Civics and the Caravan had odometer readings of 232,310 km, 241,375km and 191,704km respectively; with corresponding PM emissions of 341mg/km, 351mg/km and 137mg/km. So the Jetta had unusually high mileage as well as unusually high PM, while the three gasoline vehicles did not have unusually high mileage for their age, but were observed to smoke, indicating engine defects.

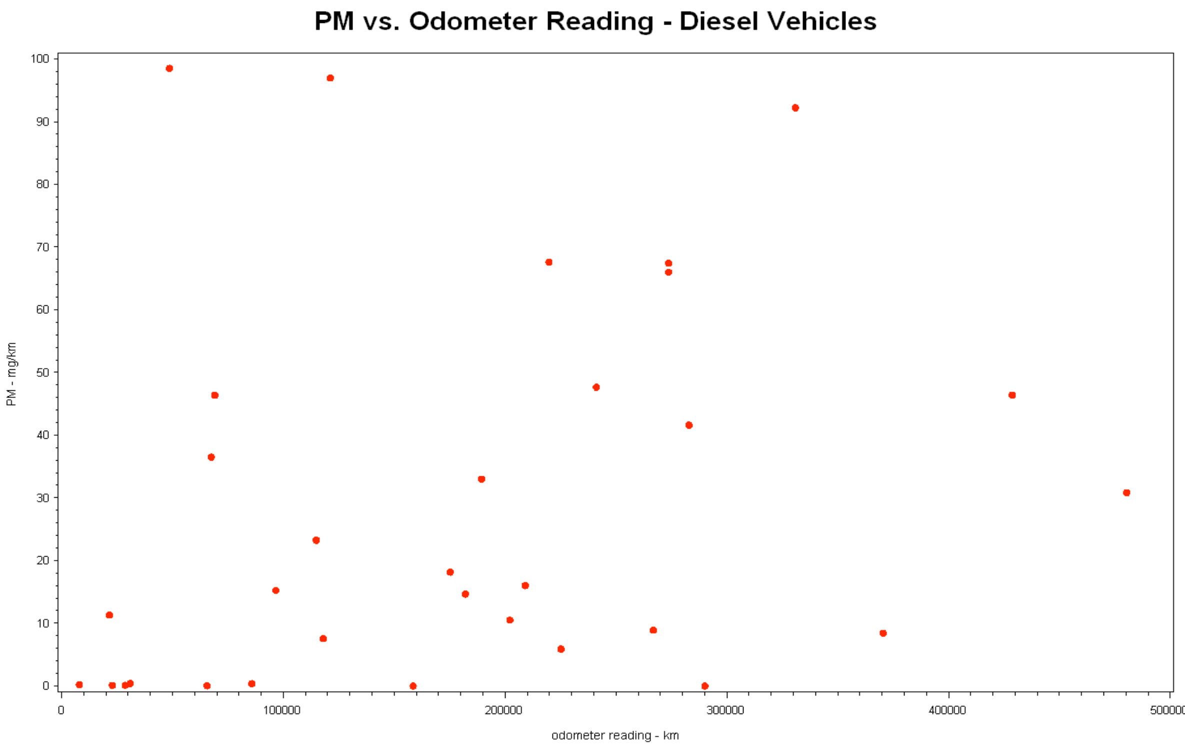

Fig 18.

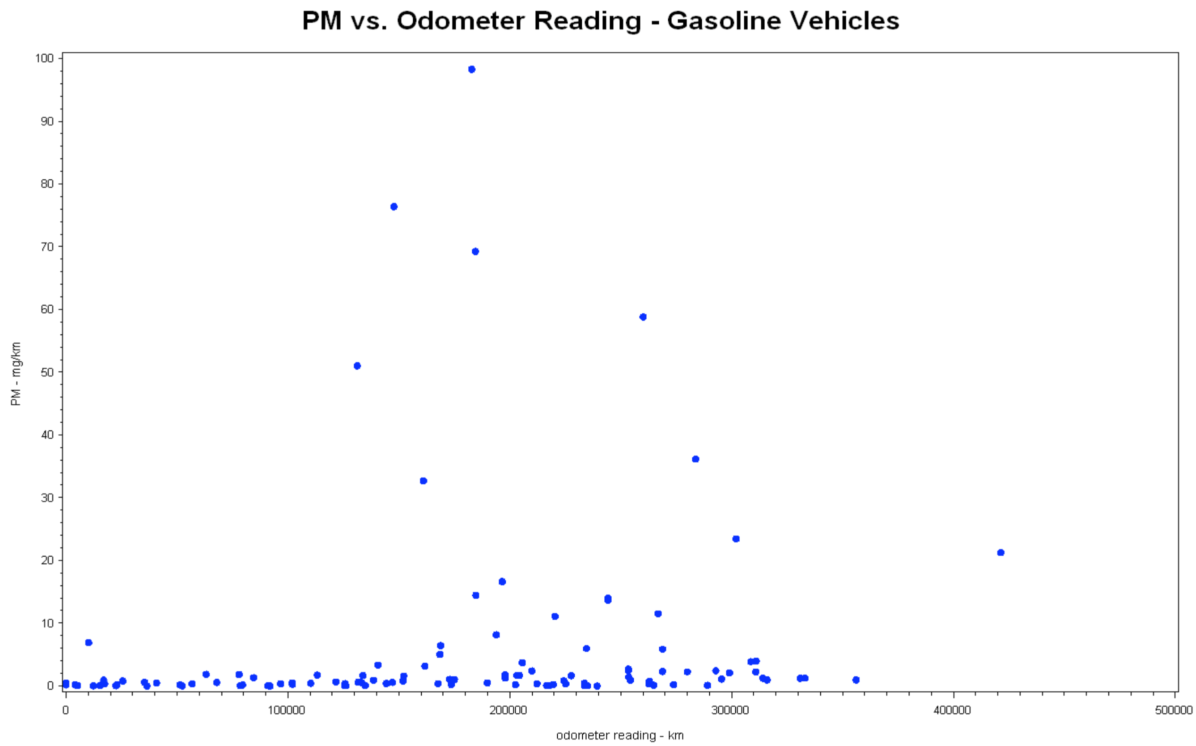

Fig 19.

Figs 20 and 21 plot odometer reading against model year. There is much variation in individual rates of mileage accumulation. Linear regressions on this data give annual kilometres travelled as averaging about 12,000 km/y for the gasoline vehicles and about 16,000 km/y for the diesel vehicles.

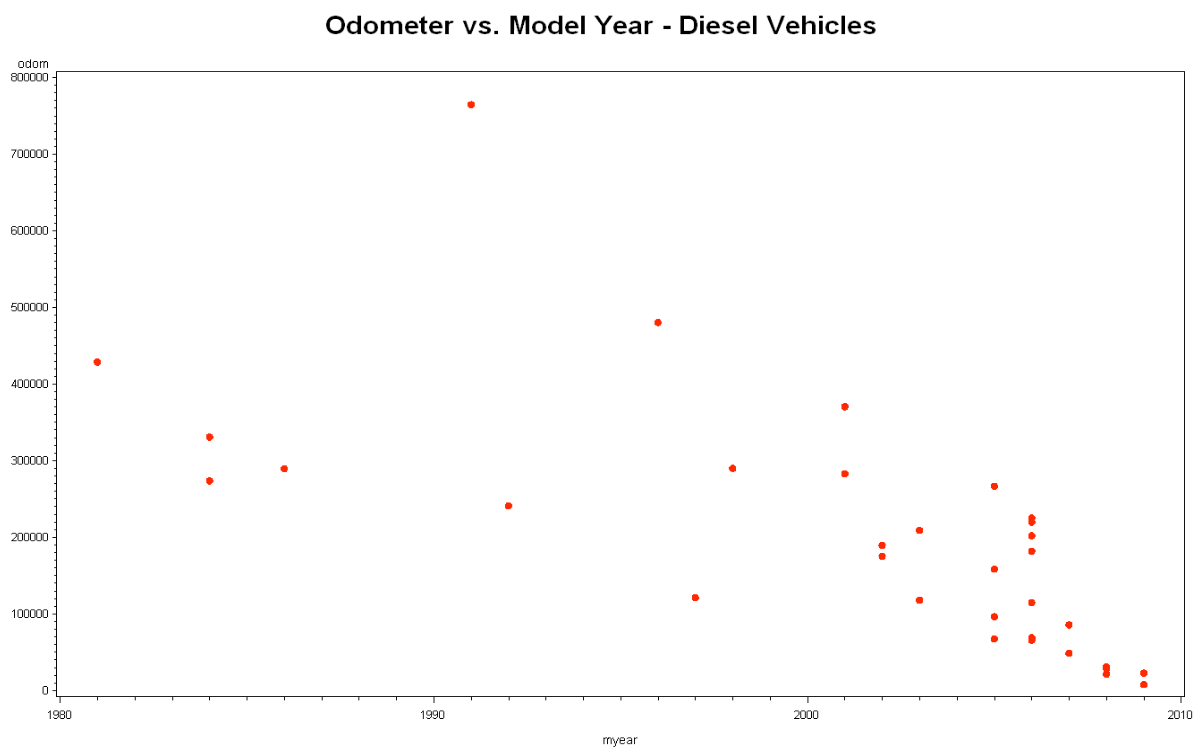

Fig 20.

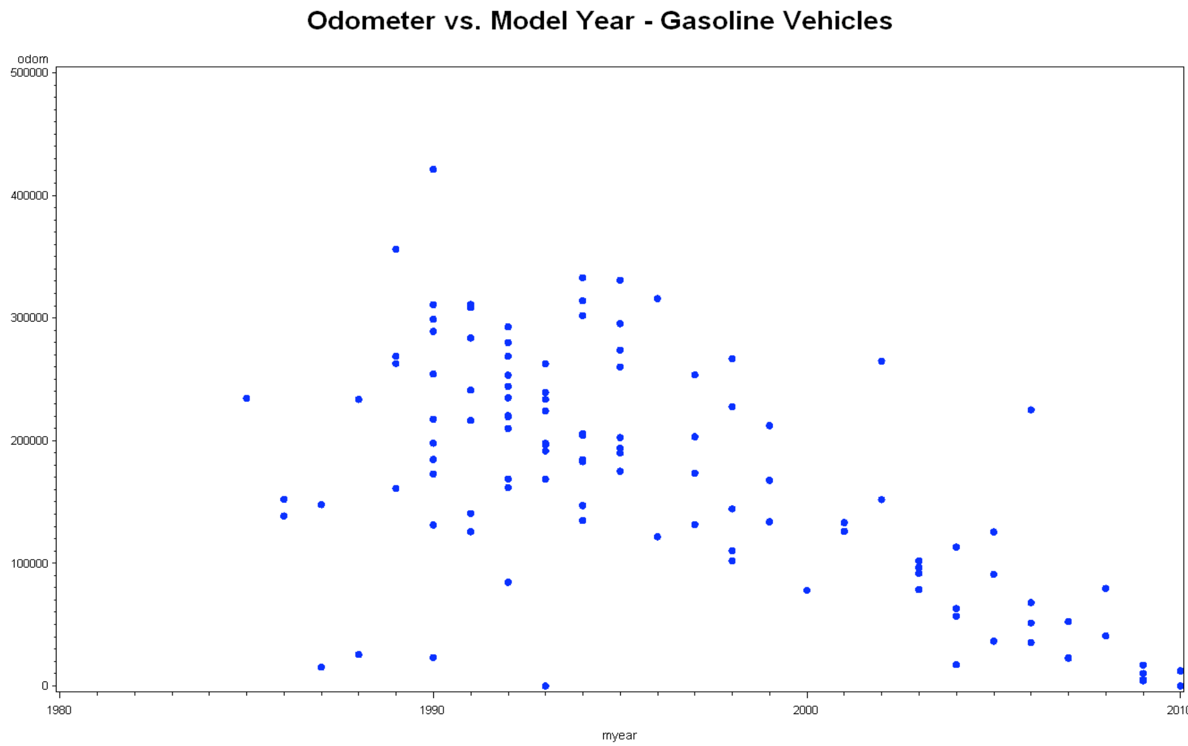

Fig 21.

Of all the above plots, the only ones that suggest a relationship between PM and any other variables are those for vehicle age and total mileage (odometer reading) . This is as expected. There is no reason to expect that PM emissions would relate to HC, CO or NOx emissions. If they did, it would be possible to use these other emissions as a surrogate for PM.

PM Mass Emission Factors

The foregoing plots clearly indicate that there is a lot of variation in the amount of PM that can be emitted by light-duty vehicles. However, although there are no other surrogate variables that could give a reliable indication of PM emissions, we can conclude that:

- PM emissions depend on whether the vehicle is diesel or gasoline.
- For diesels the PM emissions for newer vehicles can be very low.
- Although diesel engines can continue to operate to very high mileages, their PM emissions at this point are also likely to be very high.
- Gasoline PM emissions are only high when the engine is mechanically defective.

Table 6. summarises the mean, median, 75th percentile and 90th percentile values of PM emissions, by fuel and age group.

	diesel		gasoline	
model year	le 1995	ge 1996	le 1995	ge 1996
number tested	7	27	69	46
PM mg/km				
mean	102.5	21.9	21.1	0.9
median	67.5	11.3	2.1	0.4
75%ile	124.3	33.0	8.1	0.8
90%ile	273.5	67.6	58.8	1.7

Table 6. *Summary of PM Mass Emission Factors*

Comparison with Previous Work and with the MOBILE Model

In 1999 a project was undertaken at the AirCare Research Centre by Environment Canada, to collect PM emissions data from in-use gasoline vehicles[5]. It used the established gravimetric method of collecting samples on filter papers. A total of 62 light-duty vehicles were tested. They were all gasoline vehicles. The range of model years was from 1978 to 1998. The range of $PM_{2.5}$ emission rates measured was from 0.25 mg/mile to 100 mg/mile (0.16 to 62.5 mg/km). This range is contained within the range of values measured in this project for the 80 gasoline vehicles up to model year 1998 (0.04 to 351 mg/km) However, if the extreme deciles are trimmed from our present data the remaining range between the 10^{th} and 90^{th} percentiles is from 0.12 mg/km to 58.8 mg/km, which coincides very well with the full range measured by EC. This is a result that gives some confidence in the measurements from the MAHA analyser, and in the methodology of combining these continuous measurements with continuous dilute gas concentrations from CVS testing in order to derive mass emission factors.

Environment Canada also conducted a study at the Cassiar Tunnel in 2001, which included assessment of PM emissions[6]. It reported average $PM_{2.5}$ emissions for light-duty vehicles at 14.5 mg/km.

The most recent published inventory for the Lower Fraser Valley is for 2005. This was compiled by the GVRD in 2007 using the MOBILE 6.2C emissions model. One of the inputs is a table of PM_{10} emission rates, with values for each vehicle category. The factors for exhaust PM_{10} which are relevant to this project are shown in Table 7 . [7] The factors are composite values that take into account the model year distribution of the fleet. For our purposes it is reasonable to assume that about half of the in-use vehicles in 2005 were newer than model year 1995, so we can compare these composite factors to the average of the two age groups shown in Table 6.

[5] '***Gaseous and Particulate Matter Emissions from In-Use Light-Duty Gasoline Motor Vehicles'*** ERMD Report #99-67, Lisa Graham 2000

[6] '***Gaseous and Particulate Emission Factors for On-Road Vehicles Measured in the Cassiar Tunnel, Vancouver'*** EMRD Report #02-44, Lisa Graham 2002

[7] ***Personal communication from Jimmy Wong***, Project Engineer AQPM Div., Policy & Planning Metro Vancouver February 21^{st} 2011

For diesels the mean value from Table 6 comes to 62.2 mg/km, which is very similar to the value shown in Table 7 for LDDV. But it is significantly lower than the Table 7 values for LDDT12 or LDDT34.

For gasoline vehicles the mean value from Table 6 is 11.0 mg/km, which is significantly higher than the value shown for LDGV, LDGT1 or LDGT2 in Table 7.

Overall there is reasonable agreement between our current results and those obtained by Environment Canada in 2000 and 2002, but these results are typically lower than the emission rates used in the 2005 inventory. This suggests that the light-duty mobile-source 2005 inventory of PM_{10} may have been underestimated. Further work is clearly needed.

Vehicle Category	PM_{10} g/km
LDDV	0.068
LDDT12	0.128
LDDT34	0.126
LDGV	0.003
LDGT1	0.003
LDGT2	0.003
LDGT3	0.017
LDGT4	0.009

Table 7. *PM_{10} Emission Factors used for 2005 LFV Inventory*

Comparison with Original Certification Standards

For vehicles of model year 2002 and newer the Tier 2 emissions standards apply to all light duty passenger vehicles and light-duty trucks. A light-duty vehicle may comply with Tier 2 while being in any one of up to nine Bins, but a manufacturers total sales have to average emissions that are just about equivalent to Bin 4. In practice this means that on average new light-duty vehicles must emit lower than 0.01 gram/mile of PM (= 6.2 mg/km) As with all other emission standards, a new vehicle can be expected to emit far below this maximum allowable level, but deterioration will usually increase emission rates as the vehicle ages. The rates measured in this project for gasoline vehicles from 2002 and newer were all well below the Tier 2 Bin 4 standard.

Most of the diesels tested in the 2002-and-newer age group were not light-duty, but they may have been certified to Tier 2 Bin 10 or Bin 11, which are specifically for medium-duty vehicles. They allow 0.08 and 0.12 g/mile respectively of PM (= 49.6 and 74.4 mg/km). The results shown in Table 8 are mostly below these levels.

The tests only included four diesel passenger vehicles certified to Tier 2. For some reason, the 2005 VW Jetta had no measureable PM emissions, which could indicate an experimental error. The 2009 MB E320 had PM emissions at about the same level as gasoline vehicles. The 2005 VW Passat and the 2006 VW Golf both had much higher PM emissions (36 mg/km and 46 mg/km respectively), and in fact these vehicles were certified in Bin 9 which allowed 0.06 g/mile (= 37.2 mg/km). This Bin was discontinued after 2006.

For older gasoline vehicles there was no effective PM standard, because measurement as a condition of certification was waived. So this means that the certification standard is not a useful comparison. Measurement was required for diesels, and the Canadian certification standard from 1988 was 0.20 gram/mile (= 124 mg/km). Prior to 1988 there was no Canadian standard. The US first adopted a light-duty diesel PM emission standard in 1982, of 0.60 g/mile (= 372 mg/km). This was lowered to 0.20 g/mile in 1986, and to 0.08 g/mile in 1994. Since the introduction of Tier 2, standards in the US and Canada have been the same. Of the older diesels tested, only the 1991 VW Jetta at 273 mg/km was clearly emitting well above its original certification standard.

Instantaneous PM Emission Rates and Concentrations

All of the test results presented in this report have been derived from continuous measurements, and can be presented as instantaneous values of mg/sec or mg/km or mg/m^3 at any point in the test. Each point corresponds to a specific driving condition. This is the sort of information that is very valuable when diagnosing the cause of a specific emissions problem. It is also useful when designing emission controls because it identifies which driving conditions should be focused on more than others. For inventory purposes it can be used to achieve a proper appreciation of the contribution of idling versus driving, and of other aspects of the driving cycle. These types of analyses are beyond the scope of this report.

OPERATIONAL OBSERVATIONS

Remote Vehicle Emission Clinics

Initial use of the MAHA PM analyser was during a two day vehicle emissions clinic in Whitehorse in June 2009. It established the basic operating procedure for the unit and confirmed its robustness and reliability in a routine inspection environment. It has also been used in similar clinics in Williams Lake, Quesnel and Prince George, which provided 5 days of continuous use in an outdoor environment, and tested the continuous data acquisition capabilities of the analyser linked to a laptop computer. There were differences in the ambient humidity and temperatures, which did not appear to affect operations. The measurements themselves are of exhaust gas, which is not affected by ambient conditions.

Lab Operations

In the laboratory the protocol is to acquire data continuously during CVS testing. The issue that is most difficult is time alignment of the continuous PM data with the CVS data. This is partially resolved by a precisely defined test routine. It is also necessary to check the alignment of every individual data set.

CONCLUSIONS

The MAHA Analyser

The projects effort to independently establish a comparison of the MAHA measurements with other methods of measuring PM emissions did not work out as planned. However, our comparisons with SAE J1667 smoke opacity testing did indicate that both methods responded similarly to black diesel smoke. Moreover, the testing performed at CARB did correspond to what we had hoped to accomplish at EC, and it established that there is a correlation between the MAHA results and filter based methods. The correlation for the MAHA analyser was greater than for the other continuous analysers that were included in the CARB testing. The correlation is considered strong enough to indicate that the MAHA analyser could be used to reliably categorise vehicles as low, medium or high emitters of PM. The correlation claimed by the manufacturer is higher, but is for a much wider range of emission rates.

Three potential uses for the analyser are now clear:

- One of these is to provide an objective method for identifying oil-burning gasoline vehicles. Provincial regulations clearly require that non-diesel vehicles should not make visible smoke, but the assessment of smoke intensity has been subjective, and other affordable analysers have not been able to provide a quantitative measure of the type of smoke emitted by oil-burning vehicles. The results presented indicate that the vast majority of gasoline vehicles have very low PM emissions, even when they are old and have high mileage. When a vehicle starts to burn oil, however, its PM emissions are greatly increased, which means that a PM measurement, using this analyser, can provide an objective and reliable way to identify engines that are in need of mechanical repair. Such a test would not have to include a full assessment of mass emissions in terms of mg/km. It could instead set criteria for mg/m3 exhaust PM concentration at a defined operating condition, which would be analogous to using ASM or TSI testing instead of IM240.

- A second use is to continue collection of PM mass emission data by integrating the analyser into existing IM240 and D147 inspection lanes. Integration would include reliable time alignment of the PM measurements with other data, in the same way as is now applied to other analysers. This use would allow the continued collection of PM data from a much larger sample of vehicles than were included in this project. At present at least 5000 vehicles per year go through supplementary tailpipe mass emission testing at AirCare inspection facilities, specifically in order to provide mass emission data which is used to characterize the in-use fleet and to help evaluate how the inventory changes with time and as a result of the inspection program. These 5000 vehicles are representative of the full range of vehicles that are subject to AirCare requirements, regardless of what type of test is used for their regular, legally required, inspection.

- A third use would be somewhat in the future, once enough data has been collected to be able to reliably define the maximum acceptable levels of PM emissions from diesel vehicles, dependent on age, type, size, etc.. With this knowledge, the regular diesel inspection could include a maximum allowable value for PM. Introduction of the new requirement would also depend on being able to diagnose the causes of high PM emissions, so that when a vehicle fails the test it will be possible to identify what repairs it needs in order to comply. This would treat PM emissions in the same way as now applies to emissions of HC, CO and NOx.

In-Use Light-Duty Vehicle PM Emissions

There is a lot of variation in the amount of PM that can be emitted by light-duty vehicles. Our overall conclusions are:

- PM emissions depend on whether the vehicle is diesel or gasoline.
- For diesels the PM emissions for newer vehicles can be very low.
- Although diesel engines can continue to operate to very high mileages, their PM emissions at this point are also likely to be very high.
- Gasoline PM emissions are only high when the engine is mechanically defective.

NEXT STEPS

This initial project has shown that the MAHA unit does appear suitable for use in an ordinary inspection lane situation, and that the results are useful in a number of ways. Therefore, the next step would be to install the unit in one of the regular AirCare inspection lanes. The best candidate is Lane #1 at Abbotsford. This lane has a 4WD dynamometer and can test both diesel and gasoline vehicles. In addition to the usual inspection equipment in this lane, we have also installed a diesel NOx analyser and a diesel AFR/Lambda sensor. These are for the purpose of collecting light-duty diesel fleet characterization data for NOx emissions, as well as possibly developing pass/fail standards for diesel NOx that might be used as a future AirCare inspection requirement. These purposes are equivalent to the plan for the MAHA PM analyser, except that the PM data collection would also apply to gasoline vehicles.

Using the MAHA analyser in an inspection lane requires it to be integrated with the other lane equipment and software. We expect this task to be similar to that already achieved for the diesel NOx and AFR analysers. Software integration will include automated time alignment with the other data, and this means that future analyses of the data can also be much more automated than was possible in the present project.

In the first six months of 2010, Lane #1 at Abbotsford tested 11,368 vehicles, including 685 diesel and 10,647 gasoline. So after a year of data collection the total will be about 150 times the number tested in this project. Having more data will improve the reliability of analyses and may allow identification of patterns or relationships that are not discernable from the present limited data.

The reliability of the measurements themselves needs to be improved. The correlations presented in this report do not adequately establish the absolute validity of the MAHA analysers readings. To perform the necessary work we require our own gravimetric, filter-based system, installed at the AirCare Research Centre. This issue is being considered as a desirable part of the AirCare Program contract renewal process. The present inspection contract expires at the end of 2011, and it is not prudent to expend the cost of this new capability until there is more certainty regarding 2012 and beyond.

APPENDIX : LIST OF VEHICLES TESTED AND TEST RESULTS

Diesel Vehicles

Table 8

Vehicle	Engine L	Odometer km	test weight kg	TestID	THC g/km	CO g/km	NOx g/km	PM mg/km
1981 Mercedes 300TD	3.0	428,854	1,858	5930	0.14	0.91	1.13	46.43
1984 Mercedes	3.0	273,844	1,747	5479	0.10	0.92	1.39	66.01
1984 Mercedes	3.0	273,844	1,747	5480	0.10	0.88	1.40	67.46
1984 F250	6.0	330,980	3,197	5706	0.87	6.46	2.74	92.25
1986 Golf	1.8	289,700	1,047	5528	0.26	1.03	0.85	124.29
1991 Jetta	**1.6**	**764,971**	**1,200**	**6133**	**0.18**	**0.81**	**0.71**	**273.50**
1992 F250	6.0	241,279	3,097	5680	0.13	1.04	5.43	47.67
1996 Dodge Ram3500	5.9	480,445	4,644	5851	0.20	2.03	6.50	30.85
1997 Jetta	1.6	121,268	1,305	6132	0.04	0.22	0.82	97.00
1998 Dodge Ram2500	6.7	290,189	3,594	5868	0.08	1.00	6.19	0.00
2001 Dodge Ram2500	5.9	283,000	3,905	5798	0.07	0.82	6.91	41.62
2001 Dodge Ram2500	5.9	370,590	3,271	5849	0.07	0.88	5.81	8.43
2002 F350	7.3	189,484	3,877	5586	0.20	1.07	4.73	33.01
2002 Ford Handydart	6.6	175,294	4,324	6351	0.10	0.79	3.79	18.15
2003 Silverado	6.6	118,080	3,216	5503	0.15	1.42	5.18	7.57
2003 Dodge Ram3500	6.7	209,155	3,876	5870	0.12	2.18	5.34	16.01
2005 F250	6.0	266,950	3,846	5569	0.15	1.15	6.90	8.91
2005 Jetta	1.6	158,632	1,605	5709	0.02	0.00	0.63	0.00
2005 Passat	2.0	67,617	1,657	5855	0.04	0.14	0.72	36.52
2005 Sprinter	2.7	96,688	3,058	6179	0.02	0.01	1.54	15.25
2006 Golf	1.9	69,155	1,454	5576	0.02	0.00	0.42	46.38
2006 Ford E350	6.0	219,937	3,665	5721	0.20	1.93	4.20	67.62
2006 Ford E350	6.0	202,229	3,665	5767	0.20	1.75	3.65	10.51
2006 Ford E350	6.0	225,276	3,665	5832	0.27	1.71	3.79	5.90
2006 F-350	6.0	182,182	3,951	5836	0.15	1.34	4.57	14.65
2006 Dodge Ram3500	6.7	65,716	4,126	5864	0.13	2.80	3.58	0.03
2006 Dodge Ram3500	6.7	114,982	3,964	5866	0.05	1.07	4.23	23.25
2007 Dodge Ram2500	6.7	85,921	3,683	5859	0.42	1.39	0.25	0.39
2007 Ford Handydart	6.6	48,765	5,400	6357	0.12	0.88	3.01	98.55
2008 F350	6.4	31,040	4,368	5786	0.05	0.06	3.53	0.40
2008 E450	5.4	21,684	5,127	6153	0.12	0.49	2.47	11.31
2008 GMC Handydart	6.6	28,773	4,329	6354	0.00	0.00	0.89	0.12
2009 Dodge 5500	6.7	23,010	5,075	5578	0.01	0.00	4.04	0.11
2009 MB E320	3.0	8,100	1,751	5918	0.07	0.30	0.18	0.19

Gasoline Vehicles (1995 and older) Table 9

Vehicle	Engine L	Odometer km	test weight kg	TestID	THC g/km	CO g/km	NOx g/km	PM mg/km
1985 Tercel	1.5	234,635	1,057	6127	1.93	8.69	1.09	5.97
1986 Jetta	1.6	138,692	1,072	5893	0.84	9.03	2.13	0.92
1986 Grand AM	2.4	152,245	1,291	6384	1.66	5.51	0.47	1.59
1987 Lebaron	2.5	15,400	1,365	5500	1.08	12.21	2.38	0.08
1987 Civic	1.5	147,862	1,153	5724	1.80	22.28	1.17	76.42
1988 Fifth Avenue	5.2	25,590	1,689	5810	1.35	32.90	0.16	0.80
1988 Jetta	1.6	233,728	1,051	6187	0.23	3.63	0.65	0.42
1989 Celebrity	1.6	161,123	1,368	6044	2.64	58.50	0.31	32.69
1989 LeSabre	3.8	263,032	1,591	6147	0.09	3.05	0.23	0.73
1989 Tercel	1.5	268,898	1,086	6393	0.88	0.92	3.84	2.30
1989 Corolla	1.6	356,246	1,175	6398	0.26	3.17	0.35	0.95
1990 Accord	2.2	198,000	1,395	5491	0.16	3.64	0.73	1.81
1995 Accord	2.2	184,790	1,477	5546	0.08	2.62	0.22	14.46
1990 Pulsar	1.6	131,274	1,258	5590	0.30	10.82	0.63	51.04
1990 Accord	2.0	421,414	1,428	5666	2.08	108.29	0.76	21.25
1990 Mustang	2.3	172,967	1,439	5759	0.23	2.58	0.42	1.06
1990 Maxima	2.0	299,096	1,584	6073	0.23	1.89	0.51	2.10
1990 Voyager	3.3	310,994	1,591	6092	0.50	5.60	2.08	2.25
1990 Corolla	1.6	254,463	1,255	6099	0.24	1.43	0.59	0.92
1990 Civic Hatbk	1.6	289,254	1,135	6101	0.37	1.85	0.51	0.12
1990 Topaz	2.3	217,612	1,341	6114	0.18	1.94	0.77	0.06
1990 Civic Hatbk	**1.6**	**23,231**	**1,140**	**6196**	**0.58**	**5.58**	**0.84**	**341.06**
1991 Corolla	1.6	283,843	1,192	5876	0.23	2.02	0.37	36.16
1991 Mazda 323	1.6	311,178	1,183	6025	0.28	1.37	1.31	3.97
1991 Protege	1.8	140,697	1,285	6048	0.24	2.75	0.80	3.32
1991 Accord	2.0	308,721	1,356	6070	0.32	4.80	0.82	3.87
1991 Civic Hatbk	**1.6**	**241,375**	**998**	**6149**	**11.49**	**23.07**	**0.80**	**350.98**
1986 Camry	2.0	216,661	1,270	6224	0.91	15.51	0.96	0.09
1991 Tempo	2.3	125,808	1,266	6400	0.14	2.10	0.73	0.38
1992 Corolla	1.6	161,840	1,191	5768	0.12	0.53	1.02	3.17
1992 Mercury	1.5	209,998	1,280	5776	0.28	1.52	0.68	2.40
1992 Taurus	3.0	168,886	1,509	5875	0.35	2.95	0.60	6.44
1992 Passat	2.0	292,965	1,508	5897	0.43	2.63	0.58	2.42
1992 Accord	2.0	280,085	1,458	6075	0.27	2.50	0.74	2.25
1992 Ranger	3.0	268,963	1,460	6112	5.29	10.46	0.69	5.86

Gasoline Vehicles (1995 and older) Table 9 cont.

Vehicle	Engine L	Odometer km	test weight kg	TestID	THC g/km	CO g/km	NOx g/km	PM mg/km
1992 Taurus	3.0	219,680	1,518	6121	0.30	2.76	0.56	0.23
1992 Corolla	1.6	235,069	1,192	6123	0.14	0.78	0.64	0.04
1992 Tercel	1.5	244,353	1,089	6125	3.81	6.71	0.93	13.97
1992 Tercel	1.5	244,384	1,191	6142	2.25	6.46	0.53	13.64
1992 Tercel	1.5	220,479	1,191	6161	0.72	2.29	0.62	11.10
1992 Cutlass	3.3	253,507	1,497	6172	17.09	26.54	1.71	2.50
1992 Cutlass	3.3	253,507	1,497	6185	16.75	28.97	1.75	2.68
1992 Suzuki Jimmy	1.6	84,614	1,123	6332	0.63	25.54	0.44	1.32
1993 Accord	2.2	198,000	1,407	5417	0.06	1.14	0.29	1.26
1993 Caravan	3.3	239,464	1,787	5581	3.54	18.76	1.81	0.00
1993 Mazda 626ES	2.4	196,624	1,470	5691	1.07	4.91	1.88	16.65
1993 Protege	1.8	224,441	1,239	5915	0.10	1.51	0.88	0.83
1993 Caravan	**3.3**	**191,704**	**1,509**	**6085**	**0.51**	**4.07**	**0.71**	**136.60**
1993 Tempo	2.3	168,637	1,306	6212	2.31	6.79	0.82	5.01
1993 Altima	2.4	233,759	1,461	6386	4.64	66.67	0.43	0.04
1993 Caravan	3.3	262,817	1,795	6391	0.30	2.47	0.58	0.31
1994 Camry	2.0	134,922	1,615	5758	0.06	0.11	0.62	0.07
1994 Ford Escort	2.0	182,901	1,212	5931	0.86	5.83	0.71	98.31
1994 Buick Regal	3.0	184,595	1,687	6023	6.67	163.03	0.08	69.29
1994 Cavalier	2.2	204,512	1,257	6087	0.51	5.91	0.54	1.68
1994 F-150	5.4	302,169	1,914	6138	0.76	2.87	0.72	23.47
1994 Astrovan	4.3	314,191	1,817	6158	0.32	2.27	1.06	1.22
1994 Caravan	3.3	205,742	1,669	6170	0.89	7.45	0.58	3.72
1994 Intrepid	2.4	147,149	1,633	6220	0.43	5.37	0.84	0.57
1994 Caravan	3.3	333,105	1,669	6382	0.23	1.39	1.16	1.26
1995 Integra	1.6	175,180	1,289	5686	0.32	4.38	0.58	1.04
1995 Tercel	1.5	260,261	1,109	5692	0.65	6.58	0.37	58.84
1995 Civic	1.6	202,660	1,131	5905	0.23	2.99	0.56	0.18
1995 Cavalier	2.2	331,000	1,325	5908	1.27	15.04	2.24	1.23
1995 Taurus	3.0	194,053	1,599	6062	0.17	1.20	0.61	8.17
1995 Accord	2.0	295,541	1,462	6064	0.07	2.05	0.21	1.09
1995 Lumina	3.1	273,935	1,651	6194	0.17	3.10	0.36	0.21
1995 Maxima	2.0	189,965	1,642	6210	0.12	1.11	0.39	0.50

Gasoline Vehicles (1996 and newer) Table 10

Vehicle	Engine L	Odometer km	test weight kg	TestID	THC g/km	CO g/km	NOx g/km	PM mg/km
1996 Mazda 626LX	2.5	121,682	1,382	5566	0.10	2.04	0.45	0.64
1996 Silverado	6.6	316,036	2,599	5736	1.28	15.02	3.40	0.96
1997 Geo	1.3	253,705	1,013	5538	0.12	3.22	0.82	1.40
1997 Camry	2.2	173,660	1,529	5542	0.10	2.00	0.16	0.23
1997 Yukon	5.7	203,325	2,582	5682	1.14	14.85	1.68	1.69
1997 Cabrio	2.5	131,710	1,480	5894	0.32	2.69	0.70	0.58
1998 Civic	1.6	101,990	1,214	5516	0.08	5.79	0.20	0.50
1998 Civic	1.6	110,375	1,214	5518	0.04	4.65	0.08	0.42
1998 F150	4.2	266,950	3,056	5536	0.16	10.64	0.51	11.50
1998 Pathfinder	3.3	227,763	1,977	5564	0.10	2.73	0.90	1.63
1998 Civic	1.6	144,434	1,190	6054	0.02	1.96	0.02	0.40
1999 Acura	1.6	133,911	1,343	5428	0.04	7.18	0.07	1.67
1999 323i	2.5	212,335	1,529	5540	0.01	0.64	0.03	0.36
1999 Acura 1.6EL	1.6	167,763	1,343	5584	0.03	4.44	0.06	0.37
2000 Acura	1.6	78,025	1,247	5420	0.05	5.41	0.22	1.84
2001 Ford E350	5.4	126,229	2,861	5694	4.66	209.21	0.08	0.04
2001 Accord	1.8	133,273	1,556	5920	0.19	2.33	0.25	0.53
2002 Venture	3.4	265,000	1,884	5533	0.03	0.83	0.35	0.12
2002 Tracer	2.0	151,971	1,553	5588	0.04	0.60	0.08	0.78
2003 Corolla	1.8	96,816	1,290	5473	0.01	0.00	0.15	0.37
2003 Pathfinder	3.5	91,985	1,989	5514	0.02	1.89	0.31	0.00
2003 Pathfinder	3.3	78,612	1,989	6036	0.02	1.23	0.16	0.04
2003 Civic	1.6	102,103	1,312	6159	0.03	0.25	0.15	0.24
2004 Sunfire	2.2	56,866	1,311	5582	0.10	0.46	0.05	0.36
2004 Mazda PU	3.0	113,305	2,541	5923	0.10	9.35	0.11	1.74
2004 Sentra	1.8	17,442	1,346	6034	0.04	1.73	0.00	0.35
2004 Freestar	4.2	63,155	2,263	6037	0.02	0.33	0.00	1.86
2005 Matrix	1.8	125,673	1,411	5498	0.01	0.06	0.02	0.07
2005 Caravan	3.3	36,509	1,919	5531	0.02	0.32	0.01	0.00
2005 Tucson	2.0	91,065	1,630	6035	0.01	0.22	0.00	0.03
2006 Yaris	1.5	1	1,235	5422	0.10	0.69	0.15	0.45
2006 Civic	1.8	35,495	1,313	5524	0.00	0.16	0.00	0.55
2006 Civic	1.8	51,376	1,411	5594	0.01	0.25	0.00	0.16
2006 Civic	1.8	68,008	1,396	5667	0.09	0.76	0.06	0.55
2006 Ford E350	6.0	225,276	3,665	5818	0.00	0.00	0.00	0.34

Gasoline Vehicles (1996 and newer) Table 10 cont

Vehicle	Engine L	Odometer km	test weight kg	TestID	THC g/km	CO g/km	NOx g/km	PM mg/km
2007 Ranger	3.0	23,012	1,922	5434	0.01	0.11	0.00	0.20
2007 Mazda 3	2.0	22,586	1,377	5476	0.04	0.73	0.01	0.03
2007 Mazda 3	2.0	52,479	1,466	5932	0.07	0.66	0.02	0.00
2008 Yaris	1.5	40,868	1,225	5726	0.03	0.03	0.00	0.50
2006 Sierra	6.0	79,616	3,375	5752	0.10	0.33	0.59	0.16
2009 Corolla	1.8	5,223	1,402	5431	0.01	0.05	0.00	0.05
2009 Acura	2.4	17,027	1,684	5526	0.02	0.24	0.00	0.94
2009 Tucson	2.0	4,152	1,630	5544	0.01	0.10	0.05	0.22
2009 F-150	5.4	16,857	2,833	5797	0.44	0.00	6.35	0.43
2009 Tucson	2.0	10,218	1,630	6046	0.02	0.07	0.00	6.90
2010 F-150	5.4	25	2,833	5775	0.02	1.04	0.00	0.17
2010 Accent	1.2	12,367	1,202	6216	0.00	0.17	0.00	0.02