



**PUBLISHED PROJECT REPORT PPR216**

**AN INNOVATIVE DYNAMOMETER: FREE RUNNING ROLLERS TO PROVIDE A POTENTIAL CHEAP REPRESENTATIVE ROADSIDE EMISSION PROCEDURE**

Version: 6

**by S Latham**

**Client: Transport Research Foundation (TRF)**

Copyright Transport Research Laboratory, 2007

This report has been produced by TRL Limited, under/as part of a Contract placed by the Transport Research Foundation. Any views expressed are not necessarily those of the Transport Research Foundation.

Published Project Reports are written primarily for the Customer rather than for a general audience and are published with the Customer's approval.

<b>Approvals</b>	
<b>Project Manager</b>	<b>S Latham</b>
<b>Quality Reviewed</b>	<b>C Baughan</b>

TRL is committed to optimising energy efficiency, reducing waste and promoting recycling and re-use. In support of these environmental goals, this report has been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.

# CONTENTS

<b>Executive Summary</b>	<b>i</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 Objectives</b>	<b>2</b>
<b>3 Methodology</b>	<b>3</b>
3.1 Equipment and vehicles used	3
3.2 Experimental Procedure	7
3.2.1 Background	7
3.2.2 Preliminary investigations:	7
3.2.3 Experimental procedure:	8
3.2.4 Brake temperature measurement procedure	12
3.2.5 Engine operating conditions represented in the experiments	13
<b>4 Results</b>	<b>15</b>
4.1 Volkswagen Passat	15
4.1.1 Volkswagen Passat CO emissions	16
4.1.2 Volkswagen Passat HC emissions	18
4.1.3 Volkswagen Passat NO emissions	20
4.1.4 Volkswagen Passat lambda	22
4.2 Analysis of emissions petrol Ford Mondeo	25
4.2.1 Petrol Ford Mondeo CO emissions	25
4.2.2 Petrol Ford Mondeo HC emissions	27
4.2.3 Petrol Ford Mondeo NO Emissions	29
4.2.4 Petrol Ford Mondeo Lambda	31
4.2.5 Petrol Ford Mondeo Analysis of Load v Speed	33
4.3 Diesel Mondeo Emissions	35
<b>5 Discussion:</b>	<b>36</b>
5.1 Ability to operate the roller system and obtain measurements under loaded conditions	36
5.2 Repeatability of emission measurements	36
5.3 Interpretation of the data from the OBD/CANBUS	38
5.4 ABS system	39
5.5 Brake Temperatures	39
5.6 Extending range of measurements to include NOx and particulate	40
5.7 Concluding Comments	40
5.8 Returning the vehicle to the road	40
<b>6 Conclusions and recommendations:</b>	<b>41</b>
<b>7 Acknowledgements</b>	<b>43</b>
<b>8 References</b>	<b>44</b>

<b>Appendix A.</b>	<b>Vehicle Specifications</b>	<b>46</b>
A.1	Specifications Ford Mondeo Diesel	46
A.2	Specifications Ford Mondeo Petrol	46
A.3	Specifications Volkswagen Passat	46
<b>Appendix B.</b>	<b>Pyrometer specification</b>	<b>47</b>
<b>Appendix C.</b>	<b>Experimental data</b>	<b>48</b>
C.1	Experimental Results Passat	48
C.2	Experimental Results Petrol Mondeo	50
<b>Appendix D.</b>	<b>Summary Statistics</b>	<b>55</b>
D.1	CO analysis Passat	55
D.2	HC analysis Passat	55
D.3	NO Analysis Passat	56
D.4	CO & HC Analysis Mondeo:	56
D.5	NO Analysis Petrol Mondeo	56
<b>Appendix E.</b>	<b>Meteorological Data</b>	<b>58</b>
<b>Appendix F.</b>	<b>Temperature of brake discs</b>	<b>59</b>
<b>Appendix G.</b>	<b>Run order and laboratory notebook data</b>	<b>61</b>
<b>Appendix H.</b>	<b>PROTOTYPE IN-SERVICE EQUIPMENT</b>	<b>70</b>
H.1	SEMTECH QCM/MPS	70
H.2	Portable Emissions Measurement Systems (PEMS)	71

## Executive Summary

This project was to research the development of a new type of dynamometer for measuring exhaust emissions from light duty vehicles which is relatively easy and cheap but can represent conditions typical of real driving situations. The performance of a prototype system was investigated by using it with two petrol and one Diesel car. The system uses free running chassis rollers and the vehicle brakes to apply speed and load to the engine whilst emission concentrations are measured using a basic garage specification gas analyser. Combining this data with information obtained via the engine on board diagnostic (OBD) system in principle allows mass emissions to be calculated under any engine condition.

It was possible to subject all 3 car engines to a range of loads and speeds which would be commonly used on the road, although measurement runs using the highest engine speeds were not attempted. Emissions of Carbon Monoxide (CO), Hydrocarbons (HC) and Nitric Oxide (NO) were measured which allowed the engine emissions to be characterised in relation to engine speed and load.

Measurements of CO and HC emissions from the petrol cars were not very repeatable, but the system may be sufficient to identify excessive CO and HC emissions caused by gross malfunctions such as lambda sensor or catalyst failure. It is thought that the poor repeatability of CO and HC emissions may be due to variations in the catalyst temperature and fuel air ratio during the measurement run.

NO emissions on one of the petrol cars were far more repeatable than CO and HC, and were closely related to load and throttle position at most fixed engine speeds. However, NO emissions on the other petrol car which was used as the first experimental vehicle were far less repeatable. Some of this variation may be attributed to inexperience of driving the car on the rollers at this stage, although this vehicle had a turbocharged engine which is untypical of most petrol cars used on the road, and this could be an additional contributing factor to the variability.

It was not possible to obtain statistically meaningful emission measurements from the Diesel car due to these being so low they were near to the limits of resolution and repeatability of the analytical equipment. However, the same procedure was performed on the Diesel car as on the two petrol cars.

Further work would be needed to clarify how the repeatability of results from the new system compares with that of standard dynamometer procedures, and of the present in-service test on a wide range of vehicles. However, rather than using a large representative sample of vehicles for such research, vehicle faults could be purposely induced on a limited number of vehicles to produce the wide range of conditions and emissions which can be experienced on the road. The future work could also be extended to the measurement of other emissions such as particulate.

It appears that vehicle ABS and related systems have to be disengaged before performing roller or chassis dynamometer investigations. Failure to do so could limit the maximum vehicle engine speed and create subsequent problems for re-engaging the ABS system, although this latter point still requires clarification. The need to temporarily disengage the ABS system may have safety implications for a roadside test, but this would be less of a problem if the new system was used as part of the annual MOT, since the equipment, time and expertise to reactivate the system would be more likely to be available.

## 1 Introduction

It is widely accepted that current roadside emission tests (which is the same as the MOT or in-service emission test) are inadequate since the emissions measured during these procedures correlate poorly with emissions measured in type approval tests. This is because in the roadside and MOT tests the vehicles are tested under conditions not representative of those encountered during normal driving operations. It is therefore possible that some vehicles which pass the roadside test would fail the type approval test and possibly some vehicles may fail the roadside test that would pass the type approval test. Therefore, it would be beneficial to provide an improved in service test which can adequately and fairly assess exhaust emissions from motor vehicles and which is relatively quick and cheap.

Spark ignition (SI) and Diesel engines undergo different roadside/MOT emission test procedures. SI engines are tested at idle or fast idle speeds without any external load (Council of European Communities 1992), under this condition the flow of exhaust through the catalyst is minimal and the sensors are not tested throughout the range of operation. At the opposite extreme, diesels are tested at full load by accelerating the engine at full throttle against its own inertia in the 'Free Acceleration test' (Council of European Communities 1992). Both of these tests miss the more representative mid-load conditions encountered during normal driving. This is a serious problem for measuring Oxides of Nitrogen (NO<sub>x</sub>) since significant amounts of this emission are only produced at medium to high load engine conditions; for this reason NO<sub>x</sub> or NO (cheap analysers can only measure NO) are not measured during European MOT/in- service tests.

There have been numerous attempts to address this problem without having to resort to an expensive chassis dynamometer to absorb the load from the engine. One method is the "lug down" test which requires placing a vehicle on cheap *unloaded* rollers, applying full throttle to drive the road wheels to a reasonable operating speed in gear and applying the vehicle brake to apply load to the engine (Montgomerie G. 1979). This procedure was designed for diesel HGVs which have relatively powerful brakes, but it suffered from being a full load rather than partly loaded test. Although lighter loads could be applied, the actual load was not measured. Moreover, applying the vehicle's weight to the rolling wheels also had a tendency to cause tyre damage due to the forces and speeds involved, so the test was probably unsuited to roadside tests from fully laden trucks.

The possibility of applying the lug down principle to passenger cars may have been overlooked because of these issues. However, the type approval procedure for cars is a relatively light-loaded test, especially the portion which is attributed to urban driving. Therefore to be representative of this lightly loaded condition, the brakes in a lug down test need only resist a fraction of engine load and be applied for short periods until the emissions stabilise so they can be measured.

All cars can absorb more power in the brakes than they can generate through the engine (based on known acceleration/deceleration rates). Therefore despite the braking force being applied to only two wheels at one time during a 'lug down' test, the load/power absorbing capability of car brakes should enable them to withstand a sufficient period of braking without overheating. However, it is possible that the brakes may have to be cooled by a fan when the vehicle is tested statically.

The fundamental disadvantage of the conventional lug down test and similar part-load tests is that they provide no information on engine load. However, since the advent of the European on-board diagnostic standard (EOBD) for SI engines (Council of European Communities (2000b) engine load can be inferred from the vehicle's engine management computer (Electronic Control Unit or ECU). In effect, the vehicle itself could provide both the brake, and the measurement of torque applied by the brake. This means that the remainder of the dynamometer would consist simply of two pairs of free-running rollers, making it cheap to build and maintain, and reasonably portable. Such a device will, potentially permit part load emissions annual testing to be conducted at the roadside or as part of the MOT test.

In an improved roadside or MOT test the vehicle would be placed on the rollers and driven so that the engine speed is typical of that used during a type approval test (the most appropriate gear will be chosen for operational stability and minimum tyre wear). The brake would then be gradually depressed along with the accelerator until an engine speed and load typical of the type approved test was reached. Once these parameters had stabilised the emissions would be measured. This process would probably have to be repeated several times to obtain a stable estimate of emission levels. If several combinations of load and speed could be covered it would be possible to replicate more closely the measurements used in the type approval test.

A loaded test has the potential for more representative measurement of all emissions in-service, but particularly NO<sub>x</sub> which is not measured at present. The conclusion from a recent EPA report is that NO<sub>x</sub> emissions can be reduced by appropriate repair and maintenance. Other sources (Norris J 2002) suggest that the reduction catalyst (the one which reduces NO<sub>x</sub>) may be more susceptible to deterioration than the oxidising one. This type of problem could not be sensed by on board diagnostic systems.

It might be thought that on-board emissions sensors will soon render in-service testing redundant. However:

- Reliable NO<sub>x</sub> sensors have yet to be proven for in-use purposes.
- An in-service procedure will provide the possibility of using sensors for measuring particulate mass and NO<sub>2</sub> (rather than NO<sub>x</sub>), the two emissions of greatest concern; these are unlikely to be used as on-board sensors for cars in the near future.
- On-board sensors will themselves need checking in service, and the new emissions test proposed here could provide a means of doing this.

On the basis of these arguments the TRF granted funding for a project investigating the feasibility of using free running rollers for examining cars equipped with EOBD for emissions, with the objective of developing a simple, cheap procedure that is more representative than the present MOT/roadside test being used in the UK.

## 2 Objectives

This report describes the progress during year 1 of a potential 2 year project investigating a new type of dynamometer to measure emissions from light duty vehicles. The dynamometer involves driving vehicles on unloaded rollers whilst the vehicle brake is applied. This load is applied to the engine whilst emissions are measured, thereby simulating conditions more typical of normal driving than current roadside or MOT test procedures.

The basic objectives of this 1<sup>st</sup> stage of the project could therefore be described as:

- Determine if vehicle emissions can be measured under controlled conditions by using free running rollers, the vehicle brake to simulate load, the output from the engine management system to infer the load level, and a basic 5 gas MOT emission analyser to measure CO, HC and NO emissions.
- Determine if these emissions can be measured under a range of engine conditions which would cover those normally used during type approval or in-use operation.
- Determine the repeatability of the emission measurements under these conditions.

### 3 Methodology

#### 3.1 Equipment and vehicles used

TRL possess unloaded rollers which are installed near the junction of the central area and small loop of the TRL track system, these are shown in figures 1 and 2 along with the first vehicle used for this purpose, a Volkswagen Passat.

The rollers were originally designed for calibrating heavy goods vehicle (HGV) tachographs but have been used for HGV lug down procedures in previous TRL research (this type of test is briefly described in the introduction). The equipment consists of 2 sets of ramps and heavy duty rollers on which vehicles can be mounted. The rollers are operated in a similar fashion to a standard chassis dynamometer except no external load can be applied to the rollers (they can be locked when the car is driven on and off the rollers to prevent them spinning). After inspection, it was concluded that these rollers were suitable and safe for the requirements of this project. Two large cooling fans were purchased to cool each of the driving wheels and brake assemblies which also provided some airflow across the engine; these can also be seen in the photographs.



**Figure 1: Roller assembly and cooling fan**



**Figure 2: Frontal image of Passat car mounted on the rollers**

Three Euro 3<sup>1</sup> cars were used in this research, 2 were petrol fuelled, and the other one was diesel fuelled. The full specification of these vehicles are provided in Appendix A. The diesel vehicle was selected so that the feasibility of determining loaded NO<sub>x</sub> emissions from diesel cars could be examined. Although current diesel standards do not require an estimate of engine load output until 2008, in practice the means to do so is available on some vehicles including the one used in this study.

The cars were instrumented with TRL owned on-board analytical and measuring equipment which consisted of.

- **An Emissions analyser:** This was a 5-gas emissions analyser from Crypton that runs on 12 volts DC power supply (Batmanuk undated). It is a portable version of the type of analyser used in the MOT test which measures CO, CO<sub>2</sub>, HC, NO emission concentrations & lambda (the fuel air ratio). The precision for CO is in the region of 0.01% (this instrument is shown in figure 3)
- **An on Board Diagnostic (OBD) interface:** this connects the Engine OBD port on the vehicle located below the vehicle's steering wheel to a laptop computer which allows the continuous logging of vehicle speed, engine speed and relative airflow which can be translated to relative power or load. The laptop displaying the output from the Engine OBD is shown in figure 4.

---

<sup>1</sup> An abbreviation for 98/69/EC Euro 3. The EU directive specifying the type approval standards applicable to new cars from the year 2000)



**Figure 3: Crypton 5-gas emissions analyser**



**Figure 4: Laptop and OBD output**



**Figure 5 Contact thermocouple (touching on right side of disc, see upper middle area of figure)**

Two laptop PCs were used to log the data – one for the emissions analyser and one for the OBD data. The emissions data was logged continuously to a separate PC in term of emission concentrations. To obtain mass emissions from the petrol vehicles, data was obtained from the vehicle's engine management system using a 2 way interaction between the PC and the OBD system. This enabled engine speed, throttle position and an estimate of engine load based on the mass air to be continuously measured and logged. Mass emissions were then calculated from the gas concentrations and airflow rate<sup>2</sup>. On the Diesel vehicle the data acquisition process was slightly different in that the data was obtained directly from the Controller Area Network Bus Interface (CANBUS), and fuel injection rate per stroke is available as a proxy for load. The emissions analyser was subject to a routine service and calibration carried out by an approved Crypton technician within 3 months of the procedures.

A K type thermocouple was fitted to the inside of the left passenger side brake disc on each car (see figure 5). The thermocouple tip was positioned so it brushed against the inside of the brake disc as it rotated so the temperature could be constantly monitored using an attached digital display in the car facing the driver. This method had been used for other TRL work so it was already installed on the Passat car prior to this project. Since this thermocouple design could generate heat and potentially indicate a false temperature reading, a non-contact temperature sensor (a laser based pyrometer) was also used. To enable the laser to be reflected off the brake disc so a temperature reading could be taken, the wheel trim was removed. This method allowed intermittent measurement of the temperature of the brake disc at the end of each measurement run when the vehicle driving wheels were stationary.

<sup>2</sup> All mass emissions in this report are calculated and presented without any theoretical adjustments in HC and NOx concentrations to allow for differences in the analytical response of type approval (chemiluminescent and flame ionisation detector) and non standard equipment (infra red). It is proposed that further dynamometer investigations are performed, in which the cars emissions are monitored using standard type approval equipment and the Crypton equipment simultaneously and adjustment factors are then generated based on this information. This will avoid the use of numerous and potentially confusing conversion factors.

## 3.2 Experimental Procedure

### 3.2.1 Background

The nearest precedent to this new type of dynamometer under investigation was the heavy vehicle lug down procedure which was considered for use with heavy goods vehicles several decades ago, and is briefly described in the introduction. This was a simple full load procedure during a gradual deceleration which enabled diesel engine smoke to be measured throughout the engine speed operating range *at maximum load*. A further adaptation of this procedure had been devised and briefly used by the author, involving partial loads with the roller equipment for heavy vehicles described in the previous section (Latham 1995). Here, a fixed engine speed was maintained at a fixed part throttle setting until stabilised emissions had been measured. The brake is then released allowing the engine, transmission, driving wheels and rollers to accelerate. For a fixed gear, the rate of acceleration is proportional to the engine load above that required to maintain a constant speed, and can be calculated using the inertia of the rotating components and gearing between the various inertial elements. However, the use of OBD 2 systems on cars conforming to EURO 3 standards and beyond allows the *indirect* calculation of the % maximum vehicle load. This is the procedure used for *characterising* engine load for the procedures described in this report.

Ideally, an in-service procedure should conform as closely as possible to the type approval test (assuming the type approved test is itself representative of on-road driving). The type approval test for light duty vehicles consists of a variable speed test on a dynamometer using the new European driving cycle (Council of European Communities 1997). This requires constantly varying engine speeds and loads which cannot be simulated with the more basic roller equipment. However, one of the type approval ESC tests for heavy duty diesel engines (Council of the European Communities 2000) uses a series of constant engine speeds and loads which covers the engine operating range whilst emissions are measured. Subsequent weighting factors are applied to the emissions measured at each of these points so the normal on-road operation of the engine is properly represented. These weighted figures are then summated to obtain the overall emission for the engine which is compared with the legislated limit values to assess whether the engine has passed. Although the weightings for SI engined cars would be different to that of Diesel engined heavy vehicles, this type of procedure could be used on the roller equipment with more suitable weightings for the vehicle being determined at a later stage.

### 3.2.2 Preliminary investigations:

The method of controlling the speed and load of an engine by using light duty vehicle brakes had never been attempted before. As a consequence, the procedure evolved as data was obtained and the investigators gained experience.

Initial operation on the rollers involved some basic unloaded runs (without use of the brakes) to examine the correct operation of the exhaust analysis equipment, ensure the vehicle tyres did not get substantially warm whilst rolling, ensure the stability of the vehicle on the rollers, and to check that suitable engine speeds could be obtained without undue vibration or other unexpected problems. It was quickly realised that the car's inbuilt ABS/traction control system substantially limited the engine speed. TRL personnel had never previously encountered this problem, possibly because the use of ABS was not widespread at the time similar research was last performed at TRL (during the 1980s and early 90s).

Enquiries were made to investigate if this problem could be circumvented. It was found the ABS/traction control of this vehicle could be disengaged by removing the brake lights from the

vehicle. This allowed the vehicle driving wheels and engine to attain the higher speeds required for the proposed research. Subsequent vehicles used for the experiment described in this report had their ABS systems disengaged directly by removing a fuse which powers the ABS unit. This could be easily reactivated by replacing the fuse.<sup>3</sup> However, any interruption in supply generates a fault code which is temporarily logged in the OBD management computer. These codes can be accessed soon after the interruption has occurred (see discussion).

### 3.2.3 *Experimental procedure:*

**Track trials:** The vehicles were subjected to brake trials on the long straight of the TRL test track to examine the brake disc temperatures which are reached, this acted as a guide for acceptable temperatures during the roller measurements. These track trials were performed by accelerating the car from a fixed starting point until 70mph was reached; then rapidly braking to a standstill. The temperature of the brakes were then recorded using the inbuilt thermocouple on the inside of the brake disc, and a non contact pyrometer at three points on the outside of the disc; see appendix 2 for the specification of the pyrometer. The cars were then driven back to the starting point and the run repeated.

**Roller investigations:** The roller procedure was designed around the basic concepts used in the ECE 49 and ESC heavy duty diesel engine procedures. These are performed by measuring emissions over a number of fixed engine speed and load points so the result can be subsequently weighted to reflect the use of the engine on the road.

The cars were started from cold and the gas analytical equipment was turned on. This places the analyser through a warm up sequence and calibration check. The cars were driven to the roller installation during which period the car engine water temperature reached a normal operating level. The cars were stopped with the engines left idling whilst the covers protecting the rollers were removed; a 240v electrical generator was started and connected to two cooling fans. The roller system was then braked and the cars driven onto the roller assembly so the front wheels fitted squarely between the 2<sup>nd</sup> and 3<sup>rd</sup> pair of rollers (see figure 1). The roller brake was released and the car hand brake was applied so the cars front wheels could be rotated whilst the car was stationary. Once mounted upon the rollers, the cars were initially driven at an engine speed of 1500 rpm in the highest gear for 5 minutes; this would have applied a low but still significant load imposed by tyre rolling friction on the rollers. This interval was treated as a preconditioning phase, so that the exhaust catalyst should have reached a design light off temperature, prior to the experimental runs.

After the conditioning phase, the measurements were made over a set of experimental conditions. These consisted of subjecting the engine to a particular engine speed and throttle position for a long enough period so the exhaust emissions had approximately stabilised. This was to prove a difficult task due to the transient nature of emissions and difficulty in controlling the engine brake and accelerator.

For the Passat car, a fixed throttle position was achieved by using an accelerator stop. Although this arrangement is probably an impractical proposition for routine testing purposes, it allowed familiarisation of the procedures and mapping of the engine for this vehicle. For the runs on the Mondeo cars a different method was used without using an accelerator pedal stop. In this case the accelerator was depressed until the required throttle setting was indicated on the laptop display (obtained via the OBD system). It was attempted to hold the throttle in a fixed position for the remaining part of the procedure, whilst the brake was varied to meet the required engine speed. This

---

<sup>3</sup> As a precaution these vehicles had their brake components replaced and a Ford ABS system check before being returned to the road. The Passat car was subsequently scrapped as a result of work unrelated to this investigation.

method allowed steady control of load, although the engine speed was more difficult to maintain, but no more so than when using a fixed accelerator stop.

In more detail, to achieve a given throttle position and engine speed for each experimental point, the following procedure was adopted:

1. The car was accelerated through the gears until the desired engine speed was reached in the highest possible gear which would not exceed 120 kph roller speed. For most engine speeds this was 5<sup>th</sup> gear, but 4th or 3rd gear was used for some of the highest engine speeds.
2. The brake and accelerator were simultaneously depressed until a predetermined fixed accelerator position was obtained; different methods of achieving this throttle position were tried for the different cars. This allowed the approximate engine speed to be achieved (to within +/-1000rpm).
3. With the throttle fixed, finer tuning of the engine speed was achieved by moving the brake pedal (to within a tolerance of about +/- 200rpm). The inbuilt car engine speedometer on the driver's display proved more suitable for this than the digital output from the laptop.
4. The accelerator and brake pedals were held in position for approximately 10-15 seconds. In practice shorter periods were used at higher loads than lower loads due to the need to minimise brake temperatures.
5. A glance at the readings from the gas analyser were occasionally made to obtain an estimate of the length of time required to obtain more stabilised emission concentration readings. However, in practice most attention was focussed on the engine speed. Some attention was also given to the temperature display attached to the contact thermocouple during the early high loaded runs.
6. When sufficient time had elapsed, both the accelerator and brake were rapidly released and the engine taken out of gear and the car wheels and rollers were allowed to come to rest. The temperature of the brakes were recorded using the inbuilt thermocouple on the inside of the brake disc, and the pyrometer described earlier at three points on the outside of the disc.
7. The run was repeated once the temperature recorded by the non contact thermometer was below 200 C, if the temperature was already below this level the next run commenced immediately.
8. Initially up to 10 repeats of each condition were attempted, although this was later reduced to 3, in practice the number of repeats was highly variable.

Emissions of CO, HC, NO, CO<sub>2</sub> and Oxygen (O<sub>2</sub>) and several engine parameters including engine load, speed and vehicle speed were logged continuously, during and between the individual runs, which covered a total of 3-4 hours per session. Throttle position was displayed on the laptop for the Petrol Mondeo but not for the Passat. Unfortunately subsequent analysis of the data shows that throttle position was not logged due to the accidental omission of this variable during the setting up procedure, however accelerator bolt protrusions for the Passat and target % throttle positions as indicated by the OBD for the petrol Mondeo were noted in a log book. Time phase differences between the channels were also corrected and the periods corresponding to the more stabilised portion of the run immediately prior to releasing the brake were identified during subsequent analysis.

A better understanding of this process can be obtained by observing 2 examples of the engine and emissions output during runs for the petrol Mondeo. This is shown in figures 6 to 9. The first example (figure 6) is at an engine speed of 3000 rpm and 50% throttle position. This produces closed

loop conditions, that is when the fuel air ratio is being automatically controlled to stoichiometric by the inbuilt engine management and sensor technology. This is indicated by lambda being equal to 1 in figure 7, and consequently very low emissions of CO and HC are produced from the exhaust. The second example (see figure 8) is at an engine speed of 4000 rpm and a throttle position of 60%, where the CO and HC emission are substantially greater and lambda decreases to less than 1 (see figure 9) indicating a rich fuel air mixture. Emissions were measured in each run by averaging the readings taken during the 5 seconds prior to the release of the brake and accelerator. These are the readings used in the tower-plot emission maps starting with figure 10.

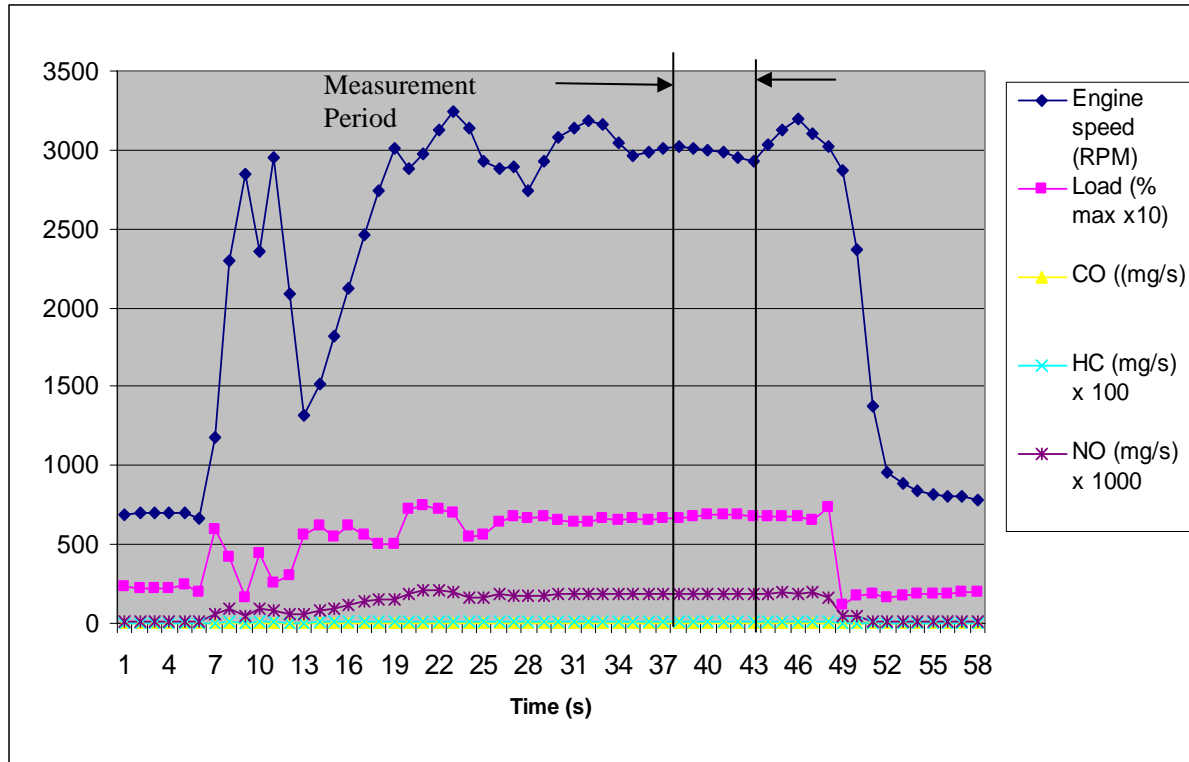


Figure 6 Emissions, medium load, medium speed (closed loop conditions)

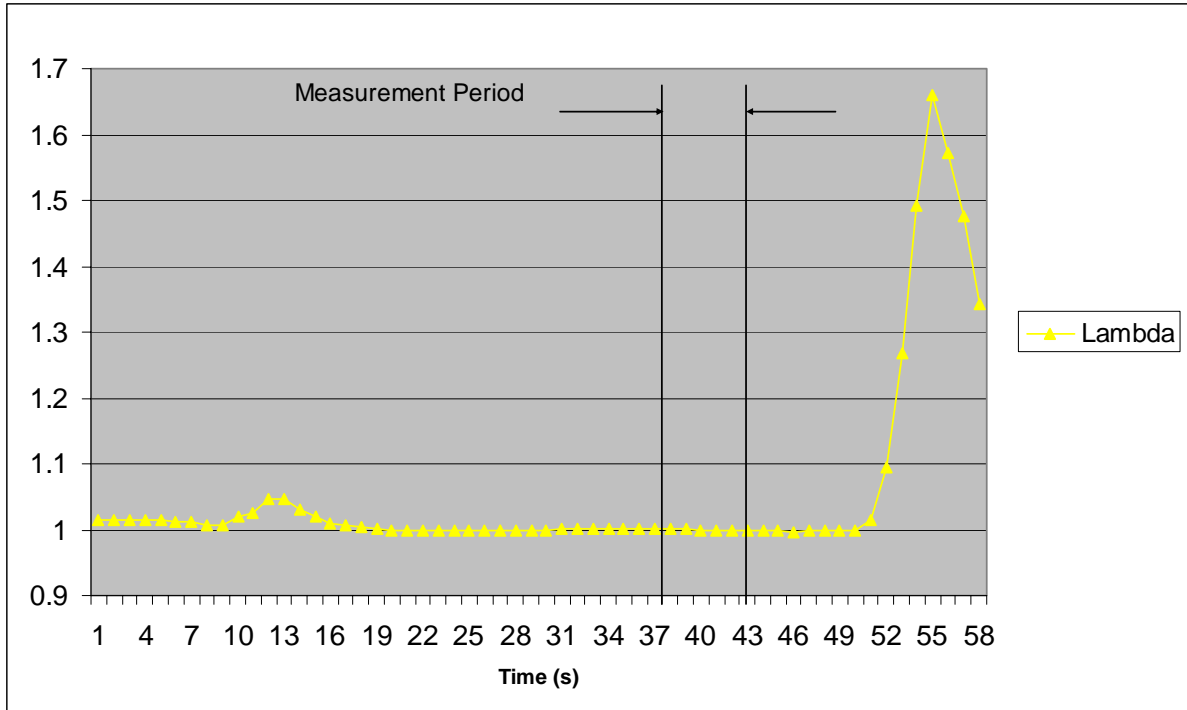


Figure 7 Lambda, medium load, medium speed (closed loop conditions)

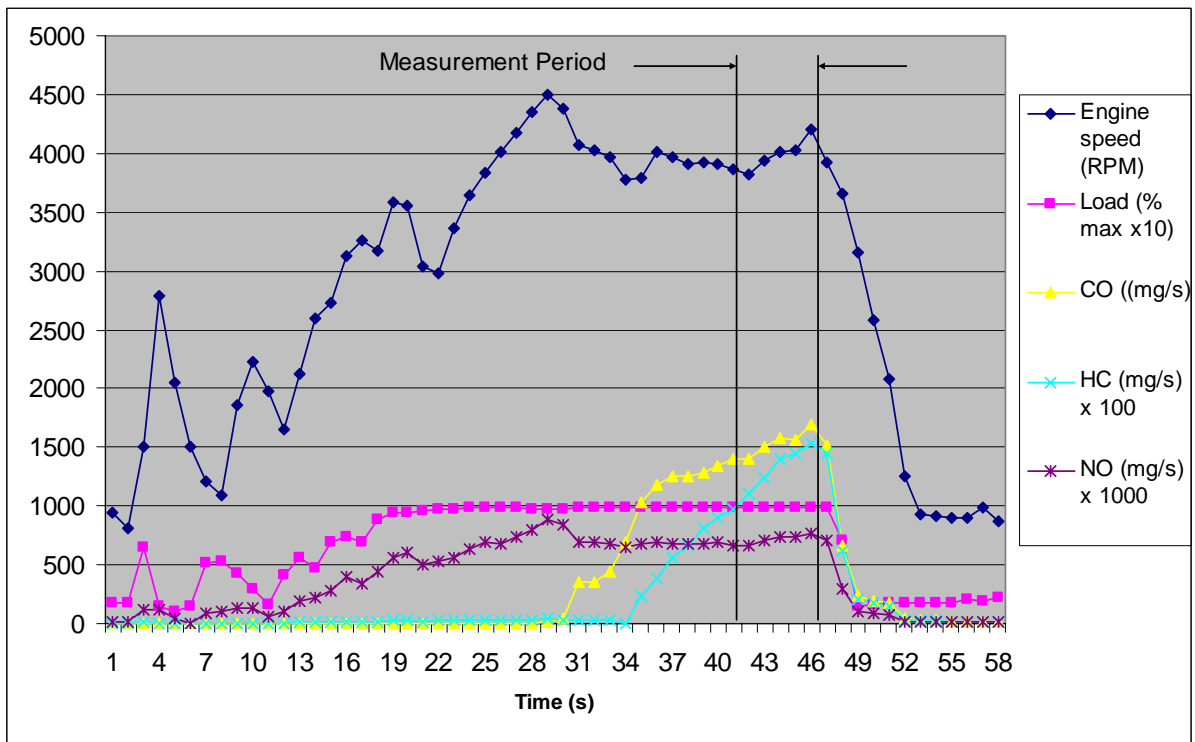
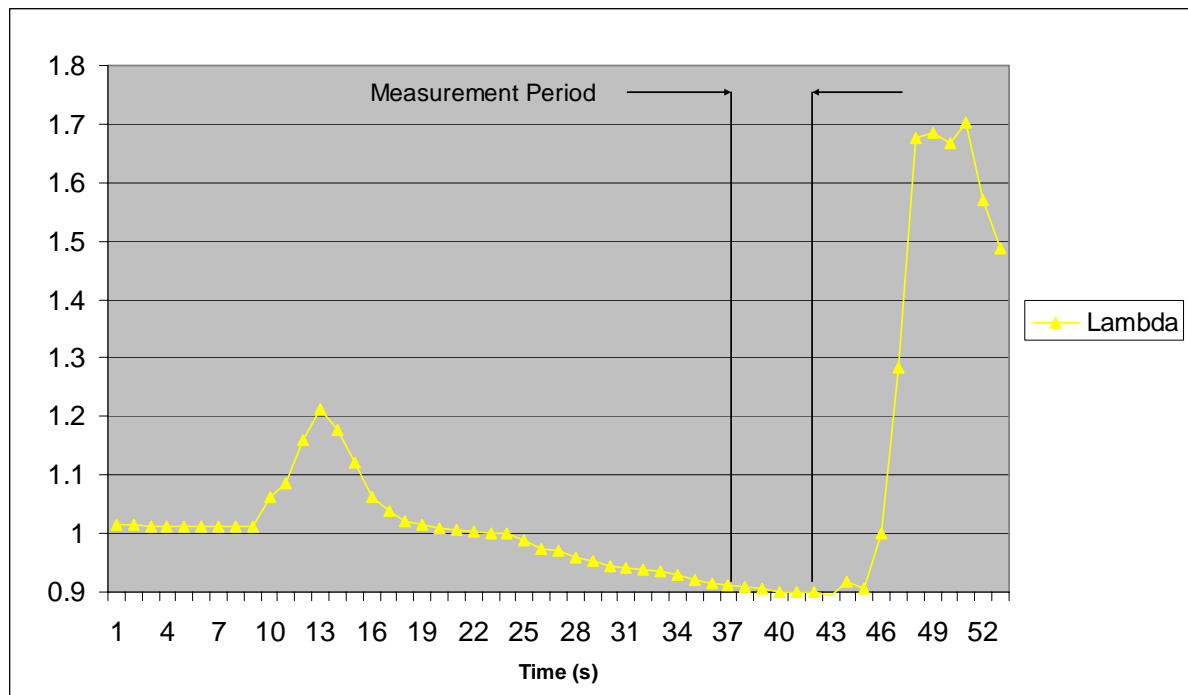


Figure 8 Emissions, high load, high speed (open loop conditions)



**Figure 9 Lambda high load, high speed (open loop conditions)**

The most important observations from these experiments are:

1. the short measurement period to minimise brake temperatures (defined here as the time during which the emission and engine data is used for characterising the engine operating condition)
2. the relatively stable application of load during the measurement period
3. the varied engine speed during the measurement period (since this varied as the accelerator was moved for a fixed brake position).
4. the increase in CO and HC emissions as the exhaust atmosphere engine catalyst cannot provide sufficient oxygen for combustion at high loads in open loop conditions.
5. relatively stable NO<sub>x</sub> levels during most of the loaded condition including the measurement period
6. the far higher CO and HC levels at high loads during the second run caused by open loop conditions.

### 3.2.4 Brake temperature measurement procedure

Between each measurement run on the rollers, the vehicle driving wheel speed was reduced to zero whilst the engine was left idling. During this time, the front, passenger-side brake disc temperature was measured using a non-contact pyrometer (see appendix B for the specification) on three locations on the brake disc and a mean taken. In all cases the instrumented brake disc was allowed to drop to below 200 °C before commencing the next run. The duration was limited so the brake rarely exceeded 300 °C. On the more lightly loaded roller runs the brake disc never reached the *starting* temperature limit of 200 °C, so the next run could be commenced more quickly. At least 30 seconds of engine idling was used between the runs which served as a conditioning phase.

### 3.2.5 Engine operating conditions represented in the experiments

**Passat car:** Emissions from the Passat were measured at various fixed levels of throttle position and engine speed so a range of operating points of the engine were covered. The accelerator position on the Passat car was controlled by a threaded bolt attached through the accelerator pedal which acted as a stop. Various adjustments of this were necessary so that different load levels could be obtained to cover the engine map. The positions here are identified as a function of the protrusion of the stop above that of the pedal structure. This distance is relatively arbitrary and not linearly related to engine load.

The combinations of engine speed and throttle position (as indicated by bolt protrusion) that were investigated for the Passat are shown in table 1. ‘Roll load’ refers to the accelerator position required to attain the stated engine speed without any additional load applied via the brake. Unlike the other points, the throttle position in this condition is not fixed and would increase slightly in relation to vehicle speed, and engine speed in a fixed gear. Roll load is the minimum accelerator position possible whilst driving the vehicle on the rollers in 5<sup>th</sup> gear at fixed engine speed. In contrast ‘full’ refers to a fully depressed throttle with the stop bolt removed.

During the roller runs excessive wheel vehicle speeds were avoided to minimise tyre wear. Therefore, to attain the higher engine speeds without exceeding 70 mph, 5th gear was used up to an engine speed of 3000 rpm, 4th gear for 3500rpm and 3<sup>rd</sup> gear for 4000rpm.

The number of repeat runs performed at each combination of engine speed and throttle position varied significantly. Initially up to ten repeat measurements were attempted for some of the conditions, but due to time limitations this was later reduced to as little as three. Moreover, subsequent analysis found that some data were not being downloaded to the PCs due to electrical connection problems or that engine load and speed were not held stable or long enough for a meaningful measurement. This reduced the number of valid measurements. In cases where a run was suspected of being unsatisfactory then further runs were performed. Subsequent analysis may have shown the original run to be satisfactory; this increased the number of valid runs. Therefore for a combination of reasons the number of satisfactory runs at each combination of load and speed varied between 0 and 10, but 3 repeat runs were typical. The number of repeat measurements which was actually used is shown in the table 3. The order of runs for all the vehicles is listed in Appendix G.

**Table 1 Planned measurement conditions: Passat**

‘Throttle’ Position	Engine speed (RPM)					
	1500	2000	2500	3000	3500	4000
<b>Roll Load</b>	X	X	X	X	X	X
<b>53mm</b>	X	X	X	X	X	X
<b>50mm</b>	X	X	X	X	X	X
<b>47mm</b>	X	X	X	X	X	X
<b>45mm</b>	X	X	X	X	X	X
<b>44mm</b>	X	X	X	X	X	X
<b>Full</b>	X	X	X	X	X	X

**Petrol Mondeo car:** Emissions on the petrol Mondeo car were also measured over various engine speeds and throttle positions which covered most of the operating engine conditions. However the means of measuring throttle position used was different to that used for the Passat. The readout from the OBD interface on the petrol Mondeo car includes throttle position; this was used as a guide to allow the driver to operate the engine at fixed intervals of throttle position on this vehicle. Although this method was more difficult than using a stop, after practice it was found to be a viable means of controlling engine load at a given engine speed. Other than this, the basic procedure for measuring emissions was almost identical to that used with the Passat. The number of attempted repeat runs

conducted at various throttle positions and engine speed conditions for the Mondeo car was usually 3. Further details and the run order are included in appendix G. The matrix of measurement conditions points is shown in table 2.

**Table 2 Planned measurement conditions: petrol Mondeo**

	<b>Engine speed (RPM)</b>					
<b>Throttle Position</b>	<b>1500</b>	<b>2000</b>	<b>2500</b>	<b>3000</b>	<b>3500</b>	<b>4000</b>
<b>Roll Load</b>	X	X	X	X	X	X
<b>30%</b>	X	X	X	X	X	X
<b>40%</b>	X	X	X	X	X	X
<b>50%</b>	X	X	X	X	X	X
<b>60%</b>	X	X	X	X	X	X
<b>70%</b>	X	X	X	X	X	X
<b>80%</b>	X	X	X	X	X	X

## 4 Results

### 4.1 Volkswagen Passat

Preliminary runs on this vehicle showed that the maximum load displayed on the OBD system did not reach the expected maximum of 100%. For example, fully depressing the throttle resulted in the load display reaching approximately only 30% at 1500 rpm and 60% at 3500 rpm. This channel should display engine load as a percentage of maximum at that engine speed, and should therefore be able to reach a theoretical 100% at any engine speed, however this was clearly not the case. Despite this, the % load display did appear to *change* in a consistent and logical fashion between the load limits as the throttle was depressed. This issue remains unresolved and the possible reasons for this anomalous behaviour are discussed later in this report.

The number of measurements under each condition is shown in table 3. The reasons for the variability in repeat measurements are discussed in the methodology section.

**Table 3 Number of satisfactory runs under different engine conditions, Passat**

<i>Indicated Load</i>	<b>Engine Speed (RPM)</b>				
	<b>1500</b>	<b>2000</b>	<b>2500</b>	<b>3000</b>	<b>3500</b>
<b>10%</b>	4	4	4	1	
<b>20%</b>	10	3	4	6	1
<b>30%</b>	1	8	4	2	1
<b>40%</b>			5	6	2
<b>50%</b>				3	4
<b>60%</b>					4

Each emission and lambda is presented as 3D ‘tower plot’ as a function of engine speed and % load<sup>4</sup> (See figure 11). The operating points on the engine are categorised in increments of 10% by load and 500 rpm by engine speed. For example, a run falling between 2750 and 3250 rpm and 35 to 45% load is included in the 3000 rpm 40% load category. Therefore, although each run may not represent exactly the same engine condition it provides an estimate of the emissions near to that point. The standard deviation of emissions is presented using the same range so the levels can be visually compared across the graphs. Unfortunately, the amalgamating of results over increments in this way could potentially add to the variability in results, although it is unlikely this would be very significant in view of the overall variability. An additional presentation is provided in figure 12 where each individual emission measurement is plotted as a function of target engine speed and the specific engine load, this should take into account differences in loading but the speeds are amalgamated into the target groups for the sake of clarity.

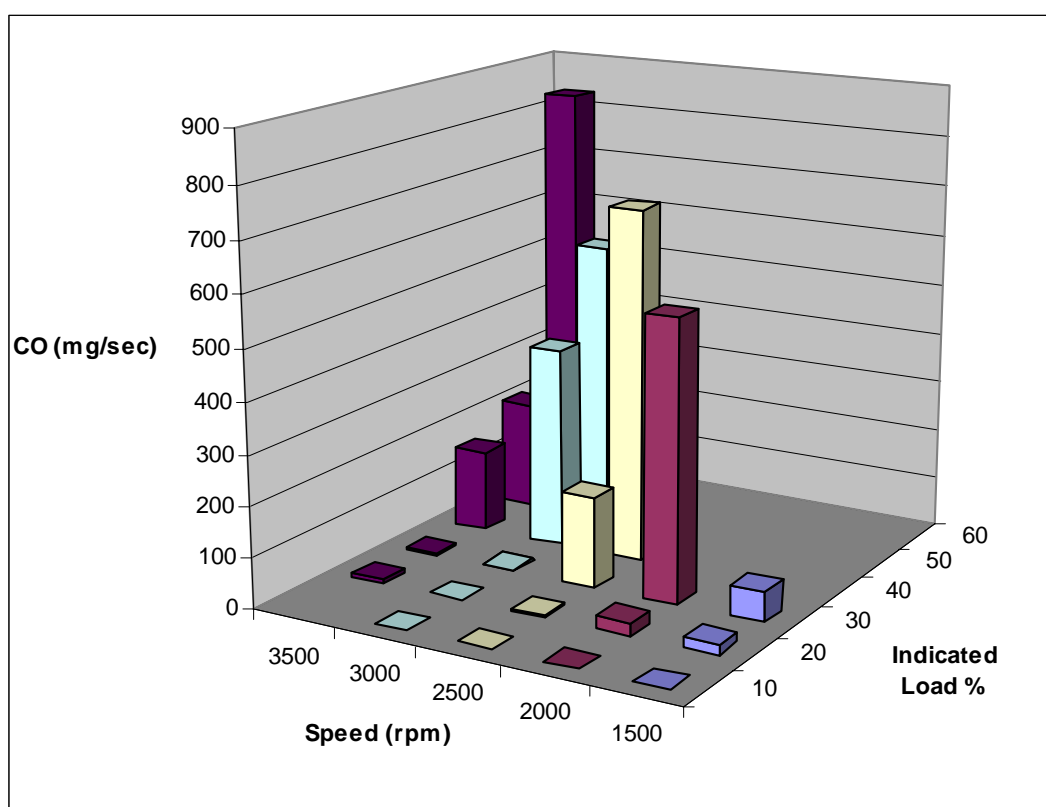
<sup>4</sup> In view of the relatively arbitrary method of controlling the throttle position through a stop mechanism which subsequently proved inconsistent, all the results for the Passat vehicle are displayed in terms of engine load (and speed) which were obtained via the OBD output and logged using a laptop computer. See, however, the caveats in the text concerning the interpretation of the OBD output

#### 4.1.1 Volkswagen Passat CO emissions

The mean CO emissions from the Volkswagen Passat car are illustrated in figure 10. These are highly sensitive to the indicated load across the range of engine speeds. The lowest positive average level is 0.36 g/s at the lowest engine speed and load (1500 and 10%) rising to over 830 g/s at the highest engine speed and load (3500 rpm and 60%). However at 10% load and 2000rpm the emissions are zero due to the concentrations being below the resolution of the gas analyser.

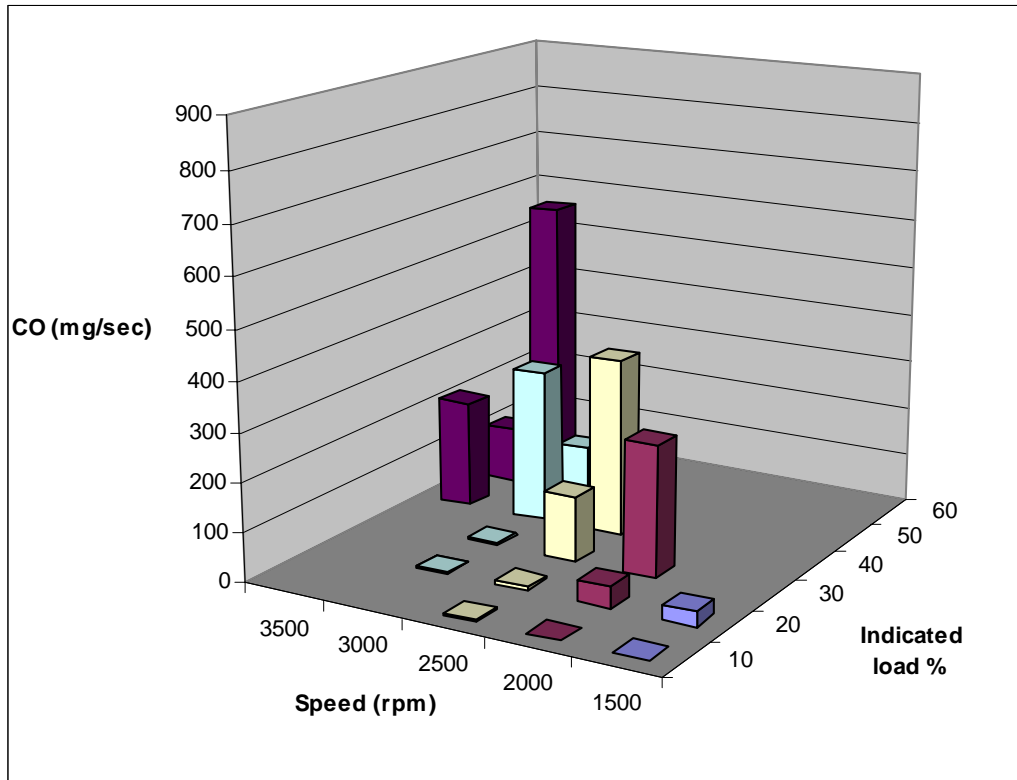
Applying a multivariate model to the data implies a positive correlation across the load range and a less sensitive negative correlation across the speed range (see appendix D). However, CO emissions are probably best described by a stepwise model in which emissions start to increase rapidly above a certain threshold load level. In general CO emissions are relatively insignificant at low loads but increase by approximately 2 to 3 orders of magnitude- beyond a load level of about 20%.

The variability in CO emissions for each operating point can be illustrated by comparing the mean data in figure 10 with the standard deviation in figure 11. In general, this comparison shows that repeatability is very poor, the standard deviation sometimes being greater than the mean at some speed-load conditions. This variability is also present when the individual operating points are compared (see figure 12). This confirms that CO emissions can vary substantially at similar load speed points, and although higher loadings can result in high emissions this effect is not consistent. However, there appears to be some relationship between CO and load for each target speed above a certain load, but the level of load at which CO starts to increase is somewhat different for different speeds.



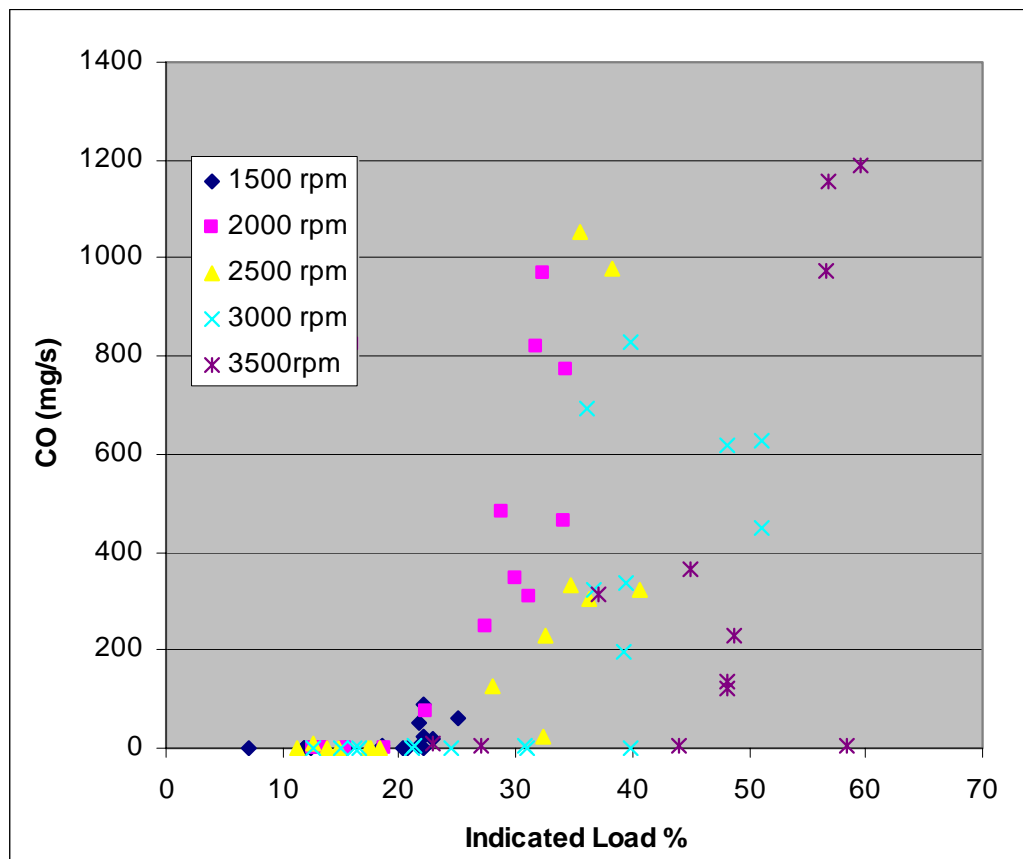
**Figure 10 Passat mean CO emissions v engine load & speed (in view of the ambiguity in the definition of load, the load as indicated by the OBS system is indicated here,<sup>5</sup>**

<sup>5</sup> Note: the indicated load from the OBS was used here; it is unknown why this did not reach 100% for all engine speeds. However, if the load was re-defined as the % of maximum load at any fixed speed, the loads at lower speeds would be



**Figure 11** Passat standard deviation CO emissions v engine load & speed

extended across the 'y' axis, and emissions would dominate near to 100% load for all engine speed conditions. This would also apply to the other emissions presented in this way to a lesser extent.



**Figure 12 Passat individual measurements CO emissions v Engine Load & Speed**

#### 4.1.2 Volkswagen Passat HC emissions

HC emissions exhibit similar characteristics to that of CO in that higher loads have a tendency to produce substantially higher emissions on average (see figure 13). In addition higher speeds also tend to produce higher HC emissions. Applying a multivariate model suggests there is a positive correlation with both engine speed and load. However, overall HC emissions are highly erratic and are less consistently related to load than CO, the lowest mean emission being 0.006 g/km at 10% load and 2000 rpm and the highest mean level being 0.581 g/km at 30% load and 3000 rpm. Comparison of means with the standard deviations in figures 13 and 14, indicate these are of a similar order of magnitude to the means indicating substantial variability. The individual data are plotted in figure 15 which provides an alternative representation of this variability at any combination of load and speed.

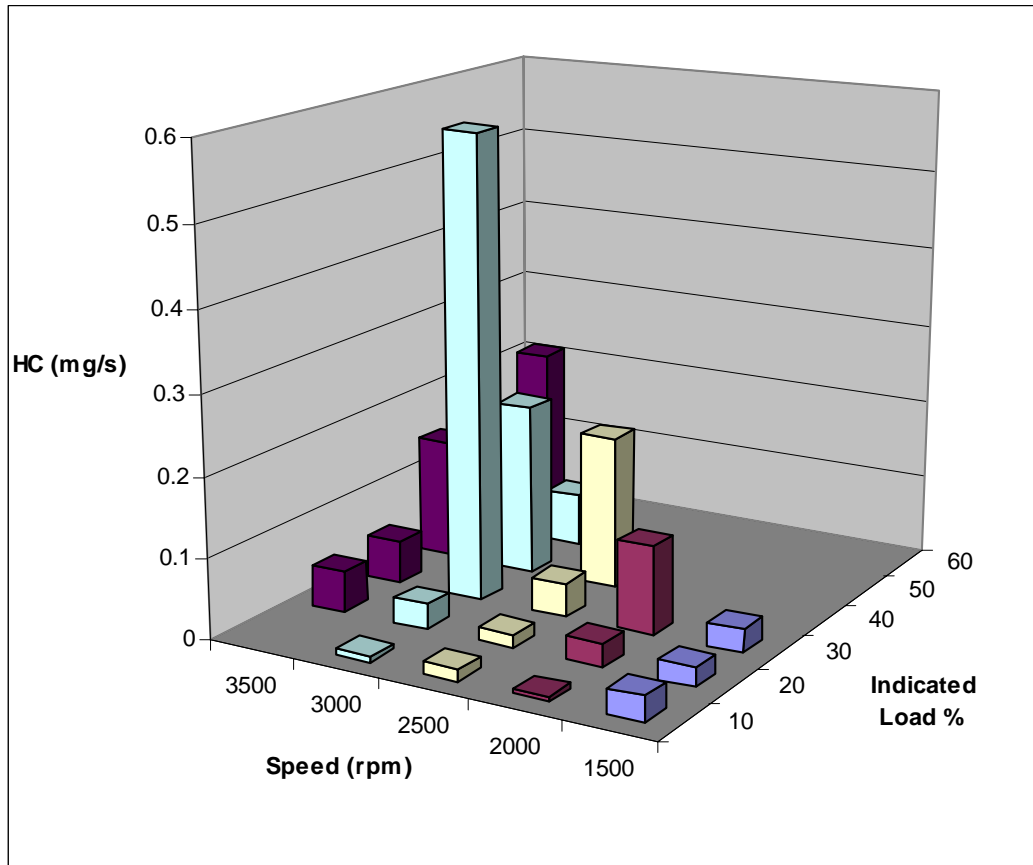


Figure 13 Volkswagen Passat mean HC emissions v engine load & speed

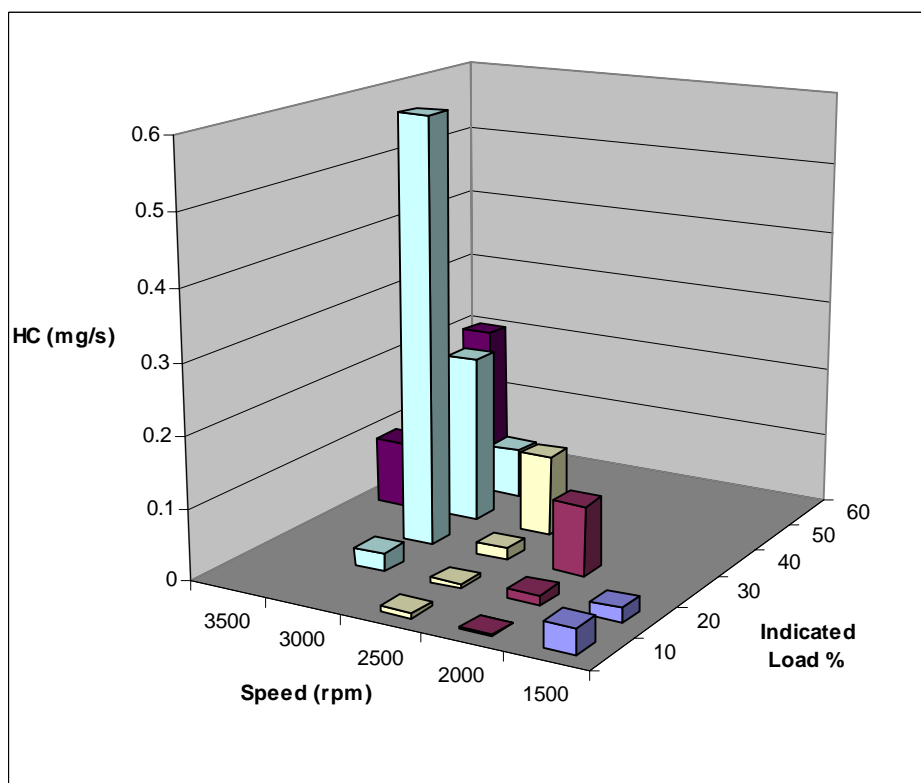
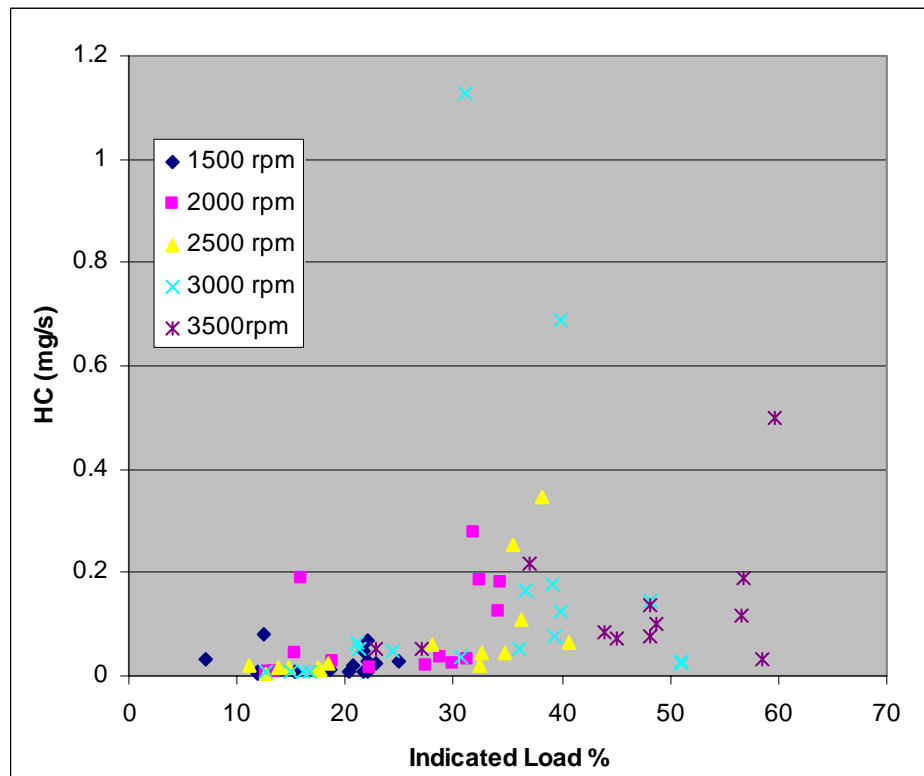


Figure 14 Volkswagen Passat standard deviation HC emissions v engine load & speed



**Figure 15 Volkswagen Passat individual measurements HC emissions v engine load & speed**

#### 4.1.3 Volkswagen Passat NO emissions

As with CO and HC emissions, NO emissions are not related to engine speed and load in a consistent fashion, but higher loads generally produce higher emissions. Applying a multivariate model implies that NO emissions are positively related to both load and speed. The highest mean NO levels are 3.63 and 3.56 mg/s found at 40 and 60% load respectively and 3500 rpm. The lowest mean NO level is 0.02 mg/s at 3000 rpm at 10% load at 0.02 mg/s (see figure 16). Repeatability is again poor with substantial variation in NO emissions in relation to the mean (see figures 16 and 17). This variability can be observed by comparing the individual data points in figure 18.

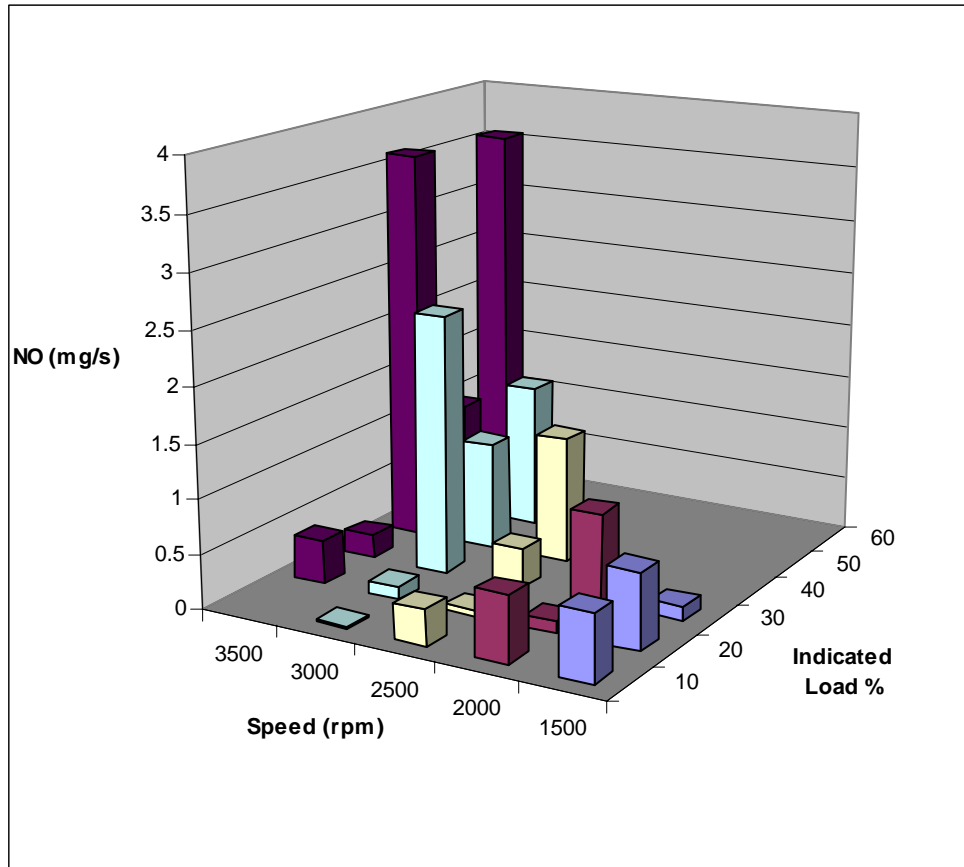
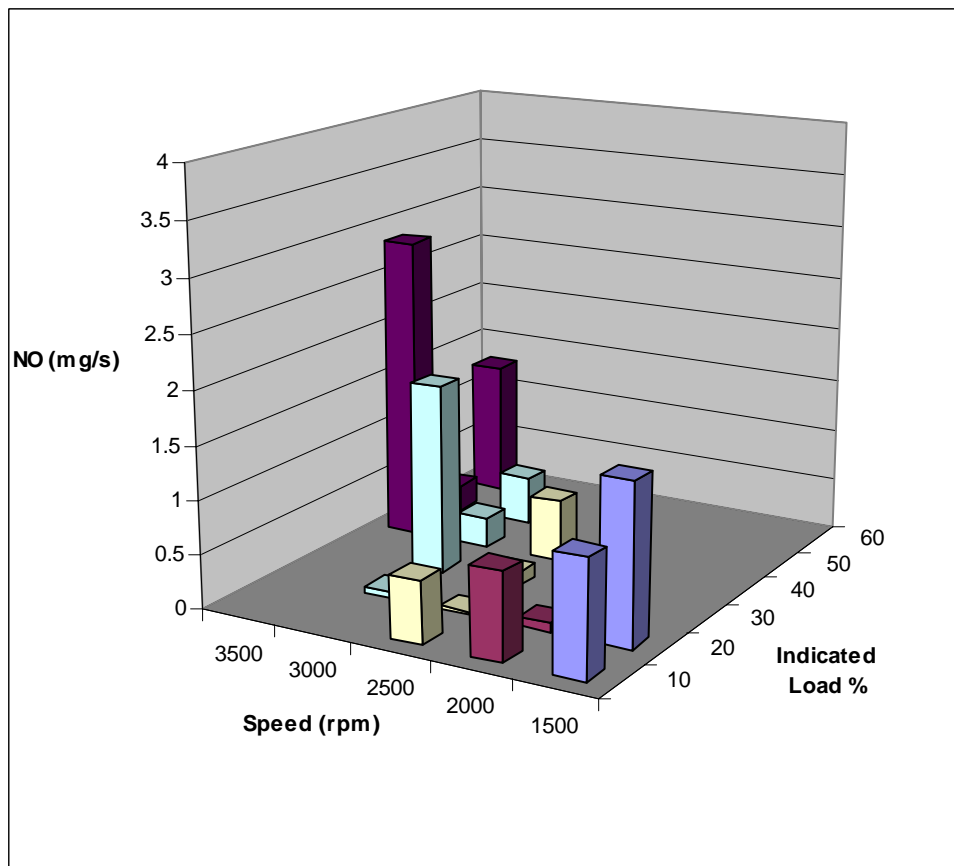
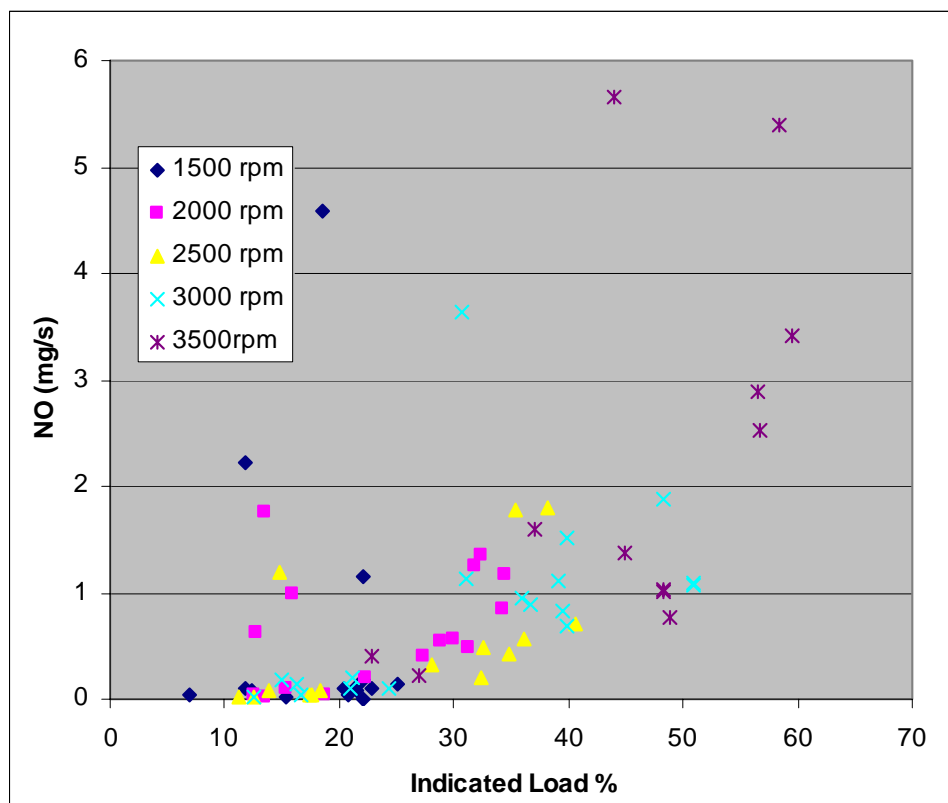


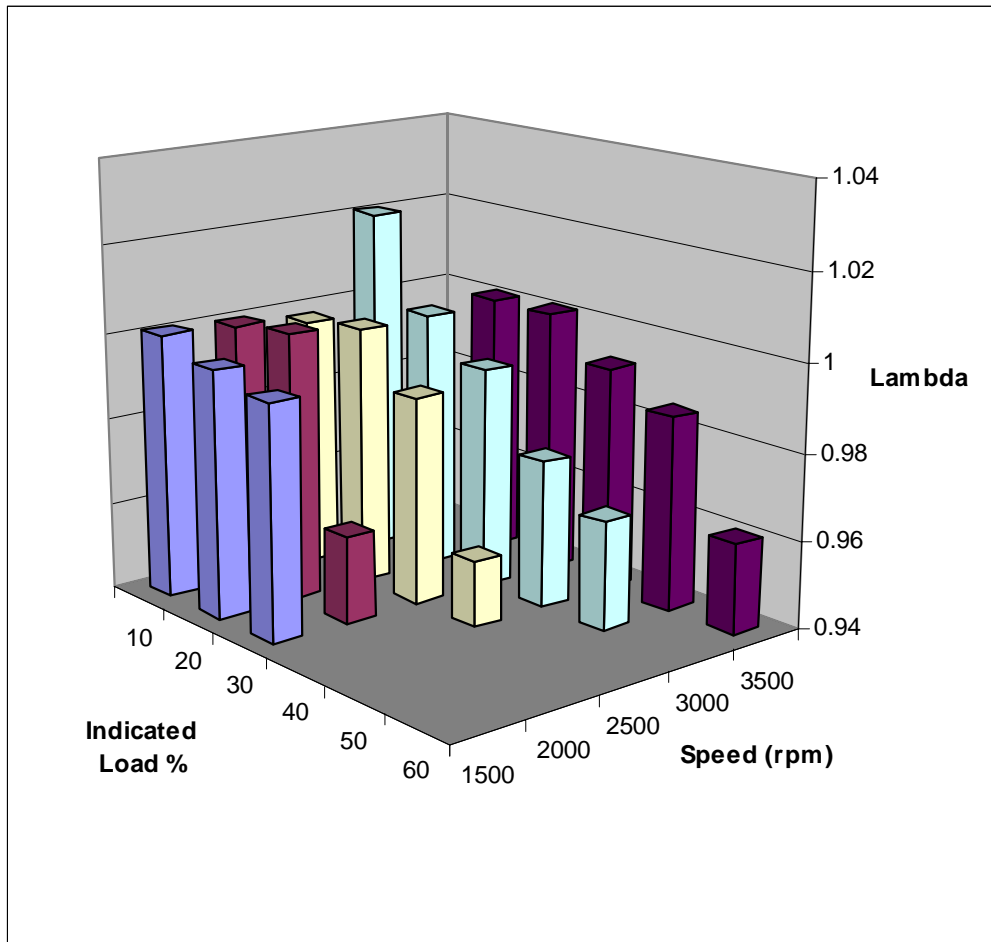
Figure 16 Volkswagen Passat mean NO emissions engine load & speed



**Figure 17 Volkswagen Passat standard deviation NO emissions engine load & speed****Figure 18 Volkswagen Passat individual measurements NO emissions v engine load & speed**

#### 4.1.4 Volkswagen Passat lambda

Lambda measurements on the Volkswagen Passat remain near to 1 below 25% load, however 2 individual data points are significantly greater than 1 (see figure 21). At higher loads, lambda generally decreases in a predictable fashion below 1 indicating a rich fuel air mixture. The lowest mean figure was recorded as 0.955 at 2500 rpm and 40% load. Comparison of the means with the standard deviations (see figures 19 and 20) show that lambda measurements are generally far more repeatable than emissions measurements.



**Figure 19 Volkswagen Passat mean lambda v engine load & speed**

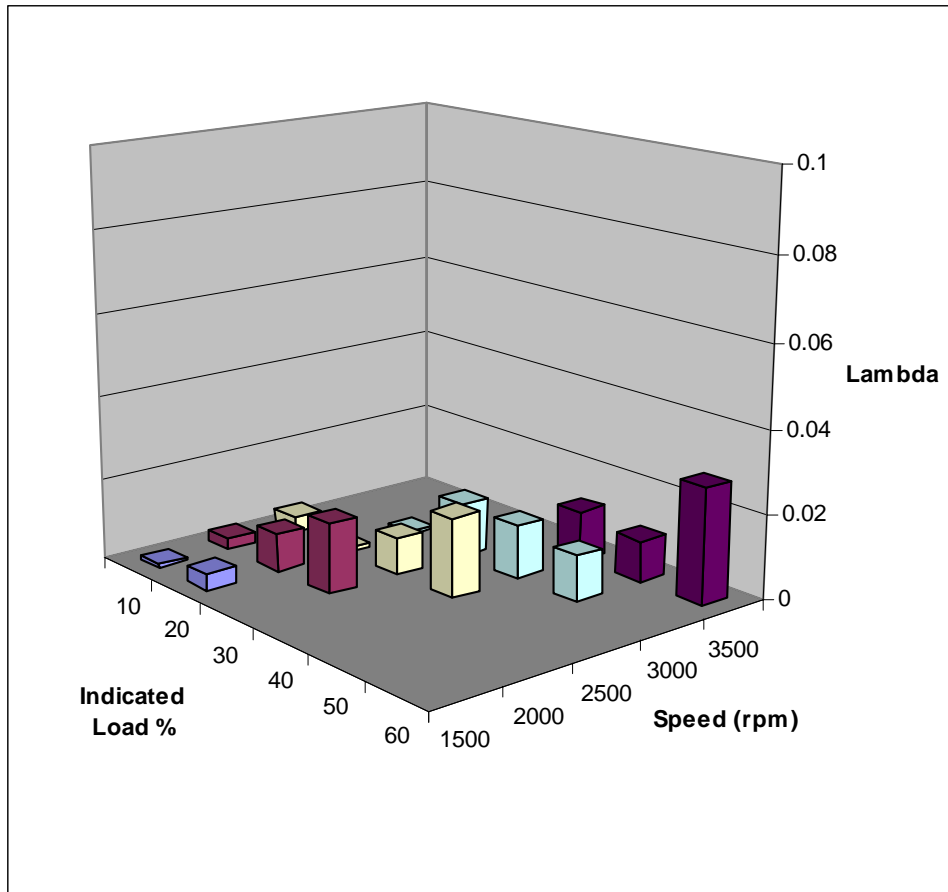


Figure 20 Volkswagen Passat standard deviation lambda v engine load & speed

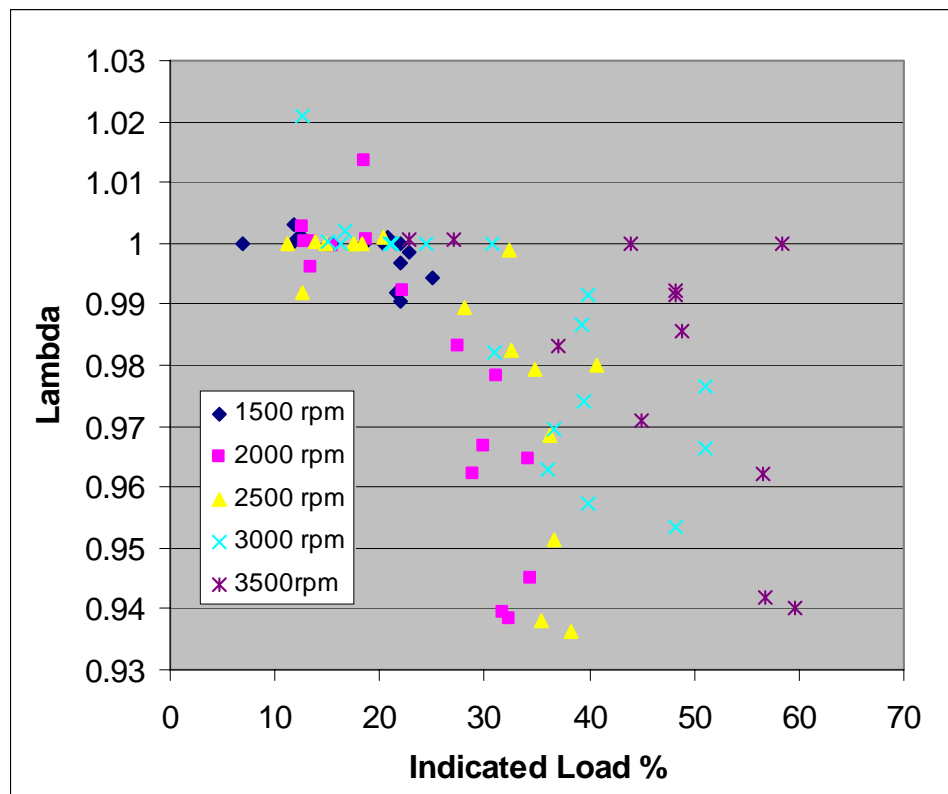


Figure 21 Volkswagen Passat individual measurements lambda v engine Load & speed

## 4.2 Analysis of emissions petrol Ford Mondeo

In the case of the Petrol Mondeo, it was attempted to explicitly control throttle position as a discrete figure as indicated by the OBD system (rather than choose an arbitrary fixed position of the throttle pedal as was the case with the Passat). Therefore, throttle position is used as the independent variable rather than load in the following presentations<sup>6</sup>. However, the trends and repeatability of emissions when described as a function of engine load and speed are similar to throttle position and engine speed. The full results are tabulated in appendix C.

The throttle position *output* from the OBD system was limited to around 80% on the petrol Mondeo, but this limit was constant and not speed dependant. The reasons for this limit is unknown, but it was not thought that this represented any real limitation in throttle position and is treated as an arbitrary maximum. Indeed the OBD load output did reach 100% when the throttle was fully depressed, and consequently it is assumed that maximum load (for the engine speed) was potentially achievable when the OBD throttle was reading 80%.

The number of satisfactory runs performed under each throttle position and engine load condition is shown in table 4.

**Table 4 Number of satisfactory runs under different engine conditions as indicated by OBD system, petrol Ford Mondeo**

<i>Throttle Position (OBD output)</i>	<b>Engine Speed (RPM)</b>					
	<b>1500</b>	<b>2000</b>	<b>2500</b>	<b>3000</b>	<b>3500</b>	<b>4000</b>
<b>20%</b>	1		1	1	1	
<b>30%</b>		8	4			1
<b>40%</b>	3	2	8	3	3	3
<b>50%</b>	3	3	6	3	3	3
<b>60%</b>	3	3	5	3	3	3
<b>70%</b>	1	3	6	3	3	3
<b>80%</b>	3	2	7			

### 4.2.1 Petrol Ford Mondeo CO emissions

Mean CO emissions mostly fall into two distinct groups, very low emissions at low and medium throttle positions, and substantially greater emissions at high throttle positions (see figures 22 and 24). Between 1500 and 3500 rpm the mean CO emissions are very low up to the 50-60% throttle position. Usually these are below 10 mg/s and sometimes register zero due to the limited resolution of the analyser which can not measure below 0.01% concentration. Above this threshold however, emissions increase substantially, the highest mean reading being 1062 mg/s at 2500 rpm and 70% throttle position. Mean CO emissions are higher at 70% than 80% load, but this may be partly due to the poor repeatability of the measurements. This can also be seen by comparing figures 22 and 23. At 4000rpm the transition to a high CO regime appears to occur at a lower throttle position of 60%. The highest individual measurement of CO was recorded at 60% load and 4000 rpm.

<sup>6</sup> The 2 figure display of % throttle position in increments of 10s was easier to observe and subsequently control. There was also substantial uncertainty in the definition of load output therefore throttle position was used.

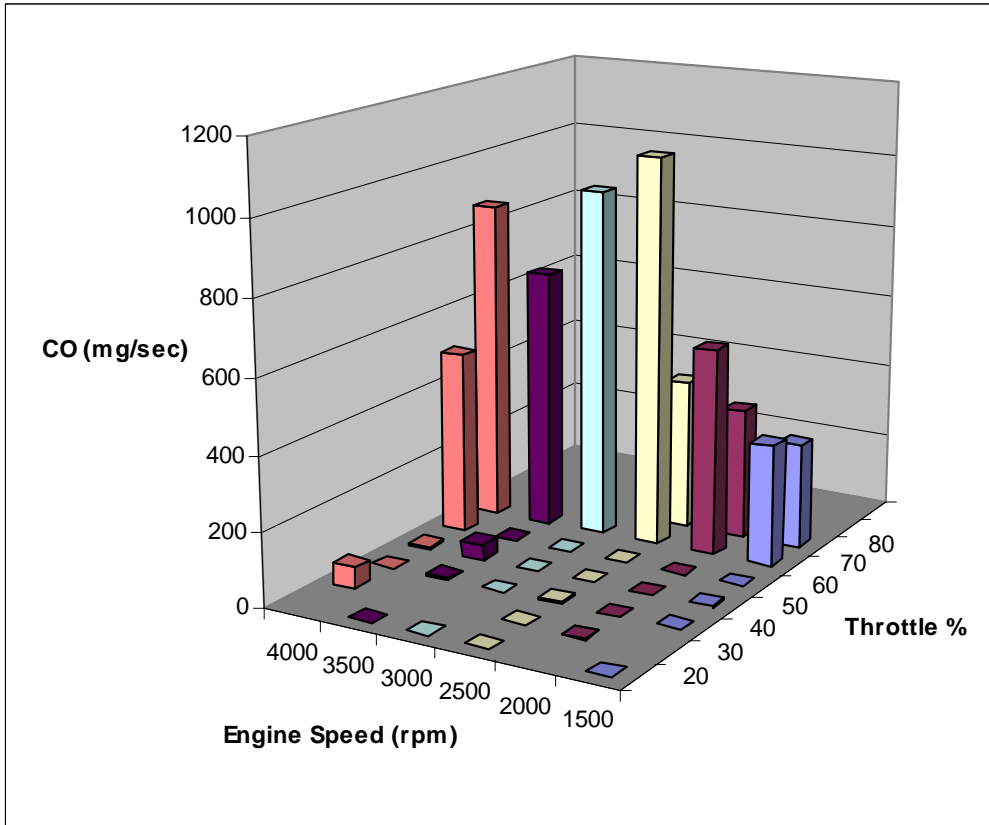


Figure 22 Petrol Ford Mondeo mean CO emissions v throttle & engine speed

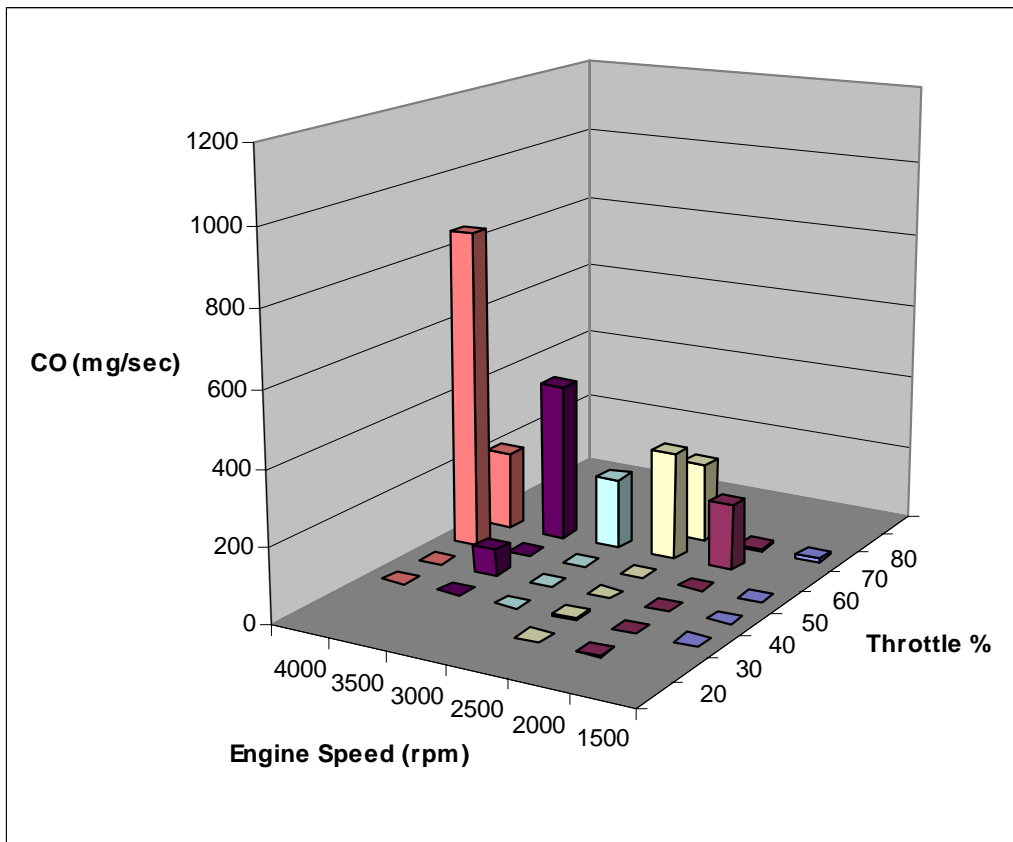


Figure 23 Petrol Ford Mondeo standard deviation CO emissions v throttle & engine speed

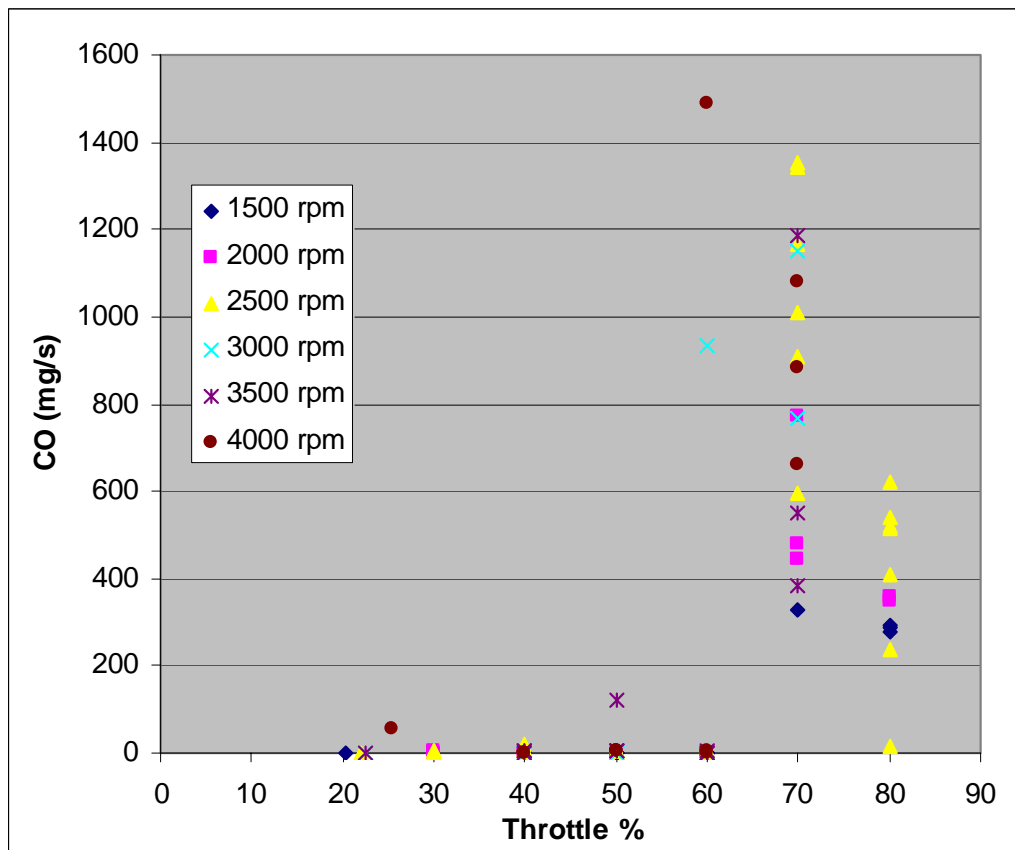


Figure 24 Petrol Ford Mondeo individual measurements CO emissions v throttle & engine speed

#### 4.2.2 Petrol Ford Mondeo HC emissions

HC emissions show a similar tendency to CO emissions, with very low emissions at low throttle positions and very high emissions above a certain threshold level of load (see figures 25 and 27). As with CO, this threshold tends to be lower at higher engine speeds. In the case of HC the threshold is about 70% throttle at 1500 rpm and 50% throttle at 4000 rpm. Also, several zero readings were obtained at low loads due to the limited resolution of the analyser. The highest mean HC emission is 0.393 mg/s at 2500 rpm and 70% load. The highest individual measurement of HC was at 60% throttle and 4000 rpm engine speed, this data was the same run for which CO was the highest. Repeatability is quite poor with the standard deviation comparable to the mean magnitude of the emissions.

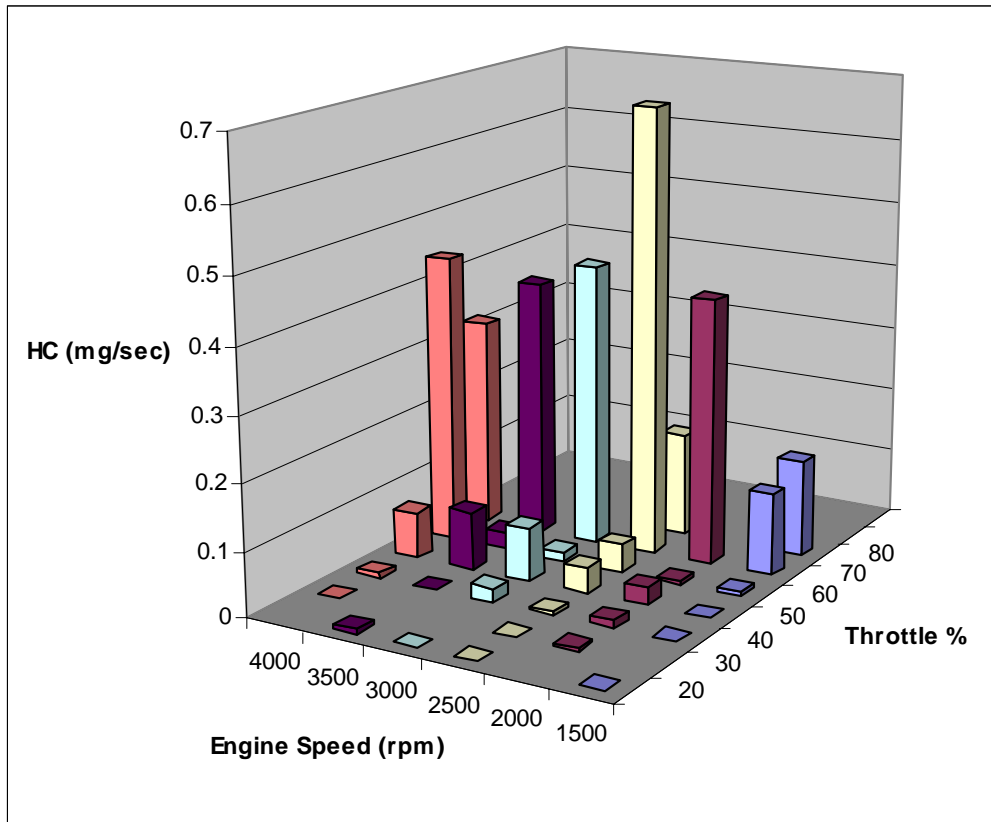


Figure 25 Petrol Ford Mondeo mean HC emissions v throttle & engine speed

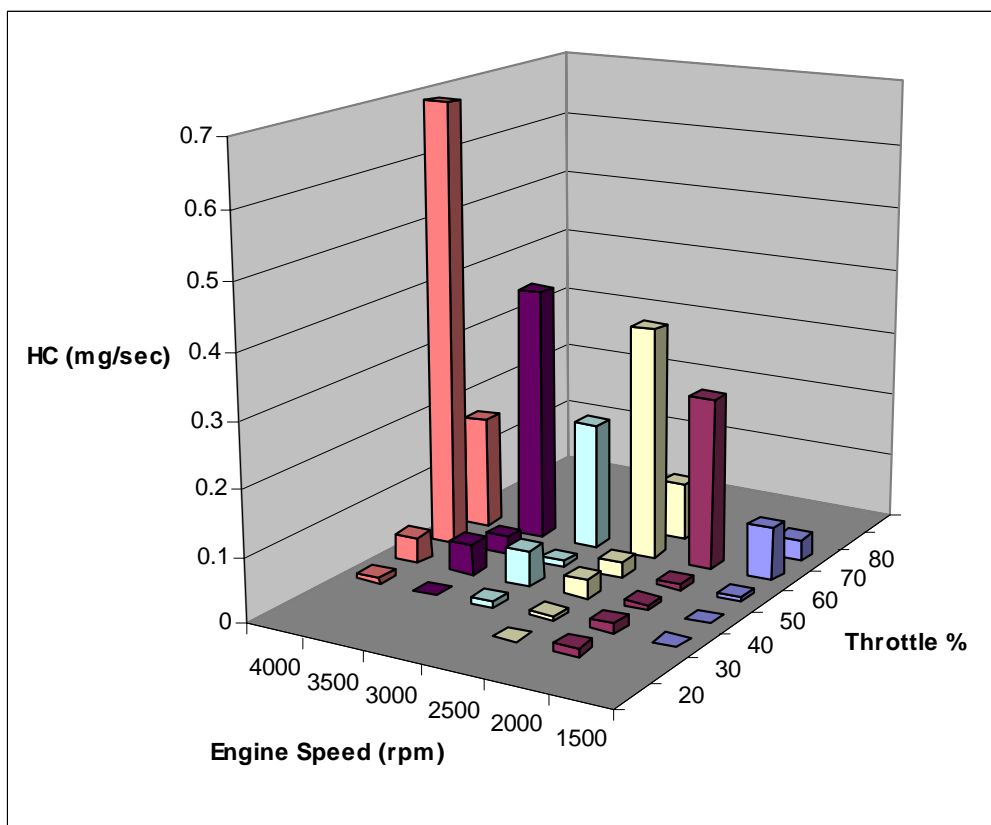
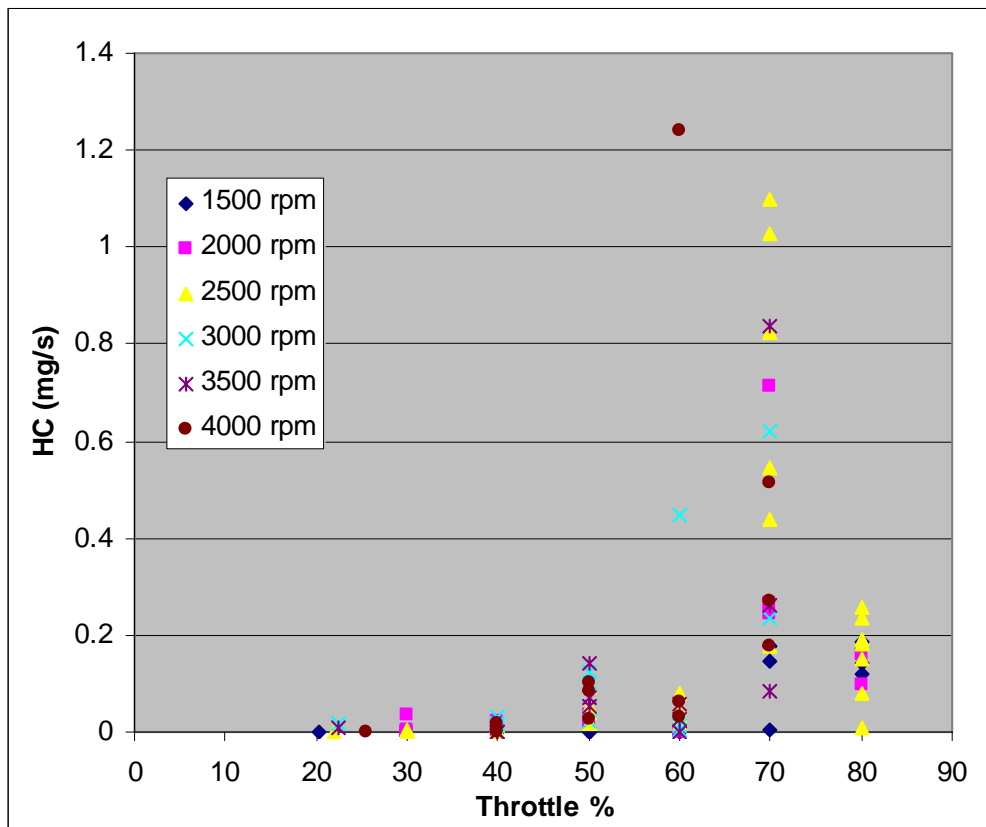


Figure 26 Petrol Ford Mondeo standard deviation HC emissions v throttle & engine speed



**Figure 27 Petrol Ford Mondeo individual measurements HC emissions v Throttle & Engine Speed**

#### 4.2.3 Petrol Ford Mondeo NO Emissions

NO emissions exhibit substantially different behaviour to that of HC and CO emissions in that they appear more linearly related to engine speed and throttle position across some of these ranges (see figures 28 and 30). NO<sub>x</sub> generally increases as a function of both engine speed and load, and exhibits better repeatability than the other emissions, this can be seen by comparing figures 28 and 29. NO is also closely related to throttle position when each individual engine speed group is analysed separately (see figure 30). At 3500 and 4000 rpm there are very good correlations between NO and throttle position ( $r^2 > 0.9$ ) although the correlation was lower at lower engine speeds.

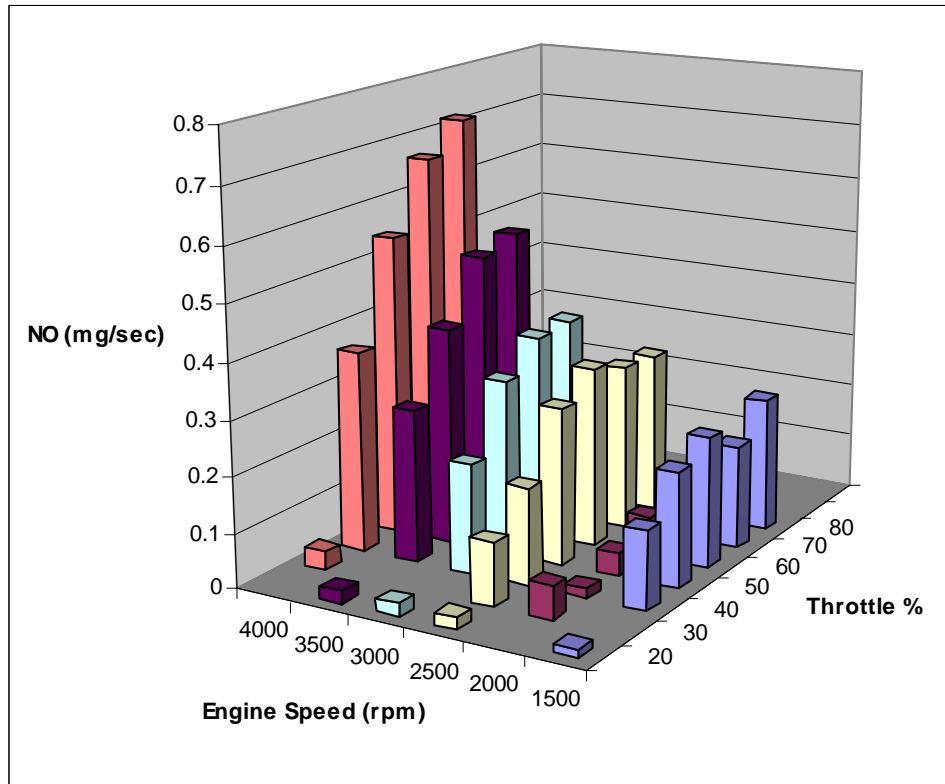


Figure 28 Petrol Ford Mondeo mean NO emissions v throttle & engine speed

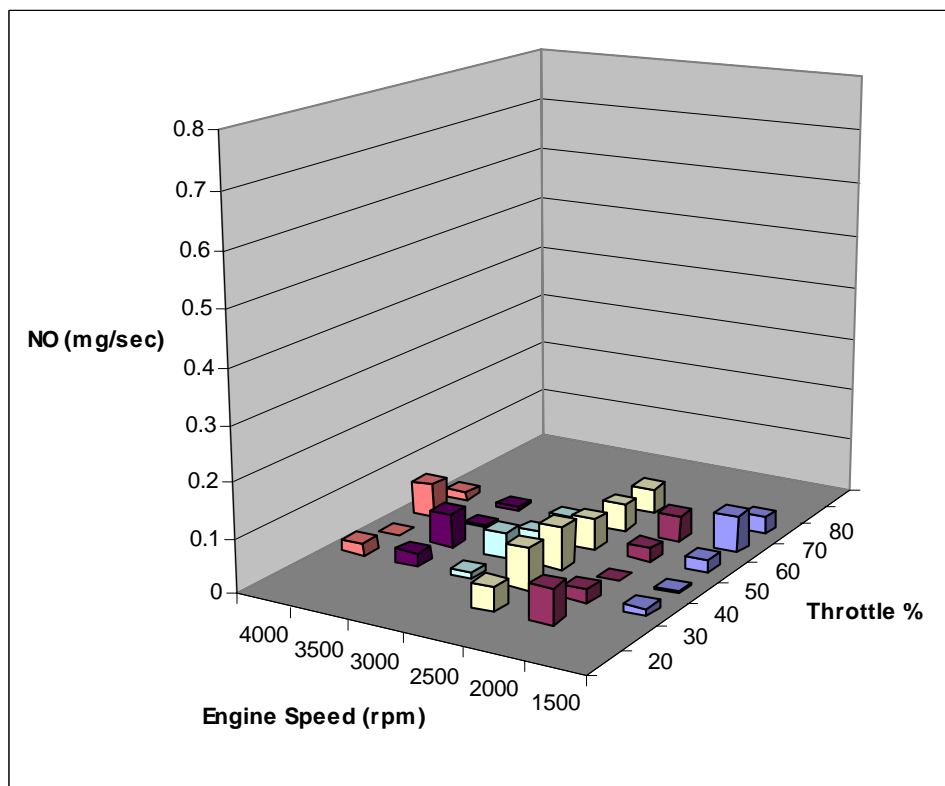


Figure 29 Petrol Ford Mondeo standard deviation NO emissions v throttle & engine speed

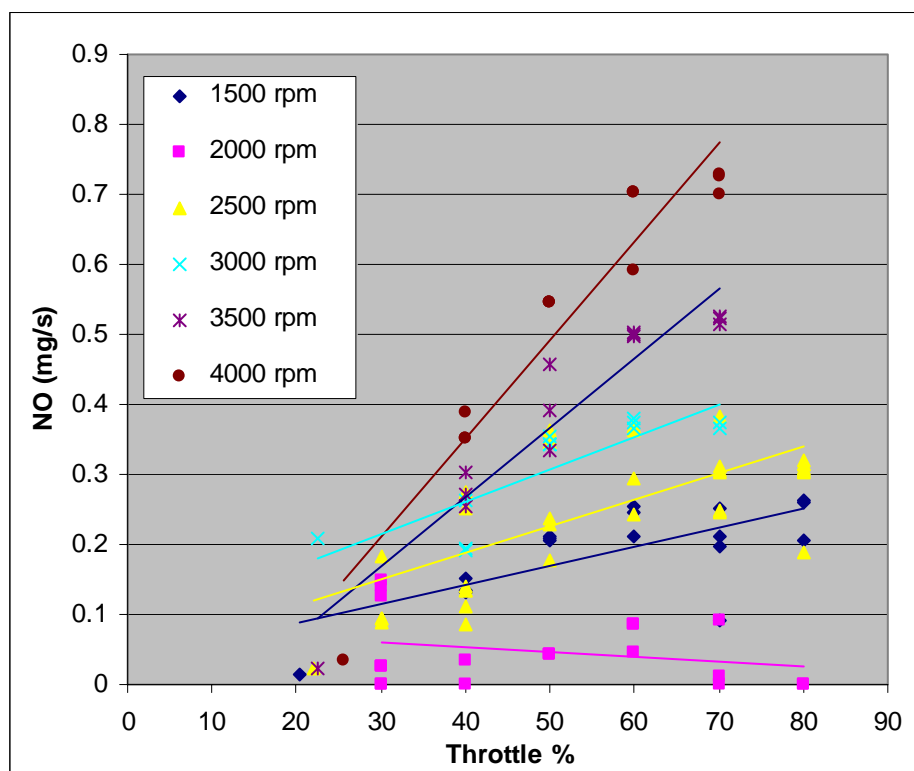


Figure 30 Petrol Ford Mondeo individual measurements NO emissions v throttle & engine speed

Table 5 Correlation between NO emissions and throttle position for a fixed engine speed

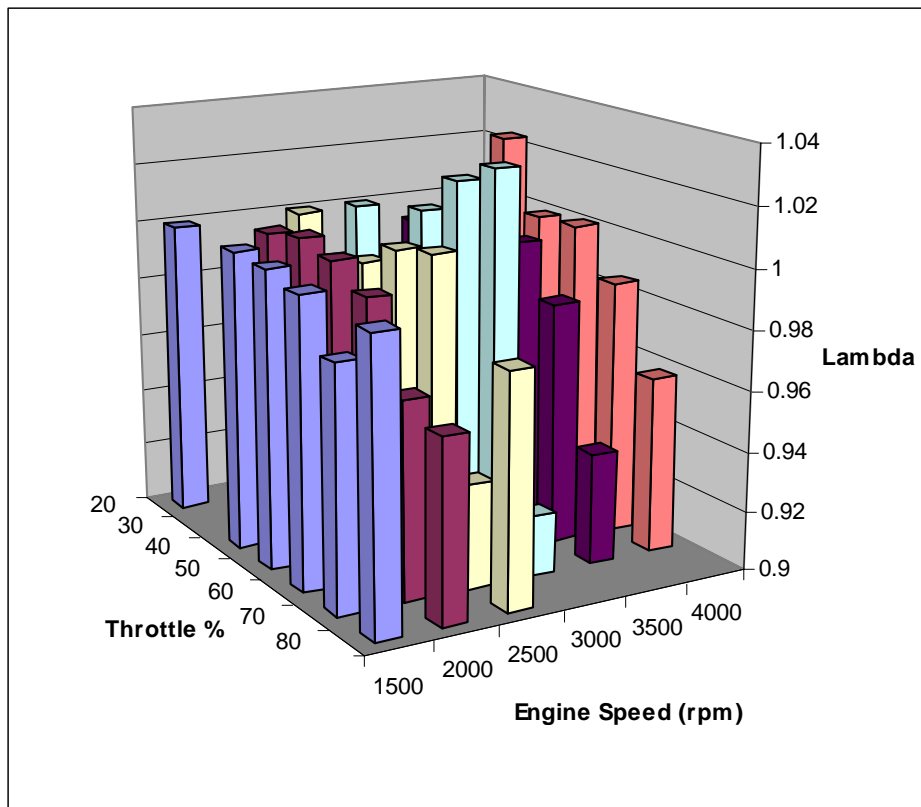
Engine Speed (rpm)	( $r^2$ )
1500	0.4732
2000	0.0671
2500	0.4629
3000	0.7189
3500	0.9054
4000	0.9135

#### 4.2.4 Petrol Ford Mondeo Lambda

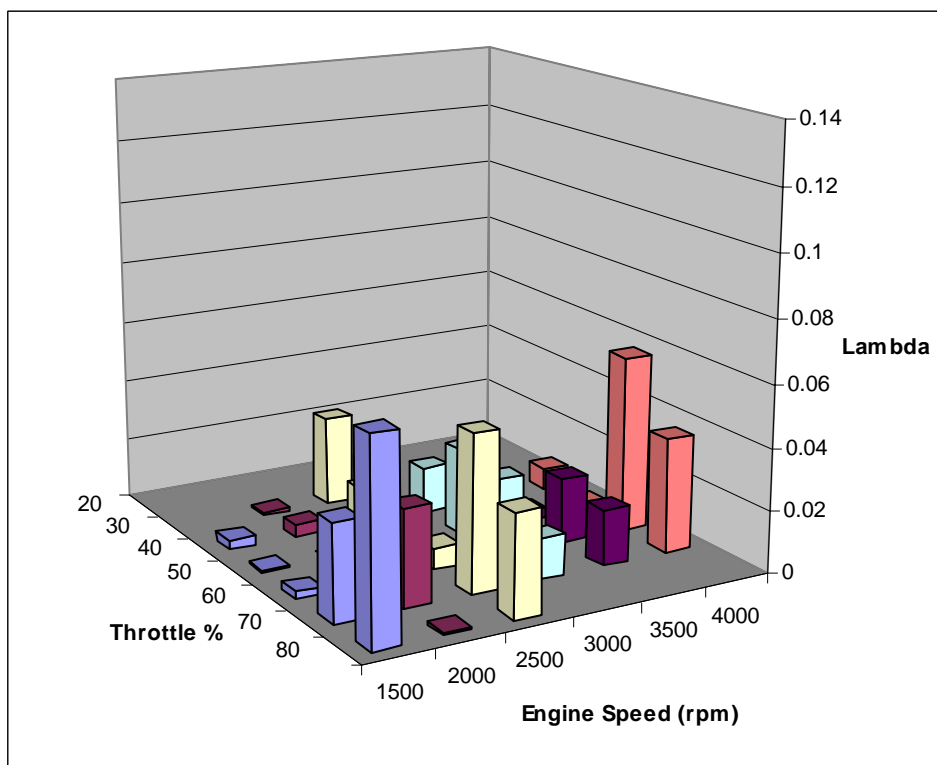
Mean lambda values remain at or near 1 for most throttle positions and engine speeds, however these start to decrease when the throttle exceeds the 60% level (see figure 31). The lowest mean lambda reading is 0.92 at 3000 rpm and 70% throttle. A highest reading of 1.024 is at 4000rpm and 30 % throttle.

The individual measurements of lambda show substantial variation (see figure 33). For example, at 1500 and 2500rpm and high throttle positions, there are many lambda values well above and below 1. At 3000 rpm all the values of lambda remain above 1 up to 60% throttle position, then at 70% throttle lambda decrease below 1. The most consistent measurements of lambda is at 2000 rpm where lambda

remains near 1 at low and medium throttle positions, then decreases below 1 at 60% throttle and beyond.



**Figure 31 Petrol Ford Mondeo mean lambda v throttle & engine speed**



**Figure 32 Petrol Ford Mondeo lambda v throttle & engine speed**

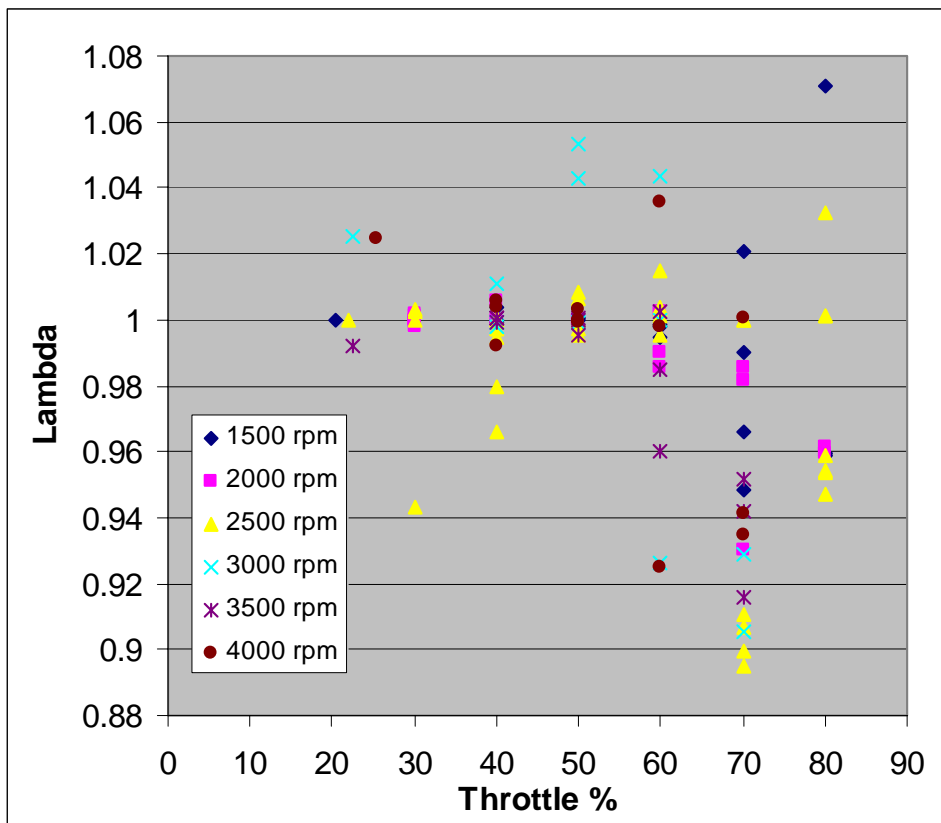


Figure 33 Petrol Ford Mondeo individual measurements lambda v throttle & engine speed

4.2.5 Petrol Ford Mondeo Analysis of Load v Speed

Engine load was not explicitly controlled as an independent variable in any of the roller runs; however, it was measured. Therefore, the emissions can be represented as a function of load subject to the limitations mentioned in the following paragraph. The magnitudes, characteristics and trends of the emissions are generally similar to those discussed above for throttle position; therefore a detailed discussion of these results is not repeated. The means and standard deviations of the emission data in terms of engine speed and load are included in appendix C.

In general, the *mean* emissions as represented by engine speed and engine load are slightly more erratic than those using engine speed and throttle position, see figures 28 and 34 for example. This is possibly because load levels from 2 different conditions could be amalgamated into the same group (for example 26% load and 34% load would be classed in the 30% group) and excluded completely from another group.

The results for NOx emissions as a function of engine load and speed are displayed as an example (see figures 36 to 39). Even higher correlations are seen between the *individual* NOx measurements and load at many engine speeds (see figure 36 and table 6) than when throttle position is used as the independent variable.  $r^2$  is greater than 0.8 for 5 of the 6 engine speeds used. A possible explanation for this is provided in the discussion.

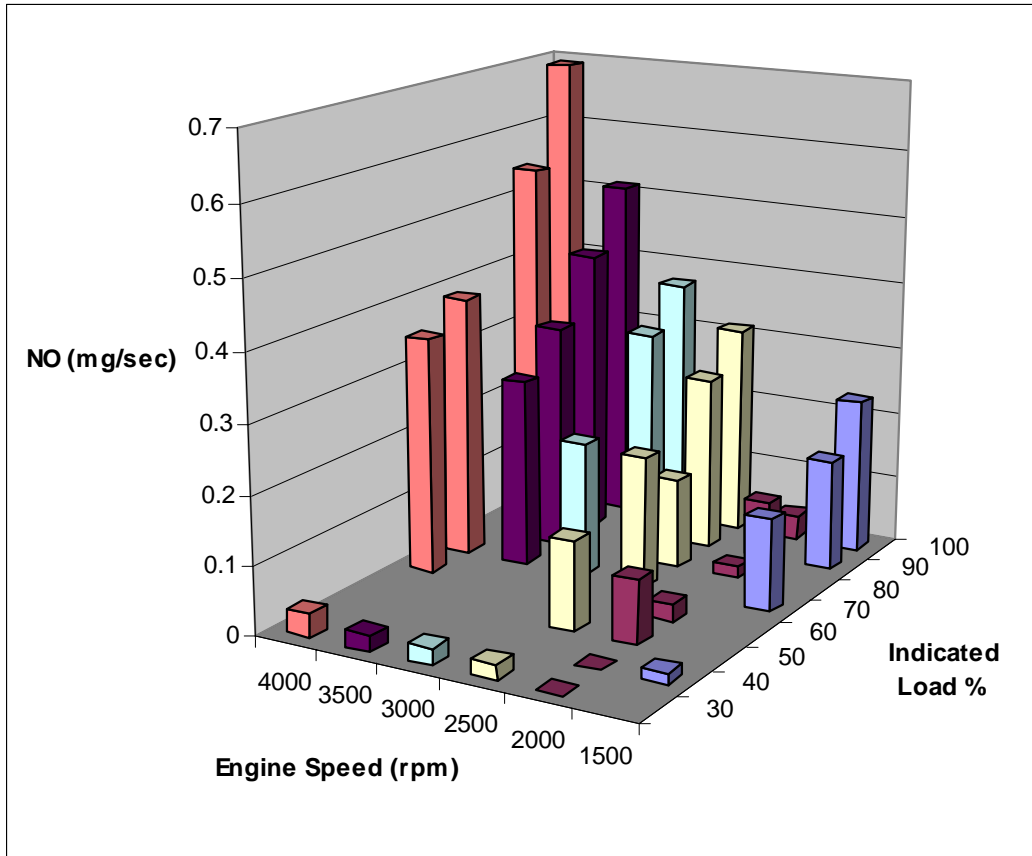


Figure 34 Petrol Ford Mondeo mean NO Emissions v engine load & speed

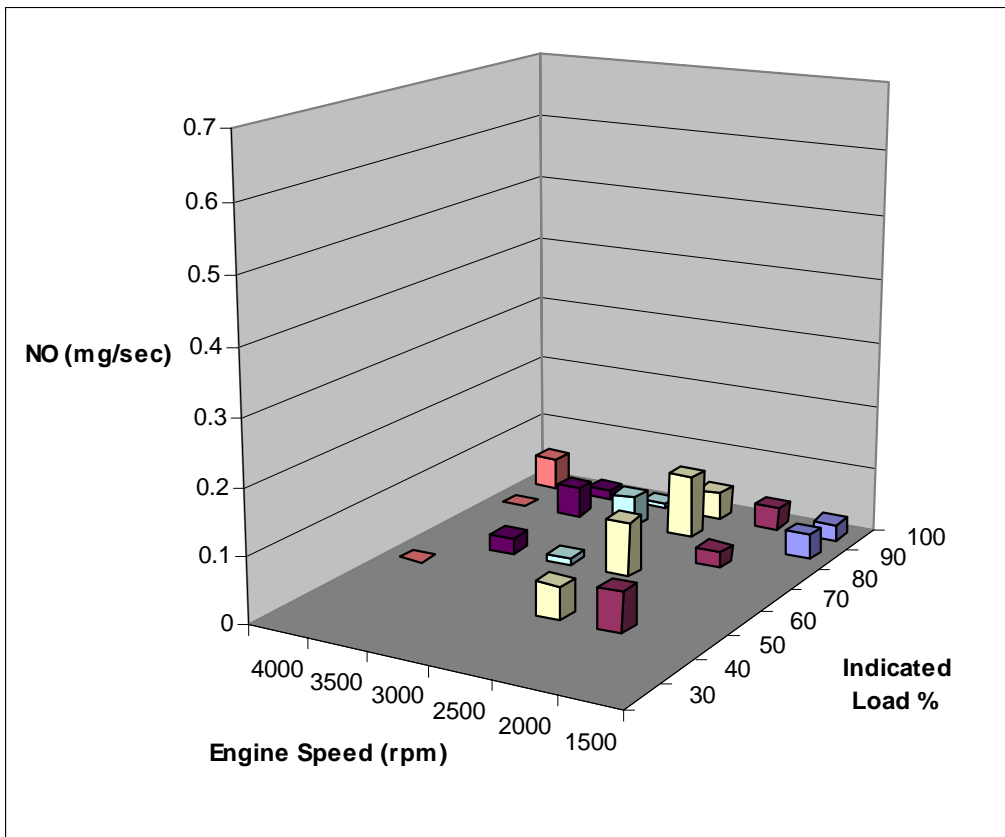


Figure 35 Petrol Ford Mondeo standard deviation NO Emissions v Engine Load & Speed

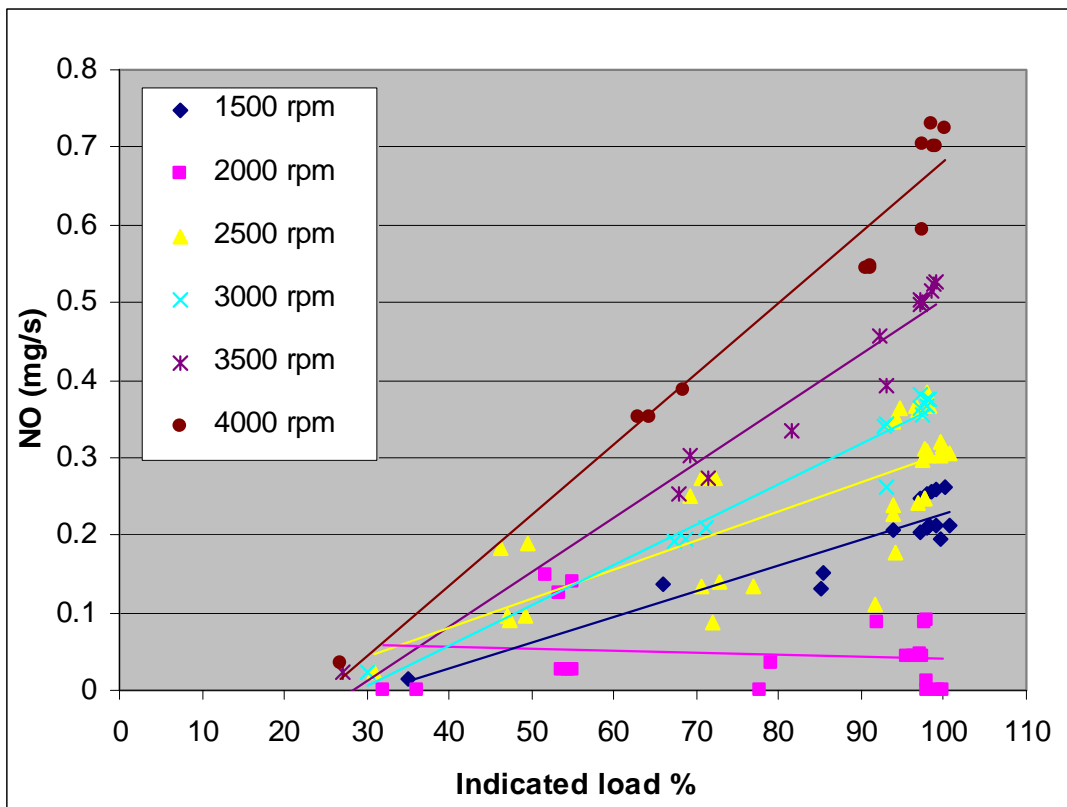


Figure 36 Petrol Ford Mondeo NO Emissions v engine load & speed

Table 6 Correlation between NO emissions and load at fixed engine speeds

Engine Speed rpm	(r <sup>2</sup> )
1500	0.829
2000	0.0149
2500	0.5879
3000	0.94730
3500	0.958
4000	0.9538

### 4.3 Diesel Mondeo Emissions

The Diesel Mondeo car was subjected to similar runs to that of the Petrol Mondeo, and it was possible to control the Mondeo Diesel engine over a similar range of throttle positions and engine speeds to that of the Mondeo petrol engine. However, this car emitted very low levels of CO, HC and NO emissions, typical concentrations being in the 0.01 to 0.02% range for CO and 0 to 2 ppm for HC and NO. Since the resolution of the analyser is only 0.01% for CO and 1ppm for HC and NO, and the drift between runs could amount to this, meaningful emission data could not be obtained from this vehicle with this equipment. However the laboratory book data for each individual run, including brake disc temperatures are included in appendix G.

## 5 Discussion:

### 5.1 Ability to operate the roller system and obtain measurements under loaded conditions

The technique of applying load to the engine via the vehicle brakes *in a controlled manner* had never to our knowledge been attempted before on a light duty vehicle equipped with hydraulic brakes such as a car. Therefore, the methodology adopted for achieving this required adaptation as difficulties were encountered and experience was gained.

The initial attempts to drive the Passat at a predetermined engine load and speed using the accelerator and brake were very difficult since the % load reading appeared to vary as a function of engine speed for a fixed accelerator position; therefore the driver had to make 2 adjustments simultaneously both of which were interdependent. This process was made even more difficult because of the short length of time allowed for each individual run due to the need to limit brake temperatures. The frequency of the OBD output was also relatively low during the runs on the Passat vehicle, although the frequency was subsequently increased by reducing the number of output variables on display.

The procedure eventually adopted was to use the throttle position as indicated by the OBD output rather than load as an independent variable. This allowed the driver to fix the accelerator position to a particular level, and then attain the required engine speed by varying the brake position. In practice, the procedure was rather more complex since both pedals have to be initially pressed simultaneously to avoid over-speeding the engine.

Although it may be easier to control throttle position rather than engine load, throttle position is less objectively useful. It is not directly related to load or universally related in any way across different vehicle types, so different throttle levels would need to be used for different vehicle specifications if this was to be defined as a variable in a legislative test.

Subsequent exploration of the data from the petrol Mondeo vehicle suggests that unlike the Passat, the indicated % load, obtained from the proxies of airflow, was constant for a given throttle position across the speed range. If this is more typical of vehicles generally and a clear definition of the load output is obtained, it is possible that the proxy for load could be explicitly controlled and used as independent variable for load when defining emissions.

In general, the roller system described and investigated in this study is capable of subjecting the engine to fixed throttle and speed conditions for short periods from which the engine emissions can be measured. These can be translated into speed and implied relative load, but the load was not explicitly controlled in the procedures described. Further work is needed to examine if target loads can be explicitly controlled across a wide range of vehicle types in the same manner as throttle position.

### 5.2 Repeatability of emission measurements

One principal objective of this work was to examine if representative and repeatable emission levels could be measured from vehicles driven on unloaded rollers whilst loading the engine via the vehicle brakes and measuring speed and load from the OBD system. However, this objective has to be judged in context with the fact that emissions from used catalyst vehicles are not always repeatable or representative even when tested with the most expensive and complex equipment. It is therefore difficult to reach any firm conclusions about the *relative* merits of using the new roller system without examining the *same* vehicles on a controlled dynamometer over the same loaded conditions and transient type approval test cycles.

It is suggested that based on these preliminary results, the roller system may be capable of repeatable quantitative measurement of NO<sub>x</sub> emissions assuming these are of a sufficiently high concentration to register on the gas analysers. For diesel vehicles it may be that only those emitting higher than normal emissions can be measured in this way. In contrast CO and HC emissions were not as repeatable, but the level of repeatability could be sufficient to identify, from an acceptably small number of runs, serious malfunctions such as lambda sensor or catalyst failure. Further work would be required whether this is a significant improvement over the current idle test for these emissions.

The poor repeatability of CO and HC measurements may be partly due to the emission characteristics of vehicles equipped with “after treatment” systems which are highly sensitive to the operating conditions immediately prior to the measurement phase. A modern spark ignition engine equipped with a 3 way catalyst (a system which encourages reactions between CO, HC and NO<sub>x</sub> and other constituents in the exhaust stream so these pollutants are diminished) is best viewed as three combustion systems mounted in series (the engine, oxidising catalyst and NO<sub>x</sub> catalyst) all of which are involved in various combustion reactions which can increase or decrease the mass flow of different emission components in the exhaust. The combustion process depends upon a range of variables which include gas temperatures, pressures, the time under these conditions, the mass flowrate of gas, the contact area and accessibility of catalyst material, and the local gas concentrations, particularly oxygen. It is therefore not surprising that emissions cannot be easily characterised by 2 independent variables such as engine speed and engine load or throttle position in this situation.

The duration of a roller run is limited to 10 to 20 seconds when subjecting the engine to high loads and speeds, since the brake temperatures need to be kept to acceptable levels. Unfortunately, CO and HC emissions do not instantaneously reach a steady state value at a given speed and load. The engine management system enables the fuel air ratio (lambda) to remain near stoichiometric for a short period after which it defaults to a rich setting, and the time elapsed before this occurs can vary. A further complication is that the oxidising catalyst has an ability to function at a non-stoichiometric mixture for a limited period of time, after which emissions increase. With regards to the runs themselves, it is difficult for the engineer to monitor emissions at the same time as controlling load; therefore the level of CO or HC emissions which are measured at the end of the run can be highly variable depending on the exact point at which the run is ended. This is reasonably clear from examining figure 8.

Another important factor influencing emissions is catalyst temperature. If the catalyst temperature changes during any individual run, this would probably influence the starting temperature of the catalyst in any subsequent run. Moreover, the lengths of individual runs differ due to difficulties in controlling the engine speed (this can lead to other variable effects, see later) and longer runs are likely to produce higher catalyst temperatures. One method of avoiding the first problem is to either wait until the catalyst has reached a given temperature or perform runs in a controlled order so at least the temperatures are consistent. This is why most controlled runs include a conditioning phase. Even if a conditioning phase is not used for each individual run, performing these in a consistent order should mean that a consistent temperature is reached at the beginning of each run. This may improve the repeatability over a suite of runs starting from the same temperature.

Although a short conditioning phase was used at the beginning of each roller run this may have not been sufficient for the catalyst temperature to stabilise. In addition it was difficult to maintain a fixed protocol since certain runs had to be repeated due to occasional errors (such as stalling), and some runs took longer than others to attain a stable working engine condition. However, errors became less frequent as experience was gained. For future roller measurements, it may be possible to attempt to perform a *suite* of runs in a given order, where the operating conditions are all different to cover the required range, then after a longer conditioning phase perform exactly the same suite of runs again for the repeat measurement. This may result in more consistent emission measurements between entire suites of runs. Obviously, there need to be some compromises made.

This study used a *minimum* of 1 minute idling time as a conditioning phase for each individual run. However, when the brakes discs had exceeded 300 deg C this conditioning phase was extended to allow the brakes to cool to 200 deg C. This should have had the effect of allowing the catalyst to cool for longer after a high loaded test attaining a more similar temperature at the start of the next test than if a fixed conditioning period was used. However, despite this potential benefit, the catalyst temperature was not directly controlled or monitored during any of these runs. One further possibility for improving repeatability would be to monitor catalyst temperature to ensure runs are started at similar catalyst temperatures. Unfortunately, current vehicles cannot provide a quantitative measure of catalyst temperature so this would require additional instrumentation and the fitting of a thermocouple into the catalyst substrate.

In contrast to CO and HC, relatively repeatable NO<sub>x</sub> measurements were recorded for the runs on the petrol Mondeo car. NO<sub>x</sub> were found to be correlated to both percentage load and throttle position for most engine speeds. One possible explanation is that the NO<sub>x</sub> catalyst was more stable than the oxidising catalyst over the range of conditions, or that the catalyst worked more efficiently over the range of conditions.

Despite achieving generally good correlations between NO<sub>x</sub> and load or throttle position at most fixed engine speeds, the correlation was still poor at 2000 rpm engine speed. This is not due to additional scatter in absolute terms but to the NO<sub>x</sub> emissions being relatively insensitive to load or throttle position at this specific engine speed (see figures 30 and 36). Moreover, the NO<sub>x</sub> emissions were lower at medium and high loads than at the other engine speeds. This observation is puzzling since NO<sub>x</sub> is sensitive to load and throttle position both above and below this engine speed. One possible explanation is that most of the 2000 rpm runs were performed at the start of the first or second day, presumably when the catalyst was cooler than during most of the other runs. However, catalysts generally become effective *above* a light off temperature. Note, the engines characteristics have not been examined independently of the catalyst, so other factors could be responsible.

Overall it is suggested that any future emissions measurements making use of the free rollers should ensure that the engine and catalyst are more fully preconditioned and that a consistent suite of runs are performed, although the ability to achieve this in practice may be limited.

### 5.3 Interpretation of the data from the OBD/CANBUS

One of the purposes of using the OBD output for this investigation was so the indicated engine load and engine speed readings could be used as independent variables to map the engine; however, this *load* reading is only an *implied load* output based on the output from an airflow sensor.

During the initial runs with the Passat car, it quickly became obvious that the maximum load reading from the OBD was limited to 30 to 60% depending on the engine speed. In contrast, the OBD load output from the petrol Mondeo was able to reach 100% at any engine speed.

Regulation 2.13 of the InterEurope Regulations 1997 (Council of European Communities 1997) refers to the OBD output standard. It states that the “ “Calculated load value” refers to an indication of the current airflow divided by the peak airflow.... and provides the service technician with an indication of the percent of engine capacity that is being used (with wide open throttle as 100%)”.

The last part of regulation 2.13 in brackets which states “with wide open throttle as 100%” could imply that the % load reading refers to the % of maximum load *at a particular engine speed*, although it ambiguous enough for the “peak airflow” to be interpreted as the maximum airflow under all engine conditions. It is possible that the OBD load output could have been set as such for the Passat. Another possibility is that there was a fault on the Passat which resulted in different OBD characteristics. For example, the Passat engine was turbocharged, and a failure for the turbocharger to maintain boost pressure would have some effect on the maximum airflow and therefore indicated

load. However, there were no obvious power limitations or other defects which were noticeable when driving the car.

Since for both cars the load reading appeared to stay constant at a constant throttle and speed, and it increased in a consistent manner in relation to throttle position, this did not prevent the use of the OBD load output being used as an independent variable for these runs, though there was some difficulty in establishing the precise meaning of the OBD % load readings. However, the interpretation of the load reading from the OBD does require further investigation.

#### 5.4 ABS system

During the initial runs on the Passat the ABS system was not disengaged and the ABS and traction control became de-activated. It was not possible to re-engage the ABS system without dealer assistance. Examination of the ABS system by a Volkswagen dealer could not find any physical damage to the brakes or ABS system and diagnosed a fault in the electronic ECU of the ABS management system. It was the view of the dealer that the fault was most likely caused by an electrical short during the instrumentation of the car although it seems possible that the differential speed between the front and back wheels may have been the cause.

Both of the Mondeo cars had their ABS systems deliberately disengaged by removal of a fuse. In both cases the ABS systems re-engaged successfully afterwards. In addition to an MOT test, the ABS systems on these cars were subsequently checked by a dealer without any defects being detected. However, the deliberate disengagement of the ABS caused specific fault codes to be activated by both vehicles OBD systems which were stored in the vehicle computer. These codes provide information to a service technician using an ABS diagnostic test that a low power supply or potential loose circuit has occurred in the recent past. These codes can be erased using the ABS diagnostic equipment or can be left to be erased automatically after a certain number of starts after the fault codes are generated.

The necessity of disengaging the ABS system prior to performing the measurement runs (and presumably any type of rolling road procedure) raises issues regarding the practicality of free-roller systems for roadside use. It is likely that all vehicles would require their ABS system disengaged before the procedure, then re-engaged afterwards. This may preclude the use of the free roller test in routine roadside monitoring since specific knowledge would be required across different models and manufacturers. The storing of fault codes is less of a problem, but it could confuse a technician if a vehicle was taken in for an ABS diagnostic test soon after a roadside test. Conversely, it is possible that the roller test could actually identify some brake problems and so improve safety. However, real or perceived difficulties in ensuring or proving that the safety of the vehicle has not been compromised may preclude the new type of test from routine use.

#### 5.5 Brake Temperatures

In view of the relatively unconventional manner of using the brakes for these experiments, the brake temperatures were monitored. A laser pyrometer was used to measure temperatures at three points on the passenger-side front brake disc after each individual run, and a spring loaded contact thermocouple rubbing on the inner side of the front passenger side brake disc was used to monitor temperatures continuously. Obviously the latter method could have created artificially high temperature readings due to friction, but in practice the pyrometer consistently measured higher temperatures than the thermocouple during the same test.

As an approximate indication of maximum acceptable brake disc temperatures, one particular manufacturer recommends that on installations running on *continuous* power input the discs should not exceed 370°C (see Kobelt undated). The maximum temperature intermittently measured during the roller runs was 377 °C, although the second highest temperature recorded was only 313 °C, with

most temperatures well below the 300 °C mark (See Appendix F). In addition, temperatures were compared with those measured during consecutive braking from 70 mph on the TRL test track, with several minutes interval between each test; although these track runs were stopped after exceeding 300°C.

The disc temperatures broadly determined the acceptable length of each roller run together with any subsequent waiting period, but this was variable depending upon the temperature reached on the previous test.

## **5.6 Extending range of measurements to include NO<sub>x</sub> and particulate**

Diesel engines still contribute significant NO<sub>x</sub> and particulate emissions to the environment (although it appears that the specific vehicle tested in this study did not produce high NO<sub>x</sub> concentrations). It is possible that the procedure could be extended to measure particulate using equipment which has become recently available in the US. Details of this equipment is included in Appendix H.

## **5.7 Concluding Comments**

Although this investigation has shown that the proposed roller system can be used to reproduce engine speed and load conditions throughout most of the engine operating range, and that emissions can be measured during these conditions, it has also yielded further questions. These questions include the apparent differences between vehicles in the way the OBD defines and calculates % load, the incidence of very low emission values beyond the resolution of basic analytical equipment, poor repeatability, the implications of disengaging & re-engaging the vehicles ABS system on safety, and interpretation of the OBD output. These issues need to be examined across a greater range of vehicle types with known faults. In general, it appears that the free-rolling dynamometer has potential to provide cheap emissions testing under measured speed and load conditions. However several issues need to be resolved before it could be used as a practical working method.

## **5.8 Returning the vehicle to the road**

The careful control of brake temperatures, together with a full MOT test and an ABS check performed by a main dealer would have been sufficient to ensure that the vehicles roadworthiness has not been compromised by the experiment reported here. However as an additional precaution it was decided to replace the front brake components with new ones before returning the vehicles to the public highway. This was to avoid any possibility of any subsequent accidents with these cars being attributed to the research described in this report. Obviously, if all vehicles subject to a roadside test required this amount of work, it would render the roller procedure unacceptable.

## 6 Conclusions and recommendations:

1. A new method for emissions testing has been explored using free running chassis rollers, engine load being applied by the vehicle brakes and garage type gas analysers for measuring emissions. Combined with information obtained via the engine OBD system, this method can measure mass emissions from the engine for short periods whilst it is subjected to various known engine speeds and loads.
2. This method requires applying the vehicle brakes for short periods which raises the temperature of the brake discs. The temperatures can be kept within acceptable levels during the run, providing the operating time is limited and there is a gap between each highly loaded run. The need to keep brake temperatures to an acceptable level does however limit prolonged high load runs which may be necessary to obtain stabilised speeds, loads and emissions.
3. The new method was used to measure the mass emissions of CO, HC and NO and values of lambda on 3 cars (2 petrol and 1 diesel) under a range of engine speeds and loads. It may be possible to extend this to other emissions such as particulate using additional equipment. However, the diesel car did not exhibit high enough emissions concentrations to be measured reliably by the analytical equipment used.
4. Measurements of NO emissions were generally far more repeatable than CO and HC emissions using the roller procedure. Despite this, the roller system may still be able to identify excessive CO and HC emissions caused by gross malfunctions such as lambda sensor or catalyst failure. Further work would be required to determine if the roller system provides more useful data than the current idle test for these emissions. Mass NO emissions on the petrol Mondeo were closely related to load and throttle position at most fixed engine speeds.
5. It is suspected that the poor repeatability in CO and HC emissions may be due to variations in the catalyst temperature and the variations in lambda when the engine management system is not controlling lambda to near stoichiometric conditions.
6. To validate the systems ability to identify high emitting vehicles it may be necessary to choose vehicles which are known to be emitting high levels of emission or to deliberately fit faulty emission related components to induce high emissions.
7. It appears that vehicle ABS & related systems have to be disengaged before performing any type of roller or chassis dynamometer measurement. Failure to do so may limit the vehicle engine speed and could create subsequent problems for re-engaging the ABS system, although this latter point still requires clarification. The need to temporarily disengage the ABS system may preclude the use of the new method as a roadside test, but this would be less of a problem if the roller procedure was used as part of the annual MOT due to the additional experience, time and facilities available.

If the free rolling dynamometer idea is to be continued the above conclusions imply a number of recommendations for further work.

1. The three cars used in the experiments should be examined for emissions on a standard chassis dynamometer over a range of steady state engine conditions and the NEDC regulatory cycle. Two of these cars should be examined on the road using on-board exhaust analysis equipment.

2. A standard roller procedure should be devised. A further five cars would need to be examined over the new roller procedure, in addition to a range of steady state engine conditions and the NEDC on a dynamometer.
3. To increase the number of measurement conditions and to ensure high emissions are produced, various emission sensitive components should be temporarily replaced with faulty components on these vehicles (catalyst, lambda sensor, air filter etc). Emissions would be measured before and after replacement to examine the effect of these faults and the efficiency of the new roller system at identifying high emitting vehicles
4. The problem of stabilisation of emissions during the reasonably short runs needs to be investigated further as does the interpretation of OBD outputs
5. The potential problems caused by a need to disengage ABS and related systems need further investigation. They have the potential to prevent the uptake of the new dynamometer for routine roadside testing.

## **7 Acknowledgements**

The work described in this report was carried out in the Infrastructure and Environment Group of TRL Limited. The author is grateful to Matt Sylvester for preparing vehicles and assisting in this research, Dr Tim Barlow for providing technical support in accessing the OBD systems of the vehicles.

## 8 References

**AP racing** <http://www.apracing.com/car/brakepad/temperature.htm> (Information on acceptable brake temperatures)

**Batmanuk (undated)** see <http://www.batmanuk.com/emissionanalysers.htm> 295 12v version

**Clear Skies News Sensors Inc (2003)** (on the road to clear skies) Vol 3.4 Oct 2003  
<http://www.sensors-inc.com/pdfs/CSN03-4.pdf>

**Council of European Communities (1970).** Council Directive 70/220/EEC Council Directive on the approximation of the laws of the Member States relating to the measures to be taken against the emissions from motor vehicles Official Journal L76, 6.4.70 (and subsequent directives to **2003/76/EC**)

**Council of European Communities (1972).** Council Directive 72/306/EEC of 2 August 1972 on the approximation of the laws of the Member States relating to the measures to be taken against the emission of pollutants from diesel engines for use in vehicles. Official Journal L190, 20/08/1972 pp1–23. (and subsequent directives up to 01/27/EEC)

**Council of European Communities (1992).** Council Directive 92/55/EEC amending Directive 77/143 on the approximation of the laws of the Member States relating to roadworthiness tests on motor vehicles and their trailers (exhaust emissions) (Official Journal L225 10.8.92) (and subsequent directives up to 2001/9/EEC). Implemented in the Road Vehicles Construction and use Amendment No 5 Regulations (1995) (SI 1195 No 2210)

**Council of European Communities (1997) L.91/49 15.3.98**

**Council of European Communities (2000).** Council Directive 1999/96/EC of the European Parliament and of the Council of 13 December 1999 on the approximation of the laws of the Member States relating to measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles and amending Council Directive 88/77/EEC. Official Journal L044, 16/02/2000 pp1-155.

**Council of European Communities (2000b).** Council Directive 1999/102/EC EC Type approval amendment (SI 2000 No. 869)

**Kobelt quality control,** [http://www.kobelt.com/34x2\\_specifications.html](http://www.kobelt.com/34x2_specifications.html) (Information on acceptable brake temperatures)

**Latham (1995)** TRL Project Report PR SE/099/95. A Preliminary Investigation Into the use of Improved In-service Emissions test Procedures for Road Vehicles, Safety & Environment Resource Centre, Transport Research Laboratory, Crowthorne, Berkshire, RG45 6AU. Version 3, June 23rd 1995

**Montgomerie, G (1997)** from the drawing board Commercial Motor London 1979-07-20 v150 n3817 p36-7 (ISSN 0010-3063)

**Norris J O W (2002).** An in-service emissions test for spark ignition engines. Phase 2b report appendix 2. Review of test procedures. Report EMStec/02/027, Issue 3 (<http://www.rmd.dft.gov.uk/project.asp?intProjectID=7909>).

**Bradley & Associates M. J. Inc (2004)** Investigation of Diesel Emission Control Technologies

on Off-Road Construction Equipment at the World Trade Center and PATH Re-Development Site  
Project Summary Report Submitted to The Port Authority of New York and New Jersey  
Materials Engineering Division by M.J. Bradley & Associates, Inc. 8030 South Willow St.  
Building 2, Suite 7 Manchester, NH 03103 August 9, 2004  
[http://www.mjbradley.com/documents/PANYNJ\\_WTC\\_Final\\_Report-09Aug04.pdf](http://www.mjbradley.com/documents/PANYNJ_WTC_Final_Report-09Aug04.pdf)

## Appendix A. Vehicle Specifications

### A.1 Specifications Ford Mondeo Diesel

Model type: Mondeo LX TDDI  
Type approval Number: E1\*98/14\*0156\*05  
Variant: D6BA1 5PBA PM Estate Diesel  
Engine Capacity: 1998 cc  
Registered: 20 05 2002  
Mass in service (Kg): 1547  
Registered emissions: (g/km)  
CO 0.076,  
NOx 0.43  
HC+NOx 0.454  
Particulates 0.044  
CO<sub>2</sub> 159

### A.2 Specifications Ford Mondeo Petrol

Model type: Mondeo LX  
Type approval Number E1\*98/14\*0155\*06  
Variant: CHBA1 5ZDA NB  
Engine Capacity: 1798 cc  
Registered: 03 07 2002  
Mass in service (Kg): 1396  
Registered emissions (g/km):  
CO 0.375  
NOx 0.091  
HC 0.077  
CO<sub>2</sub> 187

### A.3 Specifications Volkswagen Passat

EURO Level 4  
Model type: Passat Sedan 5v Turbo  
Engine Capacity: 1780 cc  
Mass in service (Kg): 1590  
Registered emissions: (g/km)  
CO 0.3  
NOx 0.018  
HC 0.014  
CO<sub>2</sub> 212.072

## **Appendix B. Pyrometer specification**

**Make:** Raytek Autopro (Non-contact Temperature Measurement) Infrared Thermometer for Automotive Diagnostics.

**Temp range:** -ve 32 to 535°C (-ve25 to 999°F).

**Accuracy:** +/- 1% @ 23°C (73°F).

**Response time:** 500ms.

**Features:** LED Area illumination.

MAX Temp display.

7 Second display hold.

LCD Backlit display \*C or \*F.

## Appendix C. Experimental data

### C.1 Experimental Results Passat

**Table A1 No. of Valid Runs Passat**

<b>Load</b>	<i>Engine Speed (RPM)</i>				
	<i>1500</i>	<i>2000</i>	<i>2500</i>	<i>3000</i>	<i>3500</i>
<b>10</b>	4	4	4	1	
<b>20</b>	10	3	4	6	1
<b>30</b>	1	8	4	2	1
<b>40</b>			5	6	2
<b>50</b>				3	4
<b>60</b>					4

**Table A2 Passat mean CO emissions (mg/s)**

<b>Load</b>	<i>Engine Speed(RPM)</i>				
	<i>1500</i>	<i>2000</i>	<i>2500</i>	<i>3000</i>	<i>3500</i>
<b>10</b>	0.36	0	2.02	0.69	
<b>20</b>	19.7	24.96	3.75	1.19	8.08
<b>30</b>	59.29	551.44	177.52	2.88	3.35
<b>40</b>			696.85	395.64	161.12
<b>50</b>				565.08	213.42
<b>60</b>					830.84

**Table A3 Passat standard deviation CO emissions (mg/s)**

<b>Load</b>	<i>Engine Speed(RPM)</i>				
	<i>1500</i>	<i>2000</i>	<i>2500</i>	<i>3000</i>	<i>3500</i>
<b>10</b>	0.71	0	4.04		
<b>20</b>	29.15	43.23	7.5	2.19	
<b>30</b>		267.44	132.76	3.8	
<b>40</b>			360.46	309.92	218.44
<b>50</b>				100.38	112.85
<b>60</b>					557.53

**Table A4 Passat mean HC emissions (mg/s)**

Load	Engine Speed(RPM)				
	1500	2000	2500	3000	3500
10	0.032	0.006	0.015	0.007	
20	0.024	0.029	0.017	0.032	0.051
30	0.03	0.11	0.042	0.581	0.053
40			0.193	0.215	0.151
50				0.066	0.097
60					0.21

**Table A5 Passat standard deviation HC emissions (mg/s)**

Load	Engine Speed(RPM)				
	1500	2000	2500	3000	3500
10	0.036	0.002	0.007		
20	0.02	0.014	0.006	0.026	
30		0.098	0.017	0.77	
40			0.112	0.237	0.095
50				0.07	0.029
60					0.203

**Table A6 Passat mean NO emissions (mg/s)**

Load	Engine Speed(RPM)				
	1500	2000	2500	3000	3500
10	0.61	0.61	0.33	0.02	
20	0.7	0.11	0.05	0.12	0.4
30	0.13	0.83	0.36	2.39	0.21
40			1.17	0.99	3.63
50				1.34	1.04
60					3.56

**Table A7 Passat standard deviation NO emissions (mg/s)**

Load	Engine Speed(RPM)				
	1500	2000	2500	3000	3500
10	1.08	0.81	0.58		
20	1.5	0.08	0.03	0.06	
30		0.38	0.13	1.78	
40			0.59	0.29	2.87
50				0.46	0.25
60					1.28

**Table A8 Passat mean lambda**

<b>Load</b>	<i>Engine Speed(rpm)</i>				
	1500	2000	2500	3000	3500
<b>10</b>	1.001	1	0.998	1.021	
<b>20</b>	0.997	1.002	1	1	1.001
<b>30</b>	0.994	0.96	0.988	0.991	1.001
<b>40</b>			0.955	0.974	0.992
<b>50</b>				0.965	0.985
<b>60</b>					0.961

**Table A9 Passat standard deviation lambda**

<b>Load</b>	<i>Engine Speed (rpm)</i>				
	1500	2000	2500	3000	3500
<b>10</b>	0.001	0.003	0.004		
<b>20</b>	0.004	0.009	0.001	0.001	
<b>30</b>		0.017	0.009	0.013	
<b>40</b>			0.019	0.013	0.012
<b>50</b>				0.011	0.01
<b>60</b>					0.028

## C.2 Experimental Results Petrol Mondeo

**Table A10 Number of valid runs petrol Mondeo**

<b>Throttle %</b>	<i>Engine speed (rpm)</i>					
	1500	2000	2500	3000	3500	4000
<b>20</b>	1		1	1	1	
<b>30</b>		8	4			1
<b>40</b>	3	2	8	3	3	3
<b>50</b>	3	3	6	3	3	3
<b>60</b>	3	3	5	3	3	3
<b>70</b>	1	3	6	3	3	3
<b>80</b>	3	2	7			

**Table A 11 Petrol Mondeo mean CO (mg/s)**

Throttle %	Engine Speed (rpm)					
	1500	2000	2500	3000	3500	4000
20	0.9		1.3	1.5	0	
30		0.8	3.5			57.7
40	2	0	6.1	0	4	0.4
50	2.1	0	3.8	1.8	43.5	5.2
60	2.2	0	3.1	0.6	1.4	498.7
70	330.2	565.4	1062.6	949.7	705.7	873.6
80	285.8	353.9	408.6			

**Table A 12 Petrol Mondeo mean CO (mg/s)**

Throttle %	Engine speed (rpm)					
	1500	2000	2500	3000	3500	4000
20	0.9		1.3	1.5	0	
30		0.8	3.5			57.7
40	2	0	6.1	0	4	0.4
50	2.1	0	3.8	1.8	43.5	5.2
60	2.2	0	3.1	0.6	1.4	498.7
70	330.2	565.4	1062.6	949.7	705.7	873.6
80	285.8	353.9	408.6			

**Table A 13 Petrol Mondeo standard deviation CO (mg/s)**

Throttle%	Engine speed (rpm)					
	1500	2000	2500	3000	3500	4000
20						
30		1.17	2.66			
40	0.63	0.00	6.20	0.00	2.12	0.77
50	0.04	0.00	0.59	2.95	68.84	0.61
60	0.04	0.00	1.30	1.00	1.56	857.58
70		179.63	289.11	191.67	424.84	210.22
80	12.13	5.52	133.78			

**Table A 14 Petrol Mondeo mean HC (mg/s)**

Throttle %	Engine speed ( rpm)					
	1500	2000	2500	3000	3500	4000
20	0.0009		0	0	0.0071	
30		0.0049	0.0009			0
40	0	0.0108	0.0049	0.0209	0	0.0071
50	0	0.027	0.0398	0.0824	0.089	0.0713
60	0.008	0.0045	0.0437	0.0132	0.027	0.4435
70	0.1256	0.4086	0.685	0.4343	0.3945	0.3198
80	0.1489		0.1579			

**Table A 15 Petrol Mondeo standard deviation HC (mg/s)**

Throttle%	Engine speed ( rpm)					
	1500	2000	2500	3000	3500	4000
<b>20</b>						
<b>30</b>	0.000	0.012	0.002			
<b>40</b>	0.000	0.015	0.007	0.012	0.000	0.009
<b>50</b>	0.000	0.009	0.030	0.014	0.048	0.039
<b>60</b>	0.007	0.008	0.024	0.009	0.028	0.690
<b>70</b>		0.265	0.360	0.194	0.392	0.174
<b>80</b>	0.032	0.043	0.063			

**Table A 16 Petrol Mondeo mean NO (mg/s)**

Throttle %	Engine speed RPM					
	1500	2000	2500	3000	3500	4000
<b>20</b>	0.015		0.022	0.024	0.023	
<b>30</b>		0.061	0.115			0.034
<b>40</b>	0.14	0.017	0.175	0.198	0.277	0.363
<b>50</b>	0.208	0.043	0.284	0.315	0.394	0.545
<b>60</b>	0.238	0.073	0.327	0.367	0.5	0.666
<b>70</b>	0.188	0.034	0.3	0.372	0.521	0.719
<b>80</b>	0.243		0.294			

**Table A 17 Petrol Mondeo standard deviation NO (mg/s)**

	<i>Engine Speed (rpm)</i>					
	1500	2000	2500	3000	3500	4000
<b>Throttle %</b>						
<b>20</b>						
<b>30</b>		0.065	0.045			
<b>40</b>	0.012	0.025	0.077	0.010	0.025	0.021
<b>50</b>	0.004	0.000	0.080	0.001	0.062	0.001
<b>60</b>	0.023	0.024	0.057	0.013	0.004	0.064
<b>70</b>		0.049	0.050	0.005	0.007	0.015
<b>80</b>	0.002	0.000	0.007			

**Table A 18 petrol Mondeo mean lambda**

<b>Throttle %</b>	<i>Engine Speed (rpm)</i>					
	1500	2000	2500	3000	3500	4000
<b>20</b>	1		1	1	0.992	0
<b>30</b>		1	0.987			1.024
<b>40</b>	1.001	1.003	0.992	1.007	1	1
<b>50</b>	1	1	1.001	1.021	0.998	1.001
<b>60</b>	0.997	0.993	1.004	1.029	0.982	0.986
<b>70</b>	0.981	0.966	0.935	0.92	0.937	0.959
<b>80</b>	0.996	0.961	0.978			

**Table A 19 petrol Mondeo standard deviation lambda**

<b>Throttle %</b>	<i>Engine Speed (rpm)</i>					
	1500	2000	2500	3000	3500	4000
<b>20</b>						
<b>30</b>		0.0009	0.0015			
<b>40</b>	0.0000	0.0065	0.0084	0.0012	0.0787	0.0089
<b>50</b>	0.0006	0.0000	0.0031	0.0031	0.0251	0.0280
<b>60</b>	0.0064	0.0007	0.0004	0.0014	0.0192	0.0226
<b>70</b>		0.0268	0.0302	0.0919	0.0329	0.0101
<b>80</b>	0.0767	0.0075	0.0640			

**Table A 20 petrol Mondeo mean NO v load**

<b>Load %</b>	<i>Engine speed RPM</i>					
	1500	2000	2500	3000	3500	4000
<b>30</b>		0	0.022	0.024	0.023	0.034
<b>40</b>	0.015	0				
<b>50</b>		0.093	0.13			
<b>60</b>		0.026				0.351
<b>70</b>	0.136		0.193	0.198	0.277	0.387
<b>80</b>		0.017	0.133		0.334	
<b>90</b>	0.163	0.086	0.259	0.315	0.424	0.545
<b>100</b>	0.229	0.036	0.312	0.37	0.511	0.692

**Table A 21 petrol Mondeo standard deviation NO v load**

<b>Throttle %</b>	<i>Engine speed RPM</i>					
	<i>1500</i>	<i>2000</i>	<i>2500</i>	<i>3000</i>	<i>3500</i>	<i>4000</i>
<b>30</b>						
<b>40</b>						
<b>50</b>		0.062	0.051			
<b>60</b>						0
<b>70</b>			0.083	0.01	0.025	
<b>80</b>		0.025				
<b>90</b>	0.039		0.098	0.047	0.046	0.001
<b>100</b>	0.025	0.034	0.042	0.009	0.013	0.051

## Appendix D. Summary Statistics

### Multiple linear models

A number linear models were applied to guide the interpretation of the relationship between emissions, engine speed, engine load and throttle positions. If a statistically significant relationships were found, then the relative change in emissions was used to examine the sensitivity to these variables across the range.

#### D.1 CO analysis Passat

The equation of the fitted model is:

$$\text{CO mg per sec} = -41.068 - 0.128561 * \text{engine speed rpm} + 20.686 * \text{Load \%}$$

$$\text{CO change due to change in load range} = 1034$$

$$\text{CO change due to change in engine speed range} = -256$$

Since the p-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 46% of the variability in CO mg per sec. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 45%.

#### D.2 HC analysis Passat

The output shows the results of fitting a multiple linear regression model to describe the relationship between HC mg per sec and 2 independent variables. The equation of the fitted model is

$$\text{HC mg per sec} = -0.0657679 + 0.0000201923 * \text{engine speed rpm} + 0.00380535 * \text{Load \%}$$

$$\text{HC change due to change in load range} = 0.19$$

$$\text{HC change due to change in engine speed range} = 0.0404$$

Since the p-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 13.422% of the variability in HC mg per sec. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 11.05%.

### **D.3 NO Analysis Passat**

The output shows the results of fitting a multiple linear regression model to describe the relationship between NO mg per sec and 2 independent variables. The equation of the fitted model is

$$\text{NO mg per sec} = -0.570576 + 0.0000366342 * \text{engine speed rpm} + 0.0484132 * \text{Load \%}$$

NO change due to change in load range = 2.42 mg/sec

NO change due to change in engine speed range = 0.0732 mg/sec

Since the p-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 30% of the variability in NO mg per sec. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 29%.

### **D.4 CO & HC Analysis Mondeo:**

Due to the stepwise response of these emissions to engine load and throttle position for this vehicle no formal model or statistical analysis was applied for these emission types

### **D.5 NO Analysis Petrol Mondeo**

The equation of the fitted model is

$$\text{NO mg per sec} = -0.441792 + 0.000169425 * \text{engine speed rpm} + 0.004686 * \text{Throttle \%}$$

NO change due to change in throttle range = 0.281

NO change due to change in engine speed range = 0.4235

Since the p-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

The R-Squared statistic indicates that the model as fitted explains 67% of the variability in NO mg per sec. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 66%.

## Appendix E. Meteorological Data

Date	GMT Hrs	Min	Description	Dry Temp	Rel humid.	Pressure	Wind dir.	Wind (m/s)
12-Sep-05	9	33	Roller Passat	18.9	68.1	1005	349.9	0.56
12-Sep-05	10	49		20.1	64.6	1005	14.9	0.2
12-Sep-05	12	50		22.6	59.4	1006	27.9	0.46
12-Sep-05	15	57		21.8	58.2	1005	184.9	0.18
13-Sep-05	9	0	Track Passat	18.5	77.9	1009	108	2.46
13-Sep-05	9	23	Roller Passat	19.9	72.3	1009	115.9	1.46
13-Sep-05	10	30		21.8	64.3	1009	108.9	4.08
13-Sep-05	12	31		22.8	57.8	1008	107.1	3.9
13-Sep-05	13	41		24.1	49.6	1007	110	4.4
17-Oct-05	12	5	Roller P Mondeo	17.35	80.4	1005	129.1	1.72
17-Oct-05	14	48		17.35	82.2	1004	289.8	0.32
18-Oct-05	8	28		10.8	82.1	999	227.9	2.98
18-Oct-05	11	23		12.45	76.3	998	213.8	3.9
09-Nov-05	16	8	Track P Mondeo	10.95	69.1	1010	97.9	4.1
06-Dec-05	10	12						
06-Dec-05	11	26						
06-Dec-05	14	13						
06-Dec-05	15	58						

NB: All data from M4 Theale site except pressure from M25 Staines site

## Appendix F. Temperature of brake discs

The graphs below illustrate the temperature of the front passenger side brake disc as measured by a radiation pyrometer as a function of time from the start of the procedure. Also shown are the same brake disc temperatures as measured during braking on the TRL long straight from 70mph.

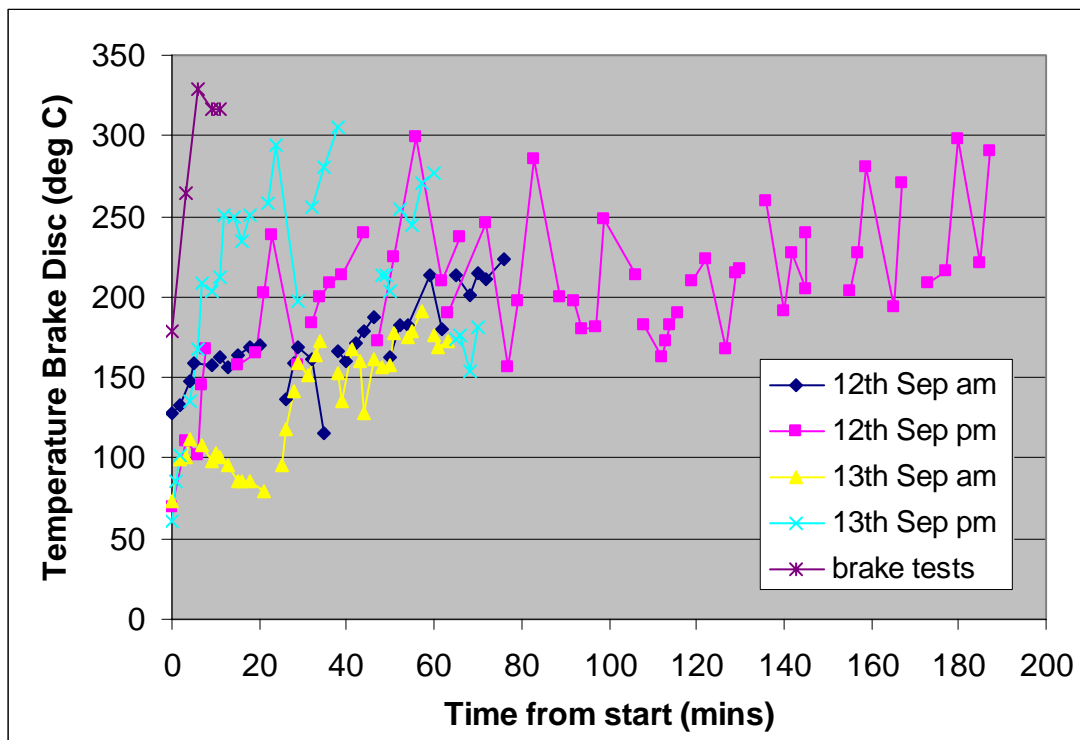


Figure A1 Temperature of front passenger side brake disc Passat

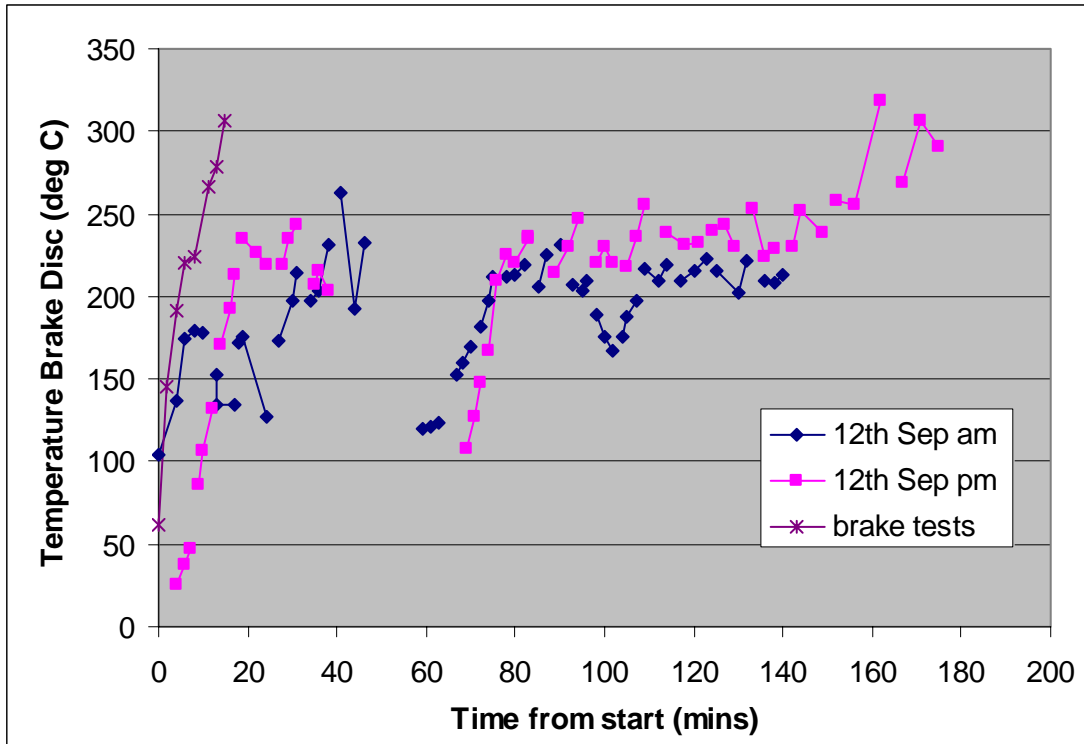


Figure A2 Temperature of front passenger side brake disc petrol Mondeo

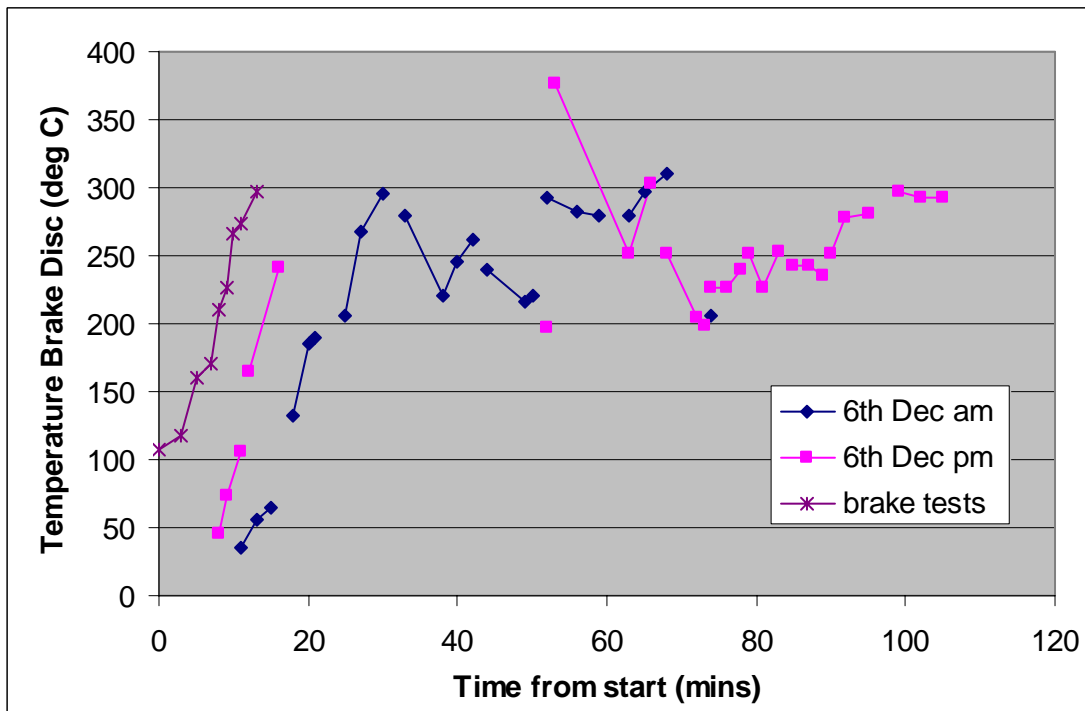


Figure A3 Temperature of front passenger side brake disc Diesel Mondeo

### Appendix G. Run order and laboratory notebook data

**Table A 22 Laboratory notebook data: Volkswagen Passat**

Date	Time BST	Time	Time elapsed	Target Speed	Appro x Load	Temp cont	Temp non-cont	Comments
	(hrs)	(min s)	(s)	(RPM)	(%)	(deg C)	(deg C)	
			0				178.8	Braking runs
			3				264.6	
			6				328.3	
			9				316.1	
			11				317	
12-Sep-05	10	33	0	1500	20		128	5th Gear
	10	35	2	1500	20		133	
	10	37	4	1500	20		148	
	10	38	5	1500	20		159	
	10	42	9	1500	20		158	
	10	44	11	2000	20		163	
	10	46	13	2000	20		156	
	10	48	15	2000	20		164	
	10	51	18	2000	20		169	
	10	53	20	2000	20		170	
	10	59	26	2500	20		137	
	11	1	28	2500	20		159	
	11	2	29	2500	20		169	
	11	5	32	2500	20		161	
	11	8	35	2500	20		115	After stall
	11	11	38	3000	20		166	
	11	13	40	3000	20		160	
	11	15	42	3000	20		171	
	11	17	44	3000	20		179	
	11	19	46	3000	20		188	
	11	23	50	3500	20		162	4th Gear
	11	25	52	3500	20		182	
	11	27	54	3500	20		182	
	11	32	59	3500	20		213	After Stall
	11	35	62	3500	20		180	
	11	38	65	4000	20		213	3rd Gear
	11	41	68	4000	20		201	
	11	43	70	4000	20		215	
	11	45	72	4000	20		211	
	11	49	76	4000	20		224	

Date	Time BST	Time	Time elapsed	Target Speed	Appro x Load	Temp cont	Temp non-cont	Comments
	(hrs)	(min s)	(s)	(RPM)	(%)	(deg C)	(deg C)	

12-Sep-05	13	50	0	4500	20		70	
	13	53	3	4500	20		110	
	13	56	6	4500	20		102	
	13	57	7	4500	20		145	
	13	58	8	4500	20		167	
	14	5	15	1500	25		158	5th gear
	14	9	19	1500	25		165	
	14	11	21	1500	25		202	
	14	13	23	1500	25		238	
	14	19	29	1500	25		158	
	14	22	32	2000	34		184	
	14	24	34	2000	34		200	
	14	26	36	2000	34		209	
	14	29	39	2000	34		214	
	14	34	44	2000	34		240	
	14	37	47	2500	42		172	
	14	41	51	2500	42		225	
	14	46	56	2500	42		299	
	14	52	62	2500	42		210	
	14	56	66	2500	42		237	
	14	53	63	3000	45		190	Stop=50mm
	15	2	72	3000	45		246	
	15	7	77	3000	45		157	
	15	9	79	3000	45		197	
	15	13	83	3000	45		285	
	15	19	89	3000	45		200	
	15	22	92	3500	50		197	4th Gear
	15	24	94	3500	50		180	
	15	27	97	3500	50		181	
	15	29	99	3500	50		248	
	15	36	106	3500	50		213	
	15	38	108	1500	22		183	
	15	42	112	1500	22		163	
	15	43	113	1500	22		173	
	15	44	114	1500	22		182	
	15	46	116	1500	22		190	
	15	49	119	2000	22		210	
	15	52	122	2000	22		224	
	15	57	127	2000	22		167	
	15	59	129	2000	22		215	
	16	0	130	2000	22		217	
	16	6	136	2500	22		259	
	16	10	140	2500	22		191	
	16	12	142	2500	22		227	
	16	15	145	2500	22		205	
	16	15	145	2500	22		240	
	16	25	155	3000	22		203	
	16	27	157	3000	22		227	
	16	29	159	3000	22		280	

	16	35	165	3000	22		193	
	16	37	167	3000	22		271	
	16	43	173	3500	22		209	
	16	47	177	3500	22		216	
	16	50	180	3500	22		298	
	16	55	185	3500	22		221	
	16	57	187	3500	22		290	

Date	Time	Time	Time	Target	Approx	Temp	Temp	Comments
	BST		elapsed	Speed	Load	cont	non-cont	
	(hrs)	(min s)	(s)	(RPM)	(%)	(deg C)	(deg C)	
13-Sep-05	10	23	0	1500	12	73		5th Gear
	10	25	2	2000	12	99		stop 44mm
	10	26	3	1500	12	101		
	10	27	4	1500	12	112		
	10	30	7	2000	12	108	119	
	10	32	9	2000	12	98	121	
	10	33	10	2000	12	103	127.3	
	10	34	11	2500	15.3	100	119.5	
	10	36	13	2500	14.5	95	112	
	10	38	15	2500	14.1	86	101.5	
	10	39	16	3000	16.1	86	101.8	
	10	41	18	3000	16.1	86	93.3	
	10	44	21	3000	16.1	80	94.4	
	10	48	25	1500	16.5	95	120	stop 45mm
	10	49	26	1500	16.5	118	148.9	
	10	51	28	1500	16.5	142	174.8	
	10	52	29	2000		159	191.7	Analyser fault
	10	54	31	2000		152	191	
	10	56	33	2000		164	198.3	
	10	57	34	2000		172	223	
	11	1	38	2500		153	189	
	11	2	39	2500		135	169.1	
	11	4	41	2500		168	202	
	11	6	43	3000		160	190.2	
	11	7	44	3000		128	190.6	
	11	9	46	3000		161	198.3	
	11	11	48	3500		156	186	4th Gear
	11	13	50	3500		158	196	
	11	14	51	3500		178	213	
	11	17	54	4000		175	221.7	
	11	18	55	4000		179	210	
	11	20	57	4000		191	254.5	
	11	23	60	4500		176	211	

	11	24	61	4500		169	242	
	11	26	63	4500		173	220.8	
	11	30	67	1500	6.7		5th Gear	
				2000	8.6			
				2500	11			
				3000	14.5			

Date	Time BST	Time (hrs)	Time (mins)	Time elapsed (s)	Target Speed (RPM)	Approx Load (%)	Temp cont (deg C)	Temp non-cont (deg C)	Comments
13-Sep-05	13	31	0	0	1500	22	53	61	5th
	13	32	1	1	1500	22	66	86	
	13	33	2	2	1500	22	90	102	
	13	35	4	4	2000	35	105	135	
	13	37	6	6	2000	35	112	167	
	13	38	7	7	2000	34	169	208	
	13	40	9	9	2500	32	172	204	
	13	42	11	11	2500	32	163	212	
	13	43	12	12	2500	32	193	251	
	13	45	14	14	3000		188	250	
	13	47	16	16	3000	39.6	193	235	
	13	49	18	18	3000	39.2	188	251	
	13	53	22	22	3500		203	258	4th
	13	55	24	24	3500	48.2	231	294	
	14	0	29	29	3500		162	197	
	14	3	32	32	4000		219	256	3rd
	14	6	35	35	4000		201	281	
	14	9	38	38	4000		256	305	
	14	12	41	41	1500				No Brake
	14	13	42	42	2000				No Brake
	14	13	42	42	2500				No Brake
	14	14	43	43	3000				No Brake
	14	15	44	44	3500				No Brake
	14	16	45	45	4000				No Brake
	14	16	45	45	4500				No Brake
	14	18	47	47	1500		125		Full throttle
	14	19	48	48	2000		165	213	Full throttle
	14	20	49	49	2500		151	214	Full throttle
	14	21	50	50	3000		170	204	Full throttle
	14	23	52	52	1500		195	255	Full throttle
	14	26	55	55	2000		195	244	Full throttle
	14	28	57	57	2500		191	271	Full throttle
	14	31	60	60	3000		209	277	Full throttle
	14	36	65	65	1500		152	174	Full throttle

	14	37	66	2000		176	176	Full throttle
	14	39	68	2500		154	154	Full throttle
	14	41	70	3000		185	181	Full throttle

**Table A 23 Laboratory notebook data: petrol Ford Mondeo**

Date	Time BST	Time	Time elapsed	Target Speed	Target Throttl e	Appro x Load	Temp cont	Temp non- cont	Comments
	(hrs)	(mins )	(min)	(RPM)		(%)	(deg C)	(deg C)	
17-Oct-05	13	5	0	2000	22.4	34.5	21.5		No brake
	13	12	7	1500	20.4	36.1			
	13	14	9	2000	21.2	32.2	21.5		
	13	15	10	2500	22	31	25.7		
	13	16	11	3000	22.4	30.2	26.8		
	13	17	12	3500	22.4	27.8	29.8		
	13	18	13	4000	25.5	29.4	31.7		
	13	28	0	2500	40		72.8	104	brake used
	13	32	4	2500	40		91.9	137	
	13	34	6	2500	40		85.8	174	
	13	36	8	2500	40	75	91.1	179	
	13	38	10	2500	40	75	120	178	
	13	41	13	2500	30	47	152	152	
	13	41	13	2500	30	47	134	134	
	13	45	17	2500	30	47	135	135	
	13	46	18	2500	50	93	172	172	
	13	47	19	2500	50	93	176	176	
	13	52	24	2500	50	93	127	127	
	13	55	27	2500	60	98	139	173	
	13	58	30	2500	60		165	197	
	13	59	31	2500	60		177	214	
	14	2	34	2500	70		176	197	
	14	4	36	2500	70		158	204	
	14	6	38	2500	70		181	231	
	14	9	41	2500	80		162	263	
	14	12	44	2500	80		156	193	
	14	14	46	2500	80		163	232	
	14	27	59	1500	30		62.7	120	
	14	29	61	1500	30		71.5	121	
	14	31	63	1500	30		74.3	123	
	14	35	67	1500	40		109.9	152	
	14	36	68	1500	40		114	160	
	14	38	70	1500	40		119	170	
	14	40	72	1500	50		137.3	182	
	14	42	74	1500	50		132	198	
	14	43	75	1500	50		150.7	212	

	14	46	78	1500	60		151	212	
	14	48	80	1500	60		150	213	
	14	50	82	1500	60		147	219	
	14	53	85	1500	70		144	206	
	14	55	87	1500	70		152	225	
	14	57	89	1500	70				
	14	58	90	1500	70		145	231	
	15	1	93	1500	80		123	207	
	15	3	95	1500	80		135	204	
	15	4	96	1500	80		127	209	
	15	6	98	2500	30		111	189	
	15	8	100	2500	30		99	176	
	15	10	102	2500	30		101	167	
	15	12	104	2500	40		115	176	
	15	13	105	2500	40		108	188	
	15	15	107	2500	40		128	198	
	15	17	109	2500	50		141	217	
	15	20	112	2500	50		126	210	
	15	22	114	2500	50		136	219	
	15	25	117	2500	60		159	210	
	15	28	120	2500	60		136	216	
	15	31	123	2500	60		149	223	
	15	33	125	2500	70		170	216	
	15	38	130	2500	70		138	202	
	15	40	132	2500	70		144	222	
	15	44	136	2500	80		154	210	
	15	46	138	2500	80		140	208	
	15	48	140	2500	80		155	213	

Date	Time BST	Time (mins)	Time elapsed (min)	Target Speed (RPM)	Target Throttl e	Appro x Load (%)	Temp cont (deg C)	Temp non- cont (deg C)	Comments
18-Oct-05	9	28	0	2000	30				
	9	32	4	2000	30		18.8	26	
	9	34	6	2000	30		20.1	37	
	9	35	7	2000	30		28.2	47	
	9	37	9	2000	40		45.9	86	
	9	38	10	2000	40		55.1	106	
	9	40	12	2000	40		73.5	132	
	9	42	14	2000	50		117	171	
	9	44	16	2000	50		142	193	
	9	45	17	2000	50		147	213	
	9	47	19	2000	60		144	235	
	9	50	22	2000	60		132	227	
	9	52	24	2000	60		122	219	

	9	56	28	2000	70		138	219	
	9	57	29	2000	70		145	235	
	9	59	31	2000	70		138	243	
	10	3	35	2000	80		125	207	
	10	4	36	2000	80		114	216	
	10	6	38	2000	80		110	204	
	10	37	69	3000	40		66.8	108	
	10	39	71	3000	40		80.1	127	
	10	40	72	3000	40		73.9	148	
	10	42	74	3000	50		114	167	
	10	44	76	3000	50		140.8	209	
	10	46	78	3000	50		149	225	
	10	48	80	3000	60		140.6	220	
	10	51	83	3000	60		161.6	235	
	10	51	83	3000	60		133	236	
	10	57	89	3000	70		138	214	
	11	0	92	3000	70		139	230	
	11	2	94	3000	70		148	247	
	11	6	98	3500	40		135	220	
	11	8	100	3500	40		126	230	
	11	10	102	3500	40		128	221	
	11	13	105	3500	50		146	218	
	11	15	107	3500	50		144	236	
	11	17	109	3500	50		166	256	
	11	22	114	3500	60		165	239	
	11	26	118	3500	60		145	231	
	11	29	121	3500	60		154	232	
	11	32	124	3500	70		162	240	
	11	35	127	3500	70		164	244	
	11	37	129	3500	70		152	230	
	11	41	133	4000	40		173	253	
	11	44	136	4000	40		139	224	
	11	46	138	4000	40		121	229	
	11	50	142	4000	50		157	230	
	11	52	144	4000	50		173	252	
	11	57	149	4000	50		182	238	
	12	0	152	4000	60		179	258	
	12	4	156	4000	60		172	255	
	12	10	162	4000	60		209	318	
	12	15	167	4000	70		149	269	
	12	19	171	4000	70		188	306	
	12	23	175	4000	70		177	291	

**Table A 24 Laboratory notebook data: Diesel Ford Mondeo**

Date	Time BST	Time	Time elapsed	Target Speed	Target Throttle %	Injection Quantity	Temp Thermo.	Temp Pyrom.	Comments
	(hrs)	(mins)	(s)	(RPM)		cc/stroke	(deg C)	(deg C)	
06-Dec-05	10	12	0	1500	16		8.4		No Load
	10	14	2	2000	19.5		10.4		No Load
	10	16	4	2500	25		11.5		No Load
	10	23	11	1500	20		16	36	
	10	25	13	1500	20		23.6	56	
	10	27	15	1500	20		25.9	65	
	10	30	18	1500	40		52.8	133	
	10	32	20	1500	40		84.4	186	
	10	33	21	1500	40		95.2	190	
	10	37	25	1500	60		100	206	
	10	39	27	1500	60		142	267	
	10	42	30	1500	60		131	296	
	10	45	33	1500	80		127	279	
	10	50	38	1500	80		121	221	
	10	52	40	1500	80		137	245	
	10	54	42	1500	80		141	262	
	10	56	44	2000	40		137	239	
	11	1	49	2000	40		118	216	
	11	2	50	2000	40		125	221	
	11	4	52	2000	60		140	293	
	11	8	56	2000	60		180	282	
	11	11	59	2000	60		168	280	
	11	15	63	2000	80		170	280	
	11	17	65	2000	80		221	297	
	11	20	68	2000	80		212	310	
	11	26	74	2500	40		116	206	

Date	Time BST	Time	Time elapsed	Target Speed	Target Throttle %	Injection Quantity	Temp Thermo.	Temp Pyrom.	Comments
	(hrs)	(mins)	(s)	(RPM)	(Roll Load)	cc/stroke	(deg C)	(deg C)	
06-Dec-05	14	13	0	1500			11.5		
	14	19	6	2500	40		18.1		
	14	21	8	2500	40			45	
	14	22	9	2500	40		32.2	74	
	14	24	11	2500	40		47.2	106	
	14	25	12	2500	60		93.5	165	
	14	29	16	2500	60		142	241	
				2500	60		148.8	266	
				2500	60		173	274	
				3000	80		171	313	
				3000	80		69	168	

				3000	80		147	251	
				3000	40		93.4	171	
				3000	40		81	157	
				3000	40		95	191	
	15	5	52	3000	40		105.5	197	
	15	6	53	3000	60		223	377	
	15	16	63	3000	60		157	251	
	15	19	66	3000	60		168	303	
	15	21	68	1500	100		133	251	
	15	25	72	1500	100		108	204	
	15	26	73	1500	100		110	198	
	15	27	74	2000	100		122	227	
	15	29	76	2000	100		140	226	
	15	31	78	2000	100		140	240	
	15	32	79	2500	100		152	251	
	15	34	81	2500	100		157	226	
	15	36	83	2500	100		129	253	
	15	38	85	1500	80		122	242	
	15	40	87	1500	80		156	242	
	15	42	89	1500	80		129	235	
	15	43	90	2000	80		146	252	
	15	45	92	2000	80		158	278	
	15	48	95	2000	80		192	281	
	15	52	99	2500	80		211	297	
	15	55	102	2500	80		184	293	
	15	58	105	2500	80		169	292	

## Appendix H. PROTOTYPE IN-SERVICE EQUIPMENT

### H.1 SEMTECH QCM/MPS

#### PM measurement systems

Sensors Inc. market two products designed by Booker Systems Ltd: the SEMTECH QCM (Quartz Crystal Microbalance) and MPS (Micro-Proportional Sampler). These allow dynamic mass measurement of the particulate matter in engine exhaust (Clear Skies News 2003).

The SEMTECH QCM uses the principle of electrostatic precipitation, whereby particles are collected from a known volume of air and deposited on an oscillating piezoelectric crystal. The natural oscillation frequency of the crystal varies in proportion to the amount of material deposited on its surface. By measuring these shifts in frequency, the SEMTECH QCM can calculate the mass of the particulate matter with a resolution approaching one nanogramme. Operation of the QCM at such a high frequency also makes the system immune to shock and vibration. The SEMTECH QCM offers several features, including:

- Traceability and precise direct mass measurement
- Fast response with high sensitivity
- Configurable for short, high-mass deposits or long-term sampling in workplace or ambient outdoor environments
- Small size and lightweight for portable applications
- 

To complement the QCM, the MPS was developed to permit transient in-use measurements. The SEMTECH MPS delivers response times of 0.1s and operational speeds of greater than 5 Hz. In addition, the compact unit is powered from a 12 VDC supply.

#### Gaseous emissions measurement system

Sensors Inc. also market the SEMTECH-D, which is an on-board system that simultaneously measures and records gaseous exhaust constituents (NO, NO<sub>2</sub>, CO, CO<sub>2</sub> and THC) with an accuracy of  $\pm 3-4\%$  of the reading. The SEMTECH-D system uses non-dispersive ultraviolet (NDUV) analysis to detect NO and NO<sub>2</sub>, NDIR to detect CO and CO<sub>2</sub>, and a FID to detect total hydrocarbons.

In electronically-controlled engines, the reporting can be also done in mass units such as g/bhp-hr or g/mile. For engines without electronic controls, additional instrumentation is provided to deliver g/bhp-hr figures.

The SEMTECH-D system has dimensions of 22"D×17"W×14"H with a weight of around 30 kg. Information can be retrieved remotely using a wireless, cellular or satellite link or it can be taken directly from the unit's message centre. The SEMTECH-D can also be rack-mounted or operated on a cart, for laboratory work.

The system is offered for engine and vehicle OEMs, research organizations, and commercial laboratories to perform such tasks as collection of engine performance data under real world conditions, engine and vehicle sub-system development, catalyst and particulate filter testing and vehicle compliance testing.

#### Use and validation

According to the manufacturer, recent testing by Caterpillar with a CAT C-10 engine showed good correlation between SEMTECH-D and laboratory results. Caterpillar also state that the Environmental Protection Agency has tested over 40 prototype and production vehicles equipped with the

SEMTECH on board system, including vehicles claiming partial zero emissions (PZEVs), or super ultra low emission vehicles (SULEVs) and alternative fuel vehicles running on hydrogen, biodiesel, LPG and compressed natural gas.

## H.2 Portable Emissions Measurement Systems (PEMS)

Clean Air Technologies in the United States have developed a range of Portable Emissions Measurement Systems (PEMS) for gasoline and diesel vehicles. The unit provides HC, CO, CO<sub>2</sub> (NDIR), NO<sub>x</sub> and O<sub>2</sub> (electrochemical cell) readings for gasoline-powered vehicles and NO<sub>x</sub>, CO, CO<sub>2</sub>, O<sub>2</sub>, PM readings for diesel vehicles. An account of using this equipment on heavy duty Diesel engines is found in (Bradley & Associates, Inc.2004)

The gas analyzer system is typical of five-gas analyzers commonly used for emissions inspection and maintenance programs, with minor modifications to obtain better stability, detection limit and response time. This uses NDIR (non-dispersive infra-red) analyzer, which simultaneously measures the concentrations of hydrocarbons (measured and reported as hexane), CO and CO<sub>2</sub>. and two electrochemical cells, one measuring nitric oxide (NO) and the other O<sub>2</sub>.

To measure PM, condensed water is separated from the sample using a water separation bowl. The sample is then heated and split into two parallel streams, with one stream being drawn at a large angle from the main stream of sample flow. Each parallel stream is then passed through two laser beams. A layer of filtered air is formed around the sample to protect the optics. A photo detector mounted away from the path of laser beam detects the intensity of the light scattered by the particles. The sample is then filtered and exhausted by an internal sample pump. The correlation of the response with particle mass, total surface area or count is dependent on the particle size distribution and the size of elemental and organic fractions. Preliminary comparison tests show relatively good correlation of the response with total particle mass, under a wide range of operating conditions.

Pollutant concentrations are obtained from a standard sample probe inserted into the tailpipe. On newer vehicles, the engine operating data are obtained from the on-board diagnostics port. On older vehicles, the engine operating data are obtained through a set of temporarily mounted sensors. On spark ignited engines, the engine speed is measured by an inductive pickup clamped around a spark plug wire. On diesel engines, the engine rpm are measured by a piezoelectric sensor clamped around a fuel line between the injection pump and injector which senses pressure pulses corresponding to individual injections.

The Montana System is available in a weather-tight case for outdoor off-road applications in a portable 20 kg unit which can be quickly installed, in 5-20 minutes, without any physical modification to the vehicle. The system uses power directly from a vehicle's 12V or 24V electrical system, consuming 8 A at 12V DC, or can be powered by AC in the case of stationary testing. The power necessary to run PEMS can be obtained either from the vehicle electrical system, or from an independent source, typically a battery bank or an on-board generator. The system samples raw, undiluted exhaust using an unheated sample line running from the sample probe attached to the tailpipe using a hose clamp, and into the vehicle, typically through a partially open window.

Data collected simultaneously collected using PEMS and laboratory-standard equipment and the portable system. The laboratory PM equipment included a tapered element oscillating microbalance (TEOM), as well as a filter-based system. For PM, there was a good correlation between the PEMS light-scattering method and the TEOM, but not when comparing the light scattering results with the filter-based measurements Comparison of the portable system and traditional laboratory results for three full-size diesel pickups shows a strong correlation between both modal and total NO<sub>x</sub> and CO<sub>2</sub> emissions.