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The Inspection of In-Use Cars in Order to Attain Minimum Emissions of Pollutants and Optimum Energy Efficiency

Detailed Report 6 - Remote Sensing

by TRL

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REMOTE SENSING

by T J Barlow

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Laboratory based emission testing over many years have shown that a large number of vehicles on the road have excessive emissions. It has also been reported that a small proportion of the vehicles on the road account for a very high proportion of the total emissions.

Identifying and correcting these high polluting vehicles could lead to a worthwhile reduction in total vehicle emissions. One way of identifying these vehicles is through an inspection and maintenance (I/M) programme. This encourages the owners to keep the vehicles in a good state of repair and the service industry to do the maintenance properly.

However, inspection and maintenance programmes rely on periodic inspections which can be one or two years apart. Between the inspections, the exhaust emissions could deteriorate dramatically. One way of supplementing an inspection and maintenance programme is the use of random roadside inspections. However, this is very labour intensive and, because it is random, will have varying success at identifying high emitting vehicles.

An alternative is to use a remote sensing system that can measure the exhaust emissions of the vehicles as they drive normally. This could either be used as a pre-screening tool to target vehicles for roadside checks or to identify possible high emitting vehicles and subsequently request the vehicle owner to submit the vehicle for testing at a local inspection and maintenance test station. Remote sensing could also be used as a means of judging the effectiveness of the local inspection and maintenance programme.

To judge the effectiveness of remote sensing, the current 'FEAT' remote sensing device owned by TRL has been operated in five locations - Thessaloniki; Greece, Lyon; France, Delft; The Netherlands and Emberton & Leicester; UK. In addition to remote sensing, a sample of vehicles passing through the system were stopped for roadside idle tests. A further sub-sample of vehicles were selected for a series of dynamometer tests.

In total, remote sensing readings from over 83,000 vehicles passing through the system were recorded, with over 76,000 valid carbon monoxide (CO) readings. 1046 vehicles were subjected to a roadside idle test and 47 vehicles were further investigated on a chassis dynamometer with 16 of these vehicles repeat tested after undergoing repairs.

Comparison of the overall remote sensing readings with the idle test results does not show a very good agreement. However, comparison of the remote sensing readings with dynamometer test results for CO emissions shows a much better agreement. This indicates that although remote sensing might be unable to detect vehicles with slightly high emissions, it can detect the gross emitting vehicles. Using just a cutpoint of 5% for CO, in addition to detecting vehicles with high CO, vehicles with high hydrocarbons (HC) were also detected in the sample subjected to dynamometer tests. It is also possible that vehicles with high oxides of nitrogen (NO_X) emissions can be detected using a remote sensing cutpoint of about 1% nitric oxide (NO), although the sample did not contain enough vehicles with high NO_X emissions to confirm this.

Based on the sample of vehicles subjected to dynamometer tests, analysis of the data shows a high Emission Reduction Rate Potential (ERRP) for carbon monoxide and hydrocarbon emissions (68% and 47% respectively), a reduction in oxides of nitrogen emissions and fuel consumption (12% and 16% respectively) and a 5% increase in carbon dioxide emissions. The reason for the increase in the carbon dioxide emissions is that the faults decrease the combustion efficiency of the engine, resulting in fuel wastage which produces high carbon monoxide and hydrocarbon emissions but lowers the carbon dioxide emissions. When the fault is repaired, the carbon dioxide emissions are restored to normal, with reductions in the carbon monoxide and hydrocarbon emissions. These ERRPs are based on just a CO cutpoint (5% CO). The inclusion of an NO cutpoint (1% ?) would modify these values, possibly increasing the NO_X reduction and decreasing the CO and HC values.

Analysis of the remote sensing data - taking into account the vehicle age as indicated by the registration number - shows that about 3% of the fleet of catalyst equipped vehicles in Greece could be gross emitters (using a remote sensing cutpoint of 5% CO). For the UK, the figure is only 0.5%, presumably due to the relatively recent introduction of catalyst cars Although this sounds like a small number, the gross emitting vehicles detected in the sample had CO emission rates up to 30 times the legislative emissions limit and HC emission rates up to 14 times the limit.

Assuming that 3% of the catalyst-petrol fleet have average CO emissions 20 times the emissions limit and the remaining 97% have average CO emissions equal to the limit, then the gross emitting vehicles will be responsible for nearly 40% of the total emissions - clearly these 3% produce a significant contribution to the total emissions and targeting just them could significantly reduce total emissions.

It is therefore concluded that remote sensing would be a useful tool in identifying these gross emitting vehicles, with the following recommendations:

- Remote sensing should be carried out at a site over a few weeks. Modern vehicles with a high number of repeat readings and a high average should be further investigated (initially using a cutpoint of 5% CO, but this could be modified according to the site location and the condition of the local traffic - investigations could be carried out on 5% of the traffic with the highest emissions).
- Further investigation could also be carried out on vehicles that produce high NO readings.
- Registration number recognition software needs to either be built into the remote sensing device or used to analyse the video images, in order to remove the large burden of visually analysing the video images.
- To provide further information about the vehicles and to categorise them according to vehicle technology, a vehicle registration database is needed.
- Speed and acceleration needs to be taken into account with the remote sensing readings - if large accelerations or decelerations are detected, then the remote sensing readings should be rejected as they will be unrepresentative of normal driving.
- After a large amount of remote sensing data has been collected, it might be possible to derive model specific cutpoints. This would prevent specific models that produce high tailpipe concentrations under certain conditions (eg low-powered vehicles that occasionally have to operate under wide open throttle conditions) from being incorrectly identified as high emitters.
- Development of the remote sensing system should allow the device to be hidden within normal street ‘furniture’, where it can operate unmanned.

Remote sensing could be used on its own to detect high emitting vehicles, followed up by letters to the owners of suspect vehicles requiring or advising them to have their vehicle checked.

Alternatively, remote sensing could assist existing random roadside checks by selecting modern catalyst vehicles with high emissions for the roadside test.

Remote sensing could also be used as a “clean-screen” device before a loaded transient test - in order to reduce the burden of the loaded transient test lanes, vehicles which exhibit low remote sensing readings can be given an immediate pass, while all other vehicles have to be tested over the transient cycle. Another use for remote sensing might be to provide an independent means of evaluating the effectiveness of Inspection and Maintenance programmes. This could also serve as a means of evaluating other road vehicle emission control strategies eg new car emission standards (in-use compliance and penetration of new standards into the fleet), new fuels etc.

1. Introduction

Laboratory based emission testing over many years has shown that a large number of vehicles on the road have excessive emissions. It has also been reported that a small proportion of the vehicles on the road account for a very high proportion of the total emissions.

Identifying and correcting these high polluting vehicles could lead to a worthwhile reduction in total vehicle emissions. One way of identifying these vehicles is through an inspection and maintenance (I/M) programme. This encourages the owners to keep the vehicles in a good state of repair and the service industry to do the maintenance properly.

However, inspection and maintenance programmes rely on periodic inspections which can be one or two years apart. Between the inspections, the exhaust emissions could deteriorate dramatically (leading to the phrase "clean for a day"). On non-catalyst cars, this deterioration can be gradual, as the carburettor drifts out of tune or as the air filter gets dirty. However, on a modern catalyst car with a closed loop control system, an engine management fault (such as a miss-fire due to a faulty spark plug or a rusty electrical connection on the lambda sensor) can lead to drastic increases in the exhaust emissions.

One way of supplementing an inspection and maintenance programme is the use of random roadside inspections. However, this is very labour intensive and, because it is random, will have varying success at identifying high emitting vehicles.

An alternative is to use a remote sensing system that can measure the exhaust emissions of the vehicles as they drive normally. This could either be used as a pre-screening tool to target vehicles for roadside checks or to identify possible high emitting vehicles and subsequently request the vehicle owner to submit the vehicle for testing at a local inspection and maintenance test station. Remote sensing could also be used as a means of judging the effectiveness of the local inspection and maintenance programme.

As part of the European project investigating alternative inspection and maintenance tests, TRL's role was to carry out several series of remote sensing tests in order to judge the effectiveness of remote sensing in identifying high emitting vehicles.

1.1 Remote Sensing Principles

An optical emissions analyser generally involves transmitting a beam of radiation through the air mixture to be investigated. In the majority of applications, absorption of the transmitted radiation is used to determine the concentration of a particular gas species within the beam path. In a conventional analyser, this process is carried out within a measurement cell mounted inside the analyser through which the air mixture being investigated is pumped from some external source (from ambient air or from the tailpipe of a vehicle). At one end of the cell is a radiation source and at the opposite end a detector, which can identify changes to a particular property of the radiation.

Remote sensing uses the same measurement principle, but the radiation source is sited at one location and the detector at another. The path between these two points defines the optical path, which could range from a few metres in length to several hundred metres.

Optical remote sensors have, for many years, been used to measure the ambient concentrations of a wide range of gas species, largely within the area of gas leakage monitoring (eg DIAL) and more recently through general environmental monitoring (eg OPSIS).

The application of remote sensing to the measurement of vehicle emissions is not new. As early as 1971, experimentation at the Lockheed Missiles and Space Corporation, under contract to the California Air Resources Board, attempted to construct a remote exhaust measurement system. Subsequently, a number of remote sensing systems have been developed, in most cases with very similar operating principles.

TRL's remote sensing system was one developed by Professor Stedman of the University of Denver. This system is a prototype device which is now marketed commercially by RSD. Since its purchase, the system has been subjected to a number of upgrades to improve its performance.

1.2 The FEAT Remote Sensing System

The FEAT (Fuel Efficiency Automobile Test) system is based upon a conventional non-dispersive infra-red gas analyser. The impetus for the original development was with regard to fuel economy issues, and therefore originally concentrated on the detection of carbon dioxide and carbon monoxide. However, significant changes have been incorporated since its original conception - the system, currently used by TRL, now also includes the measurement of hydrocarbons and opacity and also nitric oxide using an additional ultra-violet source.

The system consists of four components:
- a combined infra-red and ultra violet source
- detector
- computer
- video system

Under the standard operating procedures, the IR & UV source is positioned on one side of a single lane of traffic and the detector on the opposite side. The IR and UV beam generated by the source is directed horizontally towards the detector. The distance between the source and detector typically ranges from 6 to 15 metres, with the beam normally positioned at a height of between 20 and 30 centimetres above the road surface, corresponding with the height of the exhaust plume from most light duty vehicles.

The system takes advantage of the principle that the majority of the gas species will absorb light at particular wavelengths. For the infra-red channels, TRL's FEAT unit incorporates four Peltier cooled lead selenide detectors, with optical filters allowing the specific measurement of carbon monoxide at 4.6μm, carbon dioxide at 4.3μm, hydrocarbons at 3.4μm and a background reference channel at 3.9μm.

The introduction of the vehicle's exhaust into the beam results in a reduction in the IR and UV intensity at the detector which results in a reduction of the output voltages. This voltage reduction, measured by the individual detectors can be used to determine the concentrations of CO, CO_2, HC and NO at a point in the exhaust plume. The reference channel is used to correct for any other background variations which may effect the intensity of the beam reaching the detector.

The FEAT system operates by continuously measuring the intensity of the beam. As a vehicles passes through the beam path, the voltages from the detectors drop to zero. This beam block is used to indicate the presence of a vehicle, which triggers the video system to record an image of the passing vehicle and also triggers the measurement system. Voltages are recorded both before the beam is broken and during the beam block, this enabling the determination of background concentrations. As the vehicle continues through the beam, the beam is reformed and the change in intensity of the beam, due to the presence of the vehicle's exhaust, is recorded. Instantaneous measurements of CO, CO_2, HC and NO are recorded at a frequency of approximately 125Hz over a period of 0.5 seconds.

The precise position of the exhaust plume relative to the beam may vary widely, depending on the type and indeed model of the vehicle and the beam height and orientation. The true concentration of exhaust gas at different points in the plume may vary widely and reduces due to normal dispersion occurring. Therefore the FEAT system calculates average molar ratios (CO/CO_2 and HC/CO_2) from the instantaneous measurements

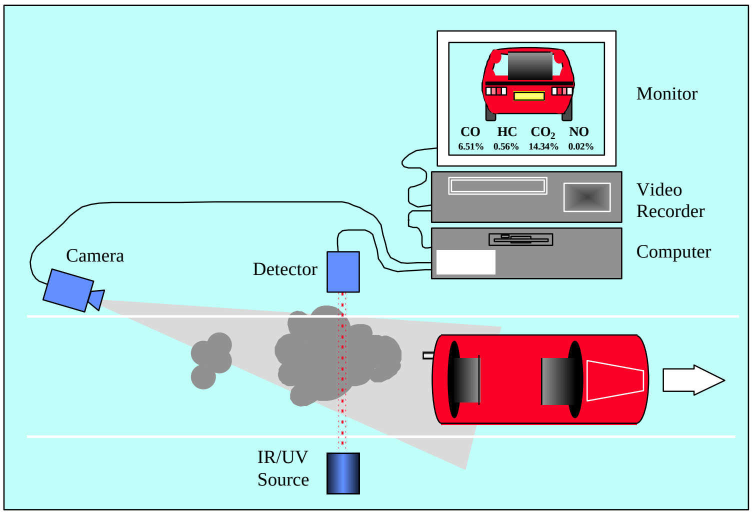
which, theoretically, remain constant within the exhaust plume, irrespective of its dispersion and subsequent dilution. These molar ratios are subsequently converted to absolute concentrations through a software algorithm based on the chemistry of hydrocarbon fuel combustion in motor vehicles.

The FEAT system further operates a number of data rejection criteria. As a large number of data points are recorded, the software is able to quantify the data scatter. If the data scatter is excessive then the data is rejected, and is recorded by the FEAT system as invalid data.

System calibration is integral to the system's performance. Initial calibration is undertaken during manufacture through the use of calibrated gas cells. The results from these calibrations are used to generate calibration curves which are implemented within the FEAT system software. During normal use, daily calibration checks are undertaken by introducing a certified gas mixture (containing known concentrations of carbon monoxide, carbon dioxide, propane and nitric oxide) into the path of the beam. The results from this daily calibration are used to adjust the FEAT data for site specific variations in its performance.

The derived FEAT data is recorded in a number of formats. The video image is instantaneously transmitted to a monitor and additionally recorded as a still image on a video tape. Superimposed onto this video image (from which vehicle details including registration number can be derived) are the vehicle's associated emissions concentrations, as illustrated by Figure 1, together with the date and time. In addition, the concentrations, date and time are also recorded numerically onto the computer's hard disc together with additional information, which on TRL's current FEAT system includes an opacity reading and the speed and acceleration of the vehicle as it passes through the beam. These two data formats can be cross referenced using the date and time information.

Figure 1. Schematic Diagram showing the operation of the FEAT Remote Sensing System



2. Tests

The remote sensing tests were carried out in the following five locations:

Greece	Thessaloniki	27 May 1996	to	1 June 1996
France	Lyon	10 June 1996	to	14 June 1996
Netherlands	Delft	19 August 1996	to	23 August 1996
UK	Emberton (near Milton Keynes)	13 January 1997	to	17 January 1997
UK	Leicester	27 January 1997	to	31 January 1997

The test work consisted of the following elements:

- remote sensing
- roadside tailpipe emissions tests on a sample of vehicles

followed a later date by:

- dynamometer tests on a sub-sample of vehicles subjected to roadside tests

The remote sensing and roadside test work was carried out over a period ranging typically from Monday to Friday (although in Thessaloniki, due to bad weather cancelling one of the test days, the work was extended to include Saturday). During each day, testing was carried out from about 09:00 until about 17:00 (the actual times were varied depending on local traffic conditions and weather/light conditions).

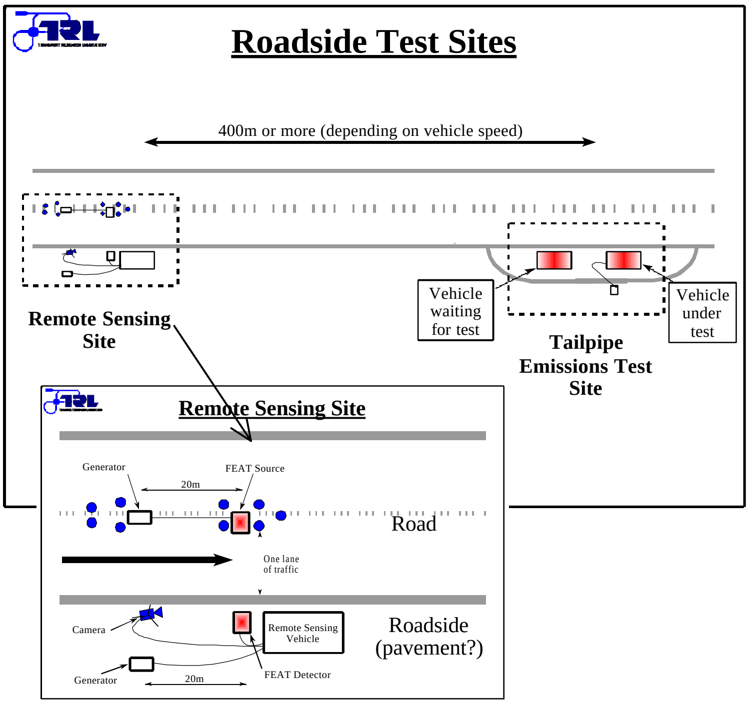
2.1 Remote Sensing

The remoter sensing system was set up on a road selected by the host partner, based on selection criteria supplied by TRL. Ideally, this required:

- a road where vehicles would be under slight load (eg slight uphill gradient).
- road layout suitable for locating the source and detector on either side of a single lane of traffic.
- a 'safe' area further down the road where selected vehicles can be stopped for a roadside emissions test.

A typical road layout is illustrated in Figure 2.

Figure 2. Remote Sensing Road Layout



The remote sensing site was operated by TRL personnel. As the vehicle passed through the remote sensing system, an image of the back of the vehicle and the measured emissions were displayed on the monitor (as illustrated by Figure 1).

Any interesting vehicles were reported to the roadside test site where police officers stopped the vehicle for further tests (apart from in Delft where, because the remote sensing site was on a slip road onto a motorway, police motorcyclists pursued the selected vehicles and lead them to the roadside test site located in a motorway service area a short distance away). The selection criteria depended on the vehicles passing through the test site - ideally catalyst cars (based on the vehicle's registration number) with high CO emissions were targeted, but in the absence of such vehicles other vehicles with valid remote sensing readings were selected.

In most cases, the targeted vehicles were stopped and subjected to a roadside test - the drivers were generally happy to participate in the tests. In some cases the vehicle driver had an urgent appointment and was allowed to continue on his/her way.

The actual sites selected for the remote sensing varied from country to country as follows:

- Thessaloniki - a major suburban dual carriageway with an uphill gradient
- Lyon - a level suburban single carriageway
- Delft - a slip road onto a motorway with a downhill gradient
- Emberton - a rural single carriageway with a slight uphill gradient
- Leicester - a suburban dual carriageway with a slight uphill gradient just after traffic lights

2.2 Roadside Emission Tests

The vehicles selected for the roadside test were subjected to, typically two tests

- an idle emissions test
- a fast idle emissions test

Conventional garage type four-gas emission analysers (which included a lambda reading) were used for the tests, powered by a generator. The host partner was responsible for providing this equipment and carrying out these tests, so different equipment was used in the different countries. The analysers included a printer, so that the test results could be printed out. Two copies of the results were printed - one of which was given to the driver of the vehicle together with an explanation letter and an exhaust emissions information leaflet.

A questionnaire about the vehicle was also completed, based on observation of the vehicle (make, model, mileage etc) and on questioning the driver (length of trip , period since last service etc).

2.3 Dynamometer Tests

Following the completion of the remote sensing and roadside tests, a sub-sample of the vehicles stopped were selected for a series of dynamometer tests in an emissions laboratory. The test procedure followed was that designed for the short test evaluation.

These tests included:

- Cold Start New European Driving Cycle (NEDC):
  Urban Driving Cycle plus Extra Urban Driving Cycle (EUDC)
- Hot Start Urban Driving Cycle
- MODEM actual cycle - a realistic cycle
- TUV Cycle - a short stylised cycle
- MODEM short cycle - a short cycle based on realistic driving
- Steady state load and speed
- Idle and fast idle

Some of the vehicles with high emissions were repaired and repeat tested, to show the effect of maintenance on emissions.

3. Results

At each site, several thousand remote sensing results were obtained. Not all of the remote sensing results are valid. If a HGV or a car with a trailer/caravan attached to it passes though the beam, the beam is broken and remade several times (the beam is set at a height typical of the exhaust level on most cars, so that it sees a multi-axle HGV as several vehicles). When this occurs, it is indicated on the remote sensing data as a reset.

The remote sensing system calculates the emissions by measuring the ratios between CO/CO_2, HC/CO_2 etc many times immediately after the vehicle has passed (ie when the broken beam in re-made). As the exhaust plume disperses, the concentration becomes more dilute, but the ratios should remain fairly constant. If the standard deviation of these ratios is too high the reading is rejected (the data files contain flags indicating ‘V’ valid and ‘X’ invalid readings). Table 1 shows the total number of valid readings (based on the flags previously mentioned) after rejecting all the readings where resets have occurred.

As can be seen from this table, a total of over 83,000 readings have been collected from these five sites, with over 76,000 valid CO readings. The majority of these vehicles are cars, but the total will also include, in smaller numbers, light goods vehicles, motorcycles etc. For CO and CO_2 , the success rate (ie the number of

valid readings) is high, due to their presence in relatively high concentrations. For HC and especially NO, which are present in much smaller concentrations, the number of valid readings is much lower.

The table also shows the total number of vehicles stopped for a roadside idle test and selected for further dynamometer based tests (repeats indicate the number of vehicles sent for servicing and then repeat tested). Comparison of the number of remote sensing reading and the number of idle tests shows one potential advantage of using a remote sensing detector.

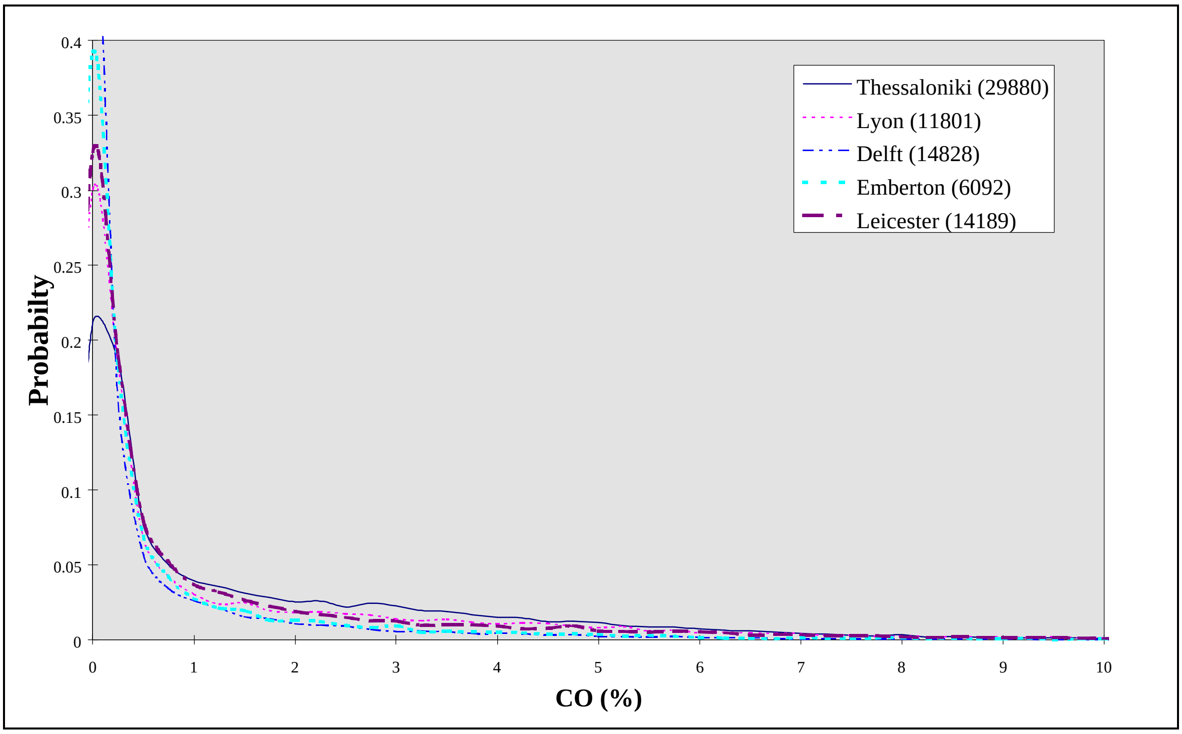
Table 1. Number of Valid Remote Sensing Readings, Idle and Dynamometer Tests

Location	No. of Vehicles	Number of Valid Readings						No. of Idle Tests	Dyno Test + Repeats
		CO	CO_2	HC	NO	Opac	Speed		
Thessaloniki	30682	29880	30227	28394	9526	25248	25004	161	11 + 4
Lyon	13422	11801	11999	7758	891	5601	12335	228	
Delft	16993	14828	14928	6666	1370	4705	15864	154	16 + 2
Emberton	7687	6092	6209	2871	643	1418	7172	199	20 + 10
Leicester	14749	14189	14331	12283	3493	5651	8878	304	
Total	**83533**	**76790**	**77694**	**57972**	**15923**	**42623**	**69253**	**1046**	**47 + 16**

3.1 Emission Distributions

From the large amount of remote sensing data, emissions distributions can be derived. Figure 3 shows the distributions of the valid carbon monoxide readings at the five different sites (the numbers in the legend refer to the number of readings at each site that the distribution is based on). All five sites show similar trends - a

Figure 3. CO Distribution at the five Remote Sensing Sites



high number of vehicles with low CO concentration and a small number of vehicles with very high concentrations

The CO distributions shows that there were a high number of low emitting vehicles in Delft, while in Thessaloniki there were a lower number of low-emitting numbers. Conversely, in the middle of the scale, Thessaloniki has the slightly higher number of high emitters, with Deft having the lowest number.

This could indicate the emissions characteristics of the vehicles passing the remote sensing detector (ie cleanest vehicles in Delft etc) or it could be due to differences in the remote sensing sites. Because the site in Thessaloniki was uphill, the vehicle's engine would be under greater load and therefore their emissions higher. In Delft, the remote sensing site was downhill and the vehicles may have been under little load as they passed, resulting in lower emissions being detected.

3.2 Effect of Age on Emissions

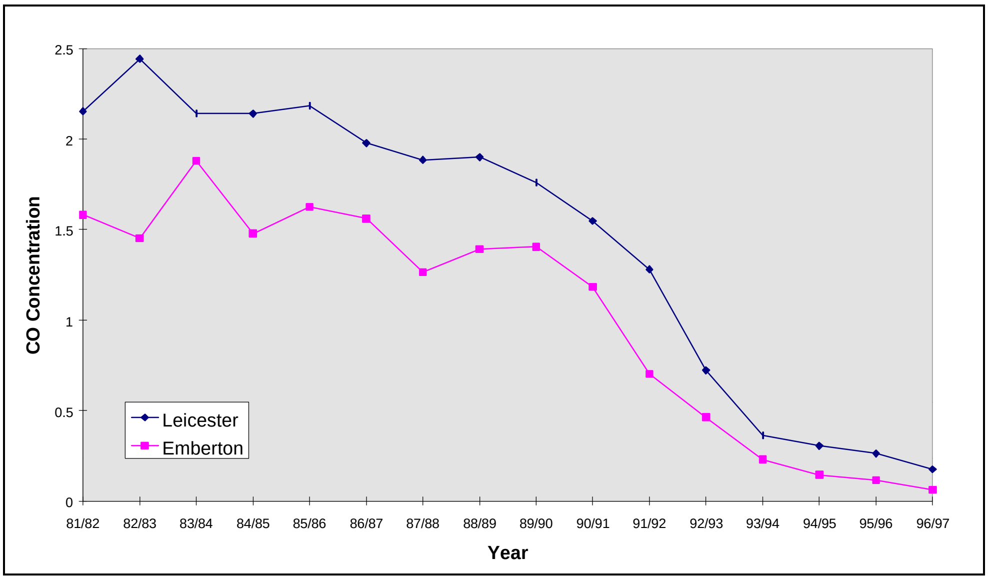
It is possible to tell the age of the vehicles in some countries by the number plate - part of the number indicates when the vehicle was first registered.

In the UK, this is very simple - the last letter (1966-1983) or the first letter (1983-current) of the registration number indicates the year of registration. This letter currently changes (increments) annually every August, so for the majority of cars the age can be easily determined (apart from a small number of vehicles with personalised number plates).

Some of the other countries use other methods for determining the age of the car or the number plate (in some countries a new registration number is issued when the vehicle changes owners).

After extracting the registration number details from the remote sensing video tapes, it is therefore possible to sort the data according to vehicle age. Figure 4 shows the average emissions of the vehicles at the two UK sites. Both sites show decreasing CO emissions with decreasing vehicle age with a large decrease with the introduction of catalyst cars.

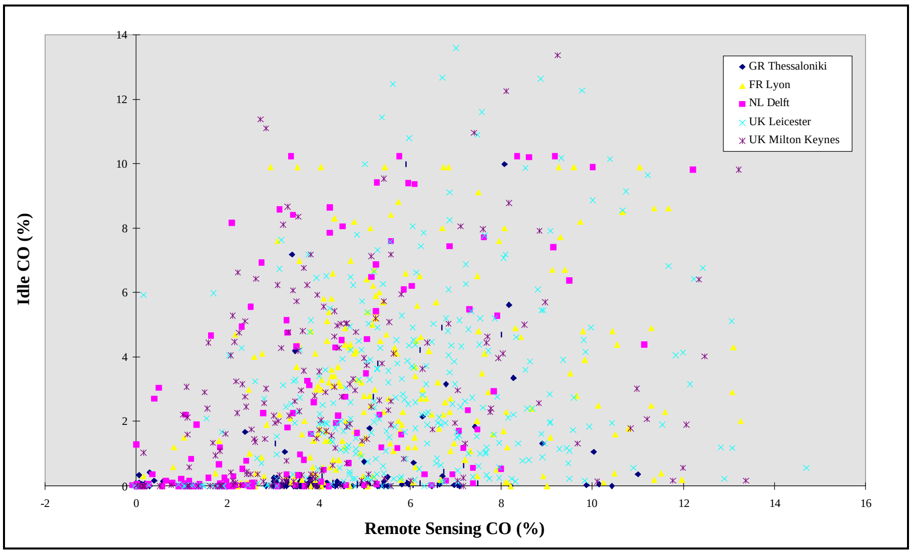
Figure 4. Average CO Emissions by Vehicle Age



3.3 Comparison of Remote Sensing with Idle Tests

The vehicles stopped at the roadside were subjected to a standard tailpipe emissions test. Figure 5 shows the comparison of the idle CO emissions measured at the tailpipe using conventional garage equipment with the corresponding remote sensing CO reading. It will be noted that there is a great deal of scatter in this graph. This large amount of scatter is not because of errors in the remote sensing measurement - it is due to the different operating conditions the vehicle was under for the two tests: under some load while passing through the remote sensing device as opposed to being under no load for the idle test.

Figure 5. Comparison of Idle Test Results with Remote Sensing Readings: All Data



In Figure 6, similar data is used (but this time from the fast idle test), but only the data for catalyst cars under almost steady speed have been plotted (ie vehicle undergoing high accelerations or decelerations have been rejected). This shows a better comparison between the two tests. With a remote sensing cutpoint of 5% CO (indicated by the vertical line on the graph), ten of the vehicles have high remote sensing and fast idle CO emissions - in comparison to a fast idle limit of 0.3% indicated by the horizontal line. There are, however, seven vehicles with high remote sensing readings and low idle readings (ie errors of commission). Some of these vehicles had only travelled a short distance from the start of their journey and may have still been running under cold start conditions when passing through the remote sensing device. There are also a large number of vehicles with high idle emissions and remote sensing readings less that 5% CO. Hence using a cutpoint of 5% will result in a number of high polluting vehicles being missed (errors of omission).

Where multiple readings have occurred (ie when the same vehicle has passed through the remote sensing site on more than one occasion) the remote sensing readings have been averaged. However, quite a lot of the data is just from single readings.

The data for catalyst vehicles that have passed through the remote sensing site a minimum of 3 times is shown in Figure 7. The average reading is shown plotted together with the range of readings indicated by the horizontal bars. Unfortunately, there are not many catalyst vehicles with more than 2 readings. However, this graph shows that using repeat readings, it might be possible to detect vehicles with very high emissions - the one vehicle with very high idle emissions has an average and range much higher than the other vehicles.

Figure 6. Comparison of Fast Idle Test Results with Remote Sensing: Catalyst Cars with low Accelerations & Decelerations

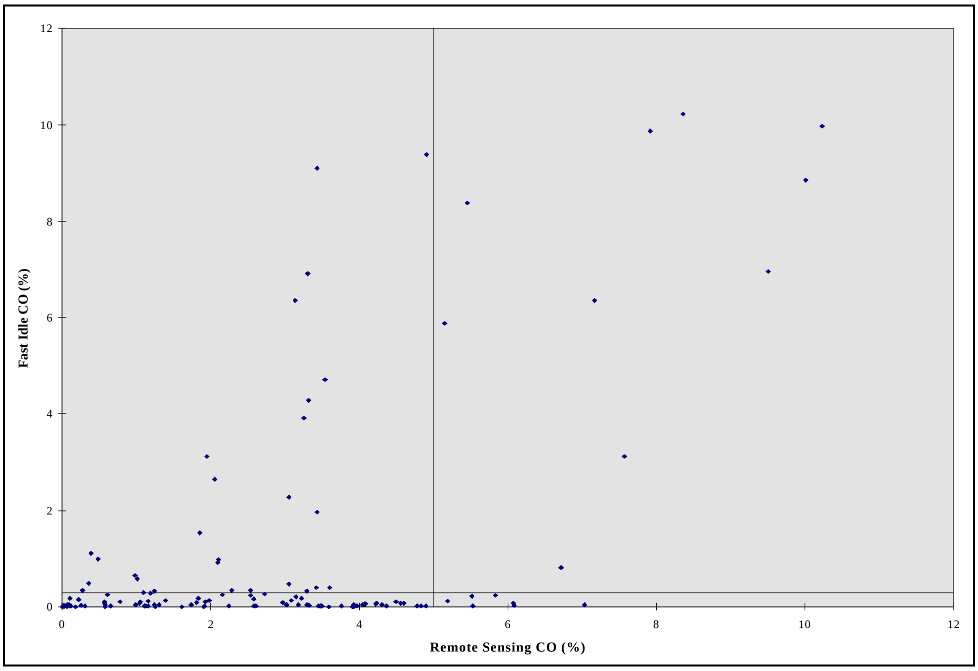
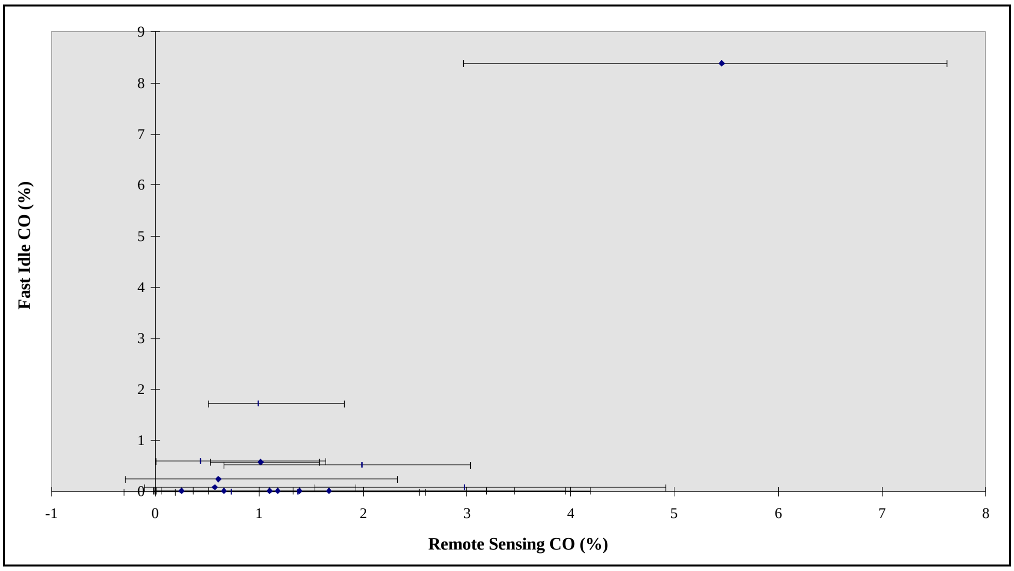


Figure 7. Comparison of Idle Test Results with Remote Sensing: Catalyst with multiple Remote Sensing Readings



3.3.1 Errors of Commission and Error of Omission

From the remote sensing and roadside idle/fast idle data the following errors have been calculated:

Errors of Commission: vehicles identified as high emitters by remote sensing but with low idle/fast idle emissions.
Errors of Omission: vehicles with low remote sensing reading but with high idle/fast idle emissions.

(however, it should be noted that the idle/fast idle test has its own errors of commission and errors of commission when compared to a NEDC dynamometer test)

The errors have been calculated according to the vehicle type:

a. all vehicles (catalyst and non-catalyst).
b. catalyst vehicles only.
c. non-catalyst vehicles only.

and according to the remote sensing readings:

1. all data.
2. remote sensing readings that occurred under almost steady state condition (measured acceleration within ±2 mph/s (±0.89 m/s^2) - ie all readings that occurred under high acceleration and deceleration have been excluded.
3. as 2 but only for vehicles that have repeat readings (more than one valid reading).
4. all vehicles that have repeat readings (more than one valid reading) regardless of their measured acceleration.

The limits used for determining the errors of commission and the errors of omission are a remote sensing cutpoint of either 5% or 7% CO for catalyst and non-catalyst vehicles respectively and the appropriate idle test limits.

For non-catalyst cars, an idle test limit of 3.5% CO has been used. The in-service exhaust emissions test according to the Directive 96/96/EC specifies limits for non-catalyst cars as either 3.5% or 4.5% CO at natural idle depending on the age of the vehicle. As the ages of all these vehicles are not known, the limit of 3.5% has been used, which is applicable to vehicles from 1986 onwards.

The emission limits for cars fitted with catalytic converters has been taken as 0.5% CO at idle and 0.3% CO at fast idle. These are the default limits as specified in Directive 96/96/EC, although in some countries the actual limits used for the natural idle test are vehicle type dependant, relying on information supplied by the vehicle manufacturer. In the calculations of the errors, a catalyst vehicle is considered a pass if both the idle CO is no greater than 0.5% and the fast idle CO is not greater than 0.3%, whereas the vehicle is considered a fail if either the idle or the fast idle exceed these limits.

The resulting errors are shown listed in Table 2 - the errors are shown both as an absolute number and as a percentage of the number of vehicles in each group. Using a remote sensing cutpoint of 5% CO for catalyst cars, the errors of commission are 10% and the errors of omission 19% when considering all the data. For the non-catalyst cars, with a remote sensing cutpoint of 7%, the errors of commission and omission are 13% and 28% respectively.

Restricting the remote sensing data to only include readings taken under low acceleration and decelerations, although decreasing the absolute numbers, has very little effect on the percentages for either the errors of commission or omission (although, if a large number of vehicles are measured under very high acceleration, then the errors of commission will be effected, due to higher than normal emissions occurring during operating conditions requiring fuel enrichment).

However, restricting the reading to only those vehicles with multiple valid readings significantly effected the errors. For both catalyst and non-catalyst vehicles, the errors of commission reduced significantly (down to 5% for catalyst and 4% for non-catalyst) regardless of whether high accelerations and decelerations were excluded or not. The errors of omission decreased for catalyst cars to 13% whereas for non-catalyst cars they increased to 36%.

Table 2. Errors of Remote Sensing in comparison with Idle Tests

	All Data	Low Accels & Decels only	.. with Repeat Passes	All Data with Repeats
a. For all Vehicles				
Number of Vehicles	747	601	110	150
Errors Of Commission	91 (12%)	73 (12%)	5 (5%)	7 (5%)
Errors Of Omission	187 (25%)	158 (26%)	32 (29%)	40 (27%)
True Failures	62 (8%)	54 (9%)	9 (8%)	10 (7%)
b. For Catalyst Vehicles only				
Number of Vehicles	253	201	42	61
Errors Of Commission	25 (10%)	20 (10%)	2 (5%)	3 (5%)
Errors Of Omission	47 (19%)	41 (20%)	7 (17%)	8 (13%)
True Failures	18 (7%)	17 (8%)	5 (12%)	5 (8%)
c. For Non-Catalyst Vehicles only				
Number of Vehicles	494	400	68	89
Errors Of Commission	66 (13%)	53 (13%)	3 (4%)	4 (4%)
Errors Of Omission	140 (28%)	117 (29%)	25 (37%)	32 (36%)
True Failures	44 (9%)	37 (9%)	4 (6%)	5 (6%)

Criteria:

EoC: Catalyst — idle CO <=0.5% AND fast idle CO <= 0.3% AND RS CO >5%
EoC: Non-Catalyst — idle CO <=3.5% AND RS CO >7%

EoO: Catalyst — (idle CO >0.5% OR fast idle CO > 0.3%) AND RS CO <=5%
EoO: Non-Catalyst — idle CO >3.5% AND RS CO <=7%

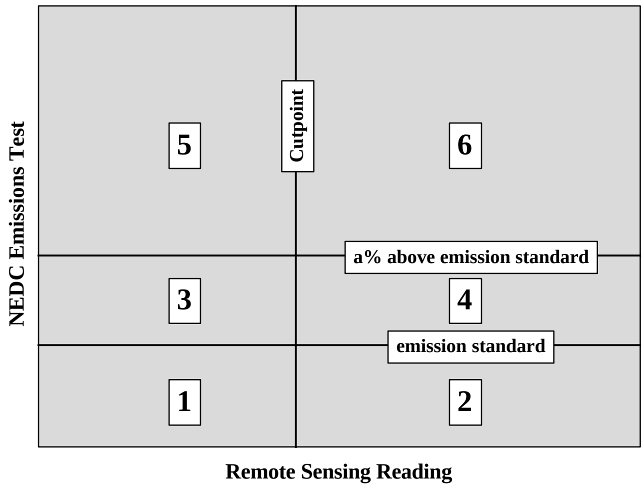
3.4 Comparison of Remote Sensing with Dynamometer Tests

A sub-sample of the vehicles stopped for the roadside idle test were submitted to a number of dynamometer based tests. All of these vehicles had passed through the remote sensing site and thus some remote sensing data was available for each vehicle. Most of the vehicles had a least one valid remote sensing CO reading. Some of the vehicles passed through the site on several occasions, resulting in a number of readings.

If the remote sensing readings are plotted against their corresponding results from a dynamometer based test (type approval emissions test), the vehicles can be categorised according to Figure 8, where:

Group 1	Vehicles correctly identified as low emitting vehicles
Group 2	Vehicles incorrectly identified as high emitting vehicles - they are in fact low emitting vehicles (errors of commission)
Group 3	Vehicles with slightly high emissions identified as low emitting vehicles
Group 4	Vehicles with slightly high emissions identified as high emitting vehicles
Group 5	Vehicles incorrectly identified as low emitting vehicles whereas they are in fact high emitting vehicles (errors of omission)
Group 6	Vehicles correctly identified as high emitting vehicles

Figure 8. Group Categories



The ideal is to identify all the vehicles with high emissions (vehicles in Group 6) and send them for maintenance so that their emissions are reduced to a normal level (the same as vehicles in Group 1).

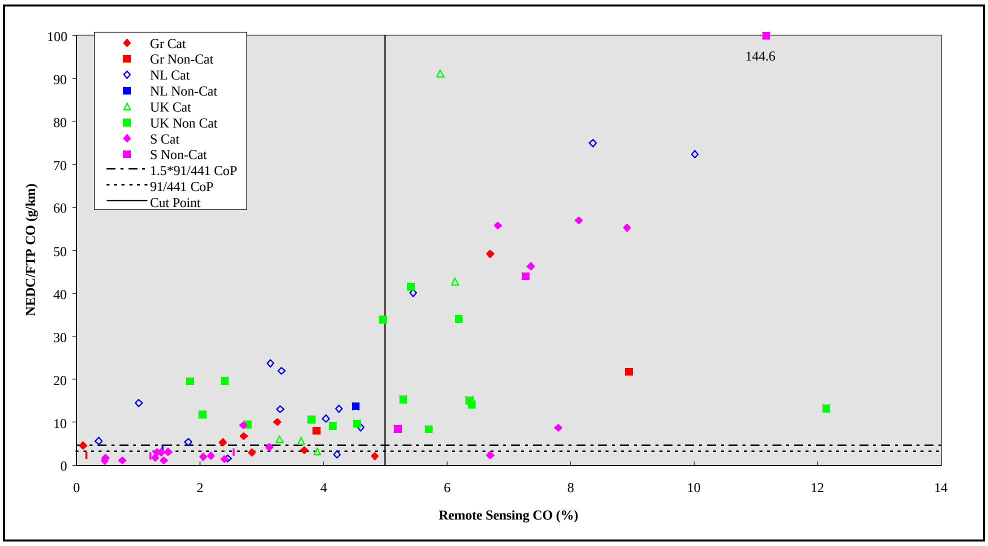
Any errors of commission (vehicles in group 2) are vehicles incorrectly identified, and thus their emissions will not change significantly even if they are subjected to maintenance.

For vehicles within group 4, because their emissions are only slightly above the limits, presumably due to a minor problem, then, again, any maintenance if unlikely to have any significant effect on their emissions.

Figure 9 shows an example of the dynamometer results plotted against the remote sensing values - further comparisons are contained within Appendix A. In this case, the CO emissions from the NEDC cycle are plotted against the corresponding remote sensing CO (the valid remote sensing readings have been averaged for each vehicle to take into account multiple passes). In addition to the data from this project, additional data from the Swedish remote sensing work has been added (Sjodin,1998) - the remote sensing data from Sweden were sampled at one site near Stockholm, and most of the data are averages from repeat sensor readings. In the Swedish work, instead of using the European legislative cycle, the vehicles were tested over their own

legislative cycle (the USA's FTP cycle). Hence the results from either the NEDC or the FTP are shown plotted against the remote sensing values.

Figure 9. Dynamometer CO plotted against Remote Sensing CO for all vehicles



The data plotted in Figure 9 is for both catalyst and non-catalyst cars. As there appears to be a much greater variation in the tailpipe concentrations in a non-catalyst car than from a catalyst car with a closed loop control system, the following analysis will deal exclusively with catalyst vehicles.

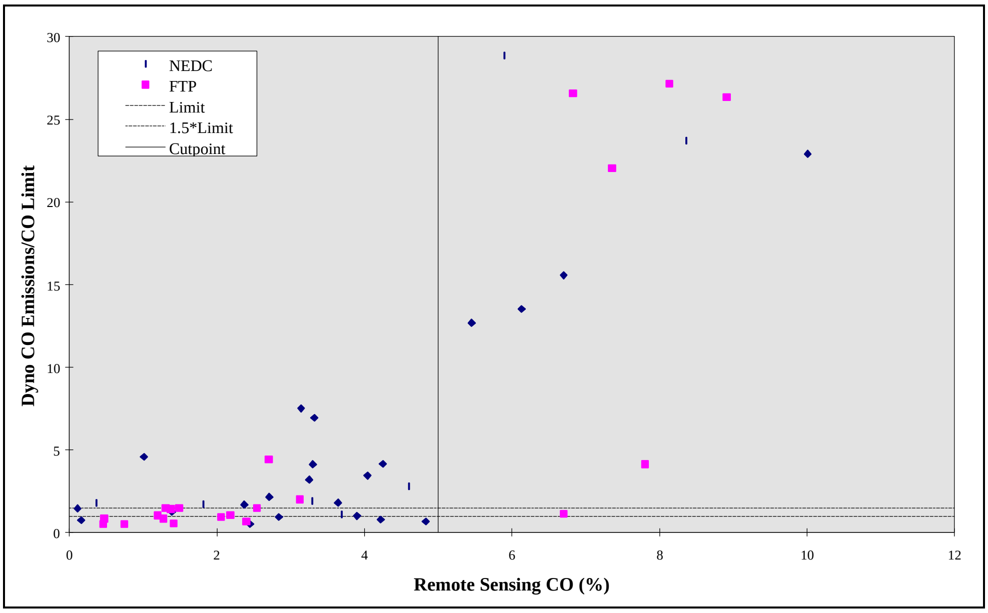
3.4.1 Carbon Monoxide (CO)

To allow for the different dynamometer tests that the vehicles from this project and the Swedish project were subjected to, the ratios of the actual emissions relative to their corresponding legislative emissions limits will be Figure 10 shows these relative CO emissions plotted against the remote sensing CO readings (again average per vehicle). The two horizontal lines indicate the legislative emissions limits and one and a half times this limit.

This graph shows that some of the vehicles had very high dynamometer CO emissions - some almost 30 times the limit. It is clear from the graph that remote sensing was able to detect these gross emitters. Setting a cutpoint of 5% CO would select 12 vehicles - all of them high emitters apart from one which is only just over the limit (Group 4 category vehicle).

Using this cutpoint, there are a number of vehicles that are over the emission limit (ranging from 1.5 to about 7 times the limit) that remote sensing would not select (Group 5 category vehicles). However, some of the remote sensing reading are based on just one reading. It is possible that multiple readings may change the situation - moving some of the vehicles from Group 5 into Group 6.

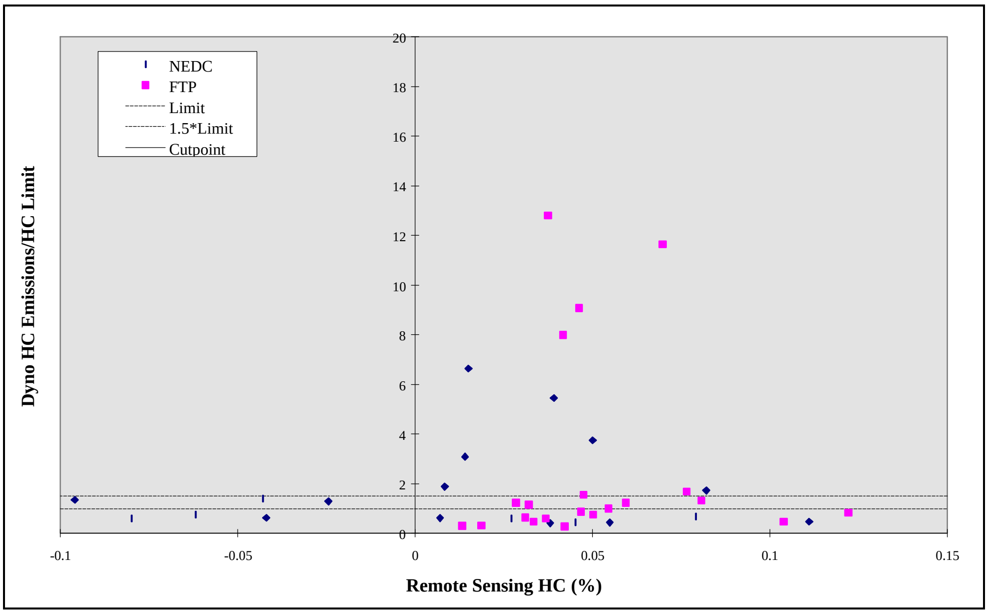
Figure 10. Dynamometer CO plotted against Remote Sensing CO



3.4.2 Hydrocarbons (HC)

For hydrocarbons, the result is not as good as for CO. Figure 11 shows the HC dynamometer results plotted against the remote sensing HC readings. Again, emission ratios are used for the dynamometer readings (for the NEDC test, the HC limit has been taken as 51% of the legislative HC+NO_X limit). The graph shows a large range of remote sensing readings for vehicle with relatively low dynamometer results. It is therefore impractical to set a cut-point for the remote sensing HC readings that will allow vehicles with high HC to be correctly selected, without including a large number of vehicles with low levels of HC.

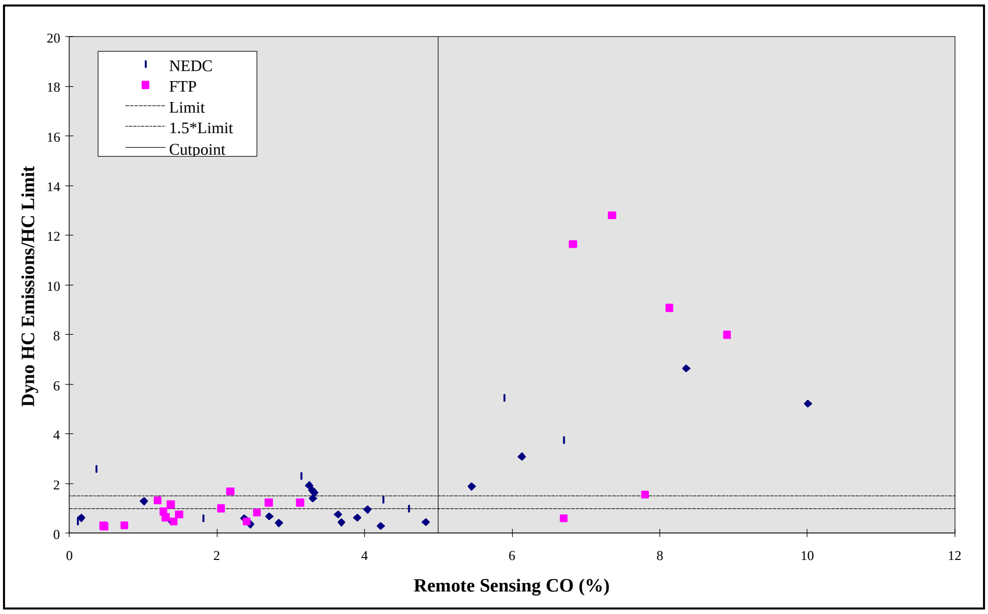
Figure 11. Dynamometer HC plotted against Remote Sensing HC



However, plotting the same dynamometer HC emission ratios against the CO remote sensing results shows a much better comparison. With the cutpoint of 5% CO, in addition to selecting vehicles with high CO

emissions, remote sensing would also select most of the vehicles with high HC emissions. It is therefore possible that hydrocarbons do not need to be measured - just targeting vehicles with high CO emissions would also select most of the vehicles with high hydrocarbons (although there will, no doubt, be some exceptions).

Figure 12. Dynamometer HC plotted against Remote Sensing CO

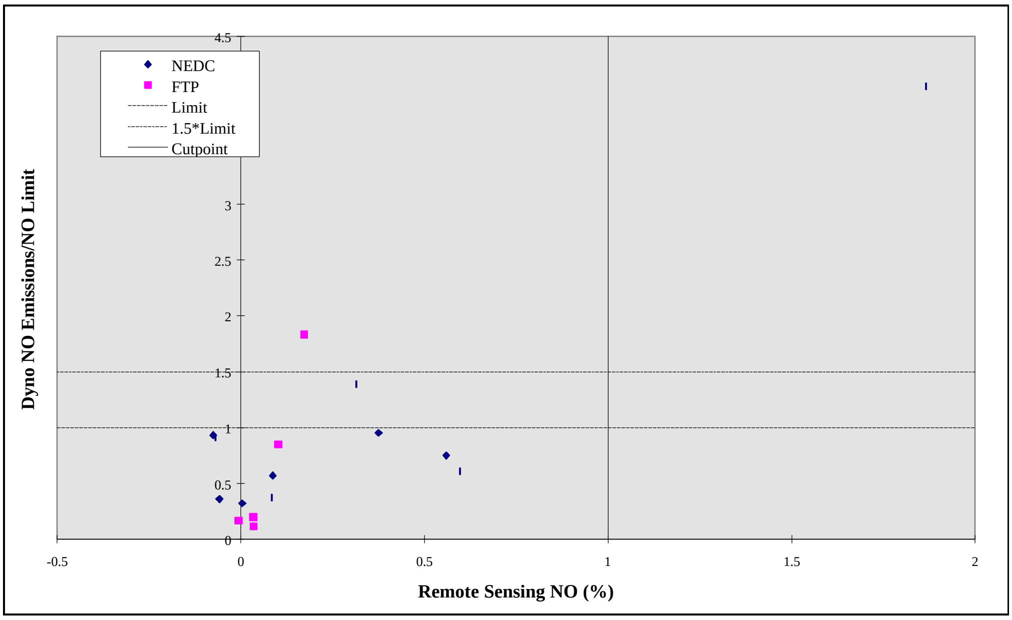


3.4.3 Oxides of Nitrogen (NO_X)

Figure 13 similarly shows the dynamometer NO_X emission ratios plotted against the remote sensing NO readings. There are a fewer number of points plotted on this graph, because of the lower success rate of the remote sensing device to detect valid NO values. Most of the vehicles subjected to the dynamometer tests were selected on the basis of being high CO emitters. Hence, most of the vehicles have low NO_X emissions. There is only one vehicle which has significantly high NO_X emissions - about 4 times the NO_X limit. This vehicle also has a high remote sensing reading.

It is therefore possible that setting an NO cutpoint of about 1% would allow vehicles with high NO_X emissions to be detected. However, this is based on a very limited sample size - further work investigating vehicles with high NO_X emissions is needed to evaluate the effectiveness of the NO channel.

13. Dynamometer NO_X plotted against Remote Sensing NO



3. Comparison of Remote Sensing with Dynamometer and Idle Tests

Vehicles that have been subject to idle & fast idle and dynamometer tests and which have valid remote sensing Table 3. This table lists the CO emissions for the various tests (the remote sensing

Out of a total of 29 vehicles, 15 vehicles have dynamometer CO emissions over 4 g/km. Eleven of the vehicles have idle and/or fast idle CO emissions greater than 1%. Of these 11 vehicles, 10 are correctly identified as

Six of the vehicles have high remote sensing CO reading. All six vehicles are correctly identified as high emitters which is confirmed by the idle tests.

Figure 14. The six vehicles mentioned above (signified by labels

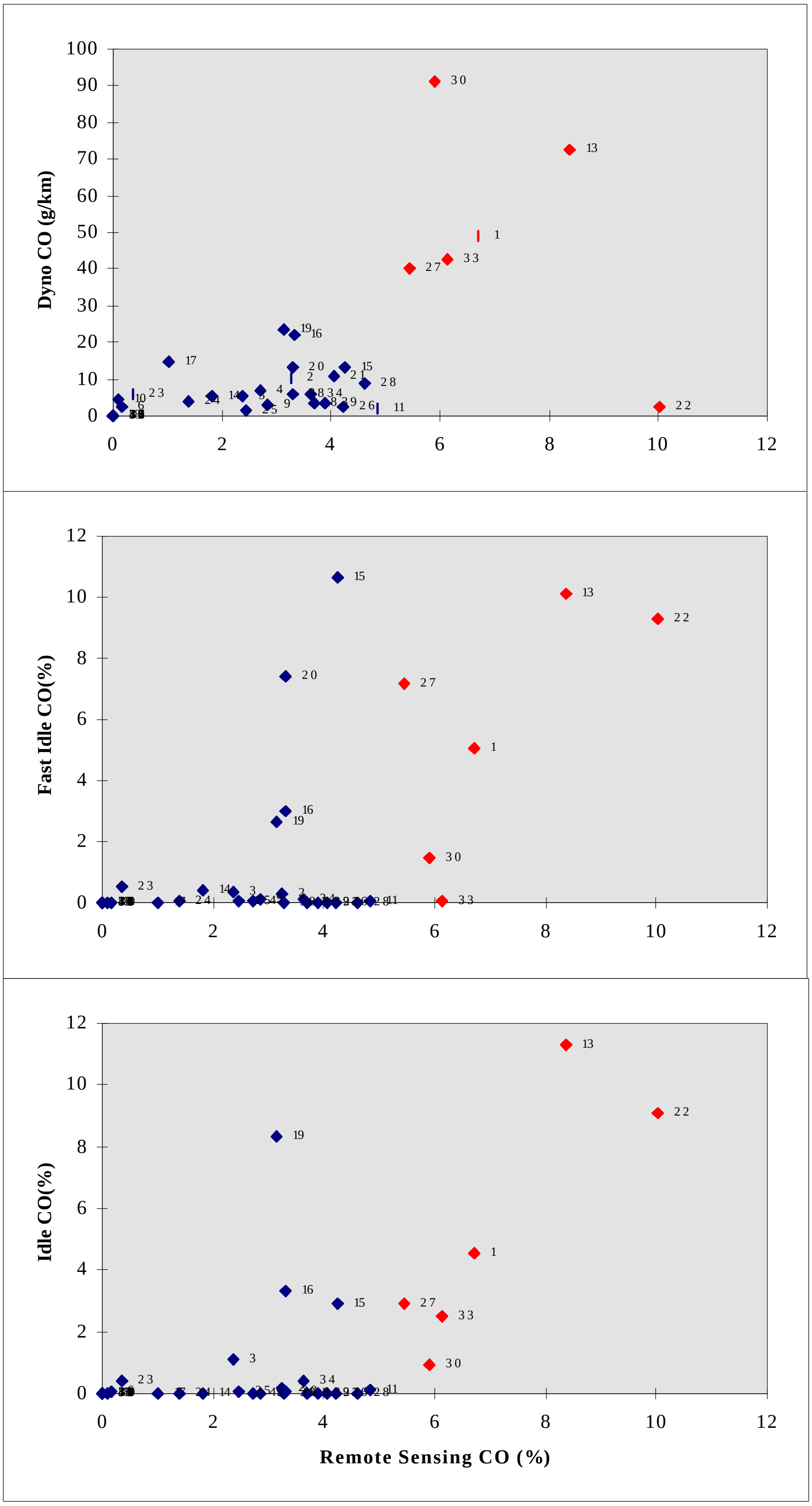
19 and 20 have high idle and dynamometer results but low remote sensing readings. However, these three vehicles have only one remote sensing reading - repeat readings could alter the comparison.

Table 3 CO Emissions for Vehicles subjected to Remote Sensing, Dynamometer and Idle/Fast Idle Tests

Lab. Ref.	Idle (%)	Fast Idle (%)	NEDC CO (g/km)	Remote Sensing (%)	Graph Label
61	**4.54**	**5.06**	**49.18**	**6.70**	**1**
62	0.15	0.32	**10.11**	3.25	2
63	1.09	0.34	5.36	2.37	3
64	0.02	0.06	**6.83**	2.71	4
66	0.07	0.01	2.36	0.16	6
68	0.01	0.01	3.50	3.69	8
71	0.01	0.14	2.99	2.84	9
72	0.02	0.02	4.62	0.11	10
73	0.11	0.06	2.11	4.83	11
551	**11.30**	**10.10**	**72.47**	**8.36**	**13**
552	0.01	0.42	5.42	1.81	14
553	**2.89**	**10.63**	**13.14**	4.25	15
554	**3.30**	**3.00**	**21.95**	3.32	16
555	0.00	0.00	**14.49**	1.01	17
557	**8.34**	**2.62**	**23.72**	3.14	19
558	0.03	**7.40**	**13.06**	3.30	20
559	0.00	0.00	**10.88**	4.04	21
560	**9.07**	**9.28**	**72.37**	**10.01**	**22**
561	0.40	0.55	5.64	0.36	23
562	0.00	0.04	3.97	1.39	24
563	0.05	0.07	1.61	2.45	25
564	0.00	0.02	2.51	4.22	26
565	**2.90**	**7.20**	**40.09**	**5.45**	**27**
566	0.02	0.02	**8.84**	4.60	28
1	0.92	1.47	**91.18**	**5.89**	**30**
4	**2.49**	0.05	**42.75**	**6.13**	**33**
5	0.40	0.11	5.71	3.64	34
9	0.00	0.01	**6.07**	3.29	38
10	0.00	0.00	3.19	3.90	39

Number of Vehicles	29
High Polluters: NEDC >6g/km	16
High Polluters: Idle and/or Fast Idle >1%	11
Correctly Identified by Idle/Fast Idle	10
High Polluters: RS> 5%	6
Correctly identified by RS	6
Confirmed by Idle	6

Figure 14. Comparison of Dynamometer, Fast Idle and Idle CO emissions with Remote Sensing CO Emissions



3.6 Emission Reduction Rate Potential

To provide consistency in the analytical approach used in the overall project, the approach follows the analysis method used in the evaluation of the short tests (Samaras & Kitsopanidis, 1998), and, as such, some of the explanation is taken from that report.

Based on a remote sensing cutpoint of 5% CO, then from Figure 10, it can be seen that there are 11 vehicles that fall into the group 6 category. The remote sensing reading and dynamometer test results for these 11 vehicles are listed in Table 4. The remote sensing reading are the average readings obtained - this might be from a number of passes or just a single pass. Because some of the vehicles were tested over the NEDC test cycle and some over the FTP test cycles, the emissions of CO, HC and NO_X are shown as ratios with respect to their corresponding limits (because the EC legislation specifies the limits in terms of the sum of CO & NO_X, the HC and NO_X limits has been approximated as being 51% and 49% of the total limit respectively).

Table 4. Catalyst Vehicles falling in Group 6 based on CO emissions

Remote Sensing				**Dynamometer**				
Avg CO (%)	**Avg HC (%)**	**Avg NO (%)**	**Avg CO2 (%)**	**CO**	**HC**	**NO_X**	**CO_2**	**FC**
				Emissions/Emission Limit			**g/km**	
10.01			7.70	22.90	5.23	0.61	130.23	79.87
8.91	0.04			26.33	8.00	0.30		
8.36	0.02		8.94	23.71	6.64	1.30	156.34	90.17
8.13	0.05			27.14	9.08	0.17		
7.80	0.05			4.14	1.56	0.73		
7.35	0.04			22.05	12.80	0.87		
6.83	0.07			26.57	11.64	1.55		
6.70	0.05		9.65	15.56	3.75	0.35	137.02	69.67
6.13	0.01	0.31	10.55	13.53	3.09	1.39	175.26	78.16
5.89	0.04	-0.06	10.85	28.86	5.46	0.36	139.92	92.36
5.45	0.01		11.22	12.69	1.89	0.91	140.80	65.29

The method of deriving the Emission Reduction Rate Potential of a test, as used in the evaluation of the short tests, is shown in Table 5.

For the remote sensing tests:

- the Emission Factor EF_{i6} has been calculated as the average of the values listed in Table 4 (ie vehicles with high remote sensing and dynamometer CO) for all the pollutants, not just CO (although for CO, HC and NO_X the actual emissions rather than the ratios have been used, the ratios being used just to categorise the vehicles).

- the Emission Factor EF_{i1} has been calculated for all pollutants from the vehicles with low remote sensing and dynamometer CO (again actual emissions rather than ratios have been used).

The resulting Emission Reduction Rate Potential are shown graphically in Figure 15

Table 5. Definition of Subscripts, Indexes and Parameters

- ***Subscripts***
  i = CO, CO2, HC, NO_X and FC (pollutants)
  j = 1, 2, 3, 4, 5 and 6 (groups)

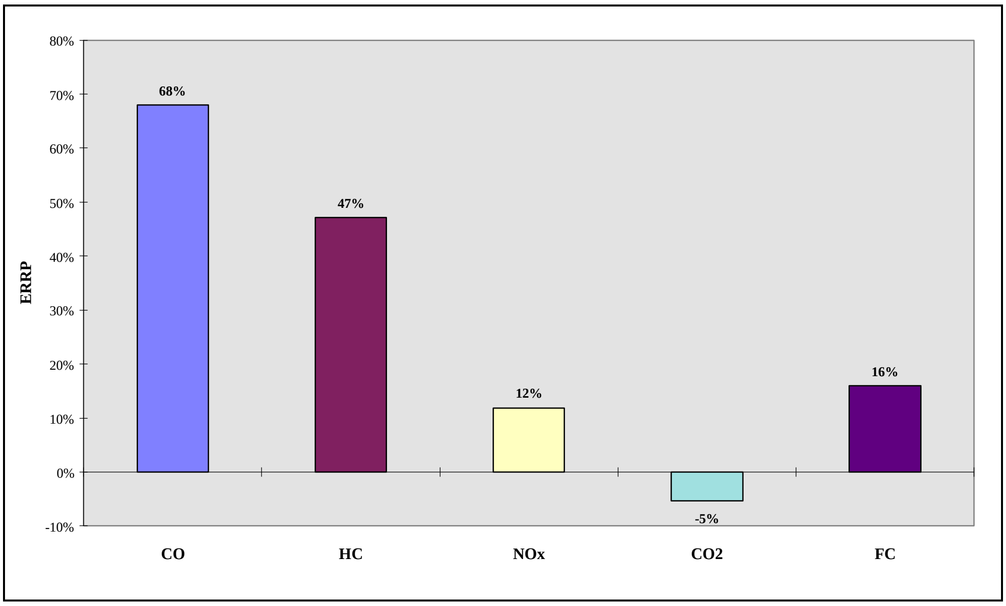
- ***Basic Indexes***
  N = number of vehicles that have been measured with the particular short test
  $\sum E_{ij}$ = cumulative emissions of *i* pollutant in *j* group
  N_{ij} = number of vehicles of *i* pollutant in *j* group

- ***Derivative Indexes***
  Emission Factor of *i* pollutant in *j* group: $EF_{ij} = \frac{E_{ij}}{N_j}$
  Emission Reduction Potential of *i* pollutant: $ERP_i = (EF_{i6} - EF_{i1}) \cdot N_6$
  Emission Reduction Rate Potential of *i* pollutant: $ERRP_i = 100 \cdot \frac{ERP_i}{\sum E_i}$

  Where one of the subscripts *i* or *j* in the above indexes is missing, then the index becomes more general (includes all pollutants or all groups respectively).

Source: Samaras & Kitsopanidis, 1998

Figure 15. Emission Reduction Rate Potential (ERRP) of Remote Sensing based on a CO cutpoint of 5%



This shows a high reduction rate potential for carbon monoxide and hydrocarbon emissions (68% and 47% respectively), a reduction in oxides of nitrogen emissions and fuel consumption (12% and 16% respectively) and a 5% increase in carbon dioxide emissions. The reason for the increase in the carbon dioxide emissions is that the faults decrease the combustion efficiency of the engine, resulting in fuel wastage which produces high

carbon monoxide and hydrocarbon emissions but lowers the carbon dioxide emissions. When the fault is repaired, the carbon dioxide emissions are restored to normal, with reductions in the carbon monoxide and hydrocarbon emissions.

The above ERRPs are based on just a CO cutpoint (5% CO). The inclusion of an NO cutpoint (1% ?) would modify these values, possibly increasing the NO_X reduction and decreasing the CO and HC values. However, as previously mentioned, there was only one vehicle with significantly high NO_X emissions - further information on vehicles with high NO_X emissions is required to fully evaluate the potential of a NO cutpoint.

It should be remembered that these Emission Reduction Rate Potentials are based on the sample used in the dynamometer tests. These were selected from the remote sensing and roadside tests and are typically high emitting vehicles. This sample is therefore a biased one, with a large number of high emitting vehicles.

To fairly evaluate the emission reduction rate potentials, an unbiased sample is required. In practise, this would require a large number of vehicle from the remote sensing survey selected at random and subjected to dynamometer tests - this would be extremely expensive and time consuming. However, the remote sensing readings from a random selection of vehicles are available - the remote sensing reading of almost all the vehicles that passed through the test sites.

These samples of vehicles are made up of various vehicle types - petrol non-catalyst, petrol catalyst and diesels. As mentioned previously, in some countries it is possible to determine the age of the vehicle from the registration number. Using assumptions about the year of introductions of catalyst, it is possible to consider just the latest vehicles which will be catalyst-petrol and diesel vehicles.

This has been carried out for the UK and the Greek test sites - after evaluating the average remote sensing reading per vehicle (to take into account repeat passes) the vehicles have been grouped into various years, and the number of vehicles with high emissions have been counted.

Table 6 and Table 7 show the results of this analysis for the UK and Greek results respectively. The tables show the total number of vehicles detected by registration index and the number with excessive remote sensing readings - based on cutpoints of 5% CO and 1% NO. The latest vehicles, shown at the top of the table, are assumed to be catalyst-petrol or diesel vehicles. All the vehicles with high CO readings are very likely to be catalyst-petrol vehicles - diesel vehicles, due to their lean mixtures, are very unlikely to produce high CO readings. The vehicles with high NO reading could include both catalyst-petrol and diesel vehicles (although in some cases it is possible to identify diesel vehicles from a badge on the video image of the vehicle, it is not possible to classify every vehicle as diesel or petrol from just the video image - the only way to do this, apart from stopping every vehicle, would be to obtain registration details from the local licensing centres, which could a very time consuming job).

From the tables is can be seen that there are a relatively small number of vehicles in the UK fleet with high CO emissions - which may be due to there relatively recent introduction. In Greece, there were a higher proportion of high emitting catalyst vehicles. This may be due to the fact that they has been around in Greece a lot longer - and therefore there were more older ones with old technology catalysts - but may also be due to the vehicles being under higher loads due to the incline at this site. It is anticipated that as the modern UK fleet of catalyst cars gets older, there will be more with high emissions.

It is therefore possible that out of the total number of catalyst-petrol and diesel vehicles, there will be 3% of catalyst cars with very high CO emissions. Another 2% of the vehicles might also have high NO emissions, some of which (but not all) will be due to faulty catalyst-petrol vehicles. However, some of these vehicles might be operating under cold start conditions, although it is impossible to tell from the data without stopping the vehicle and questioning the driver.

Figure 10 and Table 4 show that the vehicles with high CO emissions range from 4 to almost 30 times the legislative emissions limit. Assuming that the 3% of vehicles with high CO emissions have average emissions

of 40 g/km and the remaining 97% of the fleet have an average of 3 g/km, then the ERRP for the whole fleet (rather than the sample that was used above) can be approximated as:

ERRP = [40-3] * 3/[97*3+3*40] * 100%
= 27%

However, if only 0.5% of the fleet are gross CO polluters as observed in the UK remote sensing tests, then the calculation becomes:

ERRP = [40-3] * 0.5/[99.5*3+0.5*40] * 100%
= 6%

Therefore, for a fleet with 3% gross emitting catalysts cars, remote sensing might be able to reduce the total CO emissions by 27%. However, if only 0.5% of the fleet are gross emitters, then the reduction in CO emissions is only 6%.

Table 6. Number of Gross Emitting Vehicles in the UK Study

Reg. Index	Year	Emberton No. of Vehicles	Leicester No. of Vehicles	Total No. of Vehicles	No. with CO >5%		No. with NO >1%		No. with high CO or NO	
P	**96/97**	449	609	1058	4	0.38%	11	1.04%	15	1.42%
N	**95/96**	811	1067	1878	10	0.53%	38	2.02%	47	2.50%
M	**94/95**	721	1078	1799	7	0.39%	30	1.67%	37	2.06%
L	**93/94**	579	908	1487	9	0.61%	28	1.88%	37	2.49%
Sub-total for 'Catalyst' Cars				*6222*	*30*	*0.48%*	*107*	*1.72%*	*136*	*2.19%*
K	**92/93**	413	781	1194	34	2.85%	33	2.76%	65	5.44%
J	**91/92**	342	684	1026	52	5.07%	33	3.22%	84	8.19%
H	**90/91**	353	722	1075	77	7.16%	37	3.44%	111	10.33%
G	**89/90**	395	955	1350	126	9.33%	47	3.48%	167	12.37%
F	**88/89**	342	916	1258	109	8.66%	50	3.97%	156	12.40%
E	**87/88**	298	889	1187	93	7.83%	36	3.03%	127	10.70%
D	**86/87**	202	796	998	93	9.32%	38	3.81%	129	12.93%
C	**85/86**	182	585	767	87	11.34%	26	3.39%	110	14.34%
B	**84/85**	121	427	548	59	10.77%	26	4.74%	83	15.15%
A	**83/84**	107	465	572	68	11.89%	18	3.15%	81	14.16%

Table 7. Number of Gross Emitting Vehicles in the Greek Study

Reg. Index	Year	No. of Vehicles	No. with CO >5%		No. with NO >1%		No. with High CO or NO	
NBZ	**92**	510	18	3.53%	17	3.33%	35	6.86%
NBY	**95/96**	664	16	2.41%	13	1.96%	29	4.37%
NBX	**96**	125	5	4.00%	3	2.40%	7	5.60%
NBT	**95**	635	13	2.05%	22	3.46%	34	5.35%
NBP	**94/95**	639	16	2.50%	15	2.35%	31	4.85%
NBO	**94**	591	13	2.20%	16	2.71%	28	4.74%
NBN	**93/94**	578	23	3.98%	19	3.29%	40	6.92%
NBM	**93**	620	20	3.23%	22	3.55%	41	6.61%
NBK	**93**	589	10	1.70%	19	3.23%	27	4.58%
NBI	**92/93**	590	18	3.05%	13	2.20%	31	5.25%
NBH	**92**	553	23	4.16%	19	3.44%	42	7.59%
NBE	**91/92**	560	25	4.46%	16	2.86%	39	6.96%
"Cat" Sub-total		*6654*	*200*	*3.01%*	*194*	*2.92%*	*384*	*5.77%*
NBB	**91**	561	21	3.74%	16	2.85%	36	6.42%
NBA	**91**	569	18	3.16%	16	2.81%	34	5.98%
NAY	**90**	471	54	11.46%	24	5.10%	75	15.92%
NAX	**90/91**	457	29	6.35%	22	4.81%	50	10.94%
NAT	**89/90**	410	57	13.90%	30	7.32%	82	20.00%
NAP	**89**	376	44	11.70%	33	8.78%	74	19.68%
NAO	**88/89**	389	66	16.97%	40	10.28%	102	26.22%
NAN	**87/88**	286	44	15.38%	24	8.39%	67	23.43%
NAM	**87**	334	40	11.98%	21	6.29%	60	17.96%
NAI	**87**	263	49	18.63%	23	8.75%	66	25.10%
			Special Categories					
AMO	**89/90**	21	3	14.29%	4	19.05%	6	28.57%
AMY	**90/91**	25	1	4.00%	1	4.00%	2	8.00%
MOI	**91**	43	4	9.30%	4	9.30%	7	16.28%
PAO	**92/94**	118	3	2.54%	3	2.54%	5	4.24%
PAI	**91/92**	8	1	12.50%	0	0.00%	1	12.50%

4. Conclusions

Remote sensing has a number of advantages over conventional test methods:

- it can measure the emissions from a very large number of vehicles
- measurement can be made without any inconvenience to the vehicle driver
- a fully automated system would allow measurement to be made with little man-power effort

The one problem with remote sensing is the variation in a vehicle's exhaust emissions with driving parameters. Previous studies, based on fleet's comprising almost entirely of non-catalyst vehicles have identified this problem as making remote sensing ineffective. However, the introduction of closed loop control on catalyst equipped cars reduces the amount of variation that occurs.

The variation on the vehicles exhaust emissions can mean that vehicles are detected with high CO emissions, whereas under a standard idle test the CO emissions are reasonable. However, the work in this study has shown that catalyst-petrol vehicles with very high CO emissions can be detected with remote sensing - although remote sensing cannot detect vehicles with CO emissions just over the emissions limits without including a large number of errors of commission, it can detect the gross emitters.

It is possible that the system could be 'tuned' to take into account the particular road layout, the speed and acceleration of the vehicle passing and perhaps even the make and model of the vehicle to provide an even better detection rate. Certain vehicles may characteristically produce high emissions under certain conditions (eg low powered vehicles will operate under wide open throttle conditions more often than high powered vehicles, which is likely to require open loop, fuel enrichment, operating conditions).

Based on just a remote sensing CO cutpoint of 5%, the sample subjected to dynamometer test produces very high Emission Reduction Rate Potentials of 68% and 47% for carbon monoxide and hydrocarbons respectively (it should be noted, however, in that the sample was biased in that it contains a large number of dirty vehicles). There is also some reduction in the oxides of nitrogen emissions and fuel consumption, with a small increase in the carbon dioxide emissions.

Using just a CO cutpoint, the detected vehicles will also include a number of vehicles with high HC emissions (most of the vehicles with high HC emissions will also have high CO emissions). A few vehicles with high NO_X emissions will also be detected.

Faults on a vehicle with a closed loop controlled catalytic converter can be roughly categorised into two groups:

1. Catalyst failure
2. Engine management failure

Vehicles with a failed catalyst will have emission rates similar to a non-catalyst vehicle - ie CO, HC and NO_X will all be high. For vehicle falling into the second category, the actual catalyst will be working (unless the fault is so severe as to cause severe thermal degradation of the catalyst) but the mixture will be inappropriate for the efficient operation of the 3-way catalyst. If the mixture is weak, then CO and HC emissions might be normal but NO_X emissions will be high. If the mixture is rich, then CO and HC will be high, while NO_X might be normal.

Therefore vehicles with a faulty catalyst could be detected by just measuring CO emissions, but only a proportion of vehicles with engine management problems would be detected. Vehicles running lean with high NO_X emissions might go unnoticed with just a CO cutpoint. It may therefore be necessary to include an NO cutpoint. However, in our test sample, only one vehicle dynamometer tested exhibited very high NO_X emissions - further study in this are is required.

The sample selected for dynamometer testing was biased towards high emitting vehicles. Analysis of the remote sensing data shows that high emitting vehicles could account for 3% of the fleet in Greece and 0.5% of the fleet in the UK where catalysts have only recently been introduced. It is likely that the number of gross emitters would increase as the catalyst fleet gets older. Although this sounds like a small number, the gross emitting vehicles detected in the sample had CO emission rates up to 30 times the legislative emissions limit and HC emission rates up to 14 times the limit.

Assuming that 3% of the catalyst-petrol fleet have average CO emissions of 40 g/km and the remaining 97% have average CO emissions of 3 g/km, then this produces an ERRP of 27% for the whole fleet - clearly this 3% produce a significant contribution to the total emissions and targeting just them could significantly reduce total emissions. However, if only 0.5% of the fleet are high emitters, with CO emissions of 40 g/km, then the ERRP is only 6%.

It should also be noted that the remote sensing tests were carried out in countries which already have an established I/M test procedure. The number of dirty vehicles detected shows the importance of carrying out tests in addition to the annual/biannual I/M test.

5. Recommendations

Previous studies has been restricted to a few days testing, with a number of vehicles pulled for testing during the course of the work. This results in some repeat readings on the vehicles stopped for testing, but not for all vehicles. It may be more interesting to visit a single site for a few weeks, analyse the data to identify vehicles with a large number of repeat readings and high emissions and then try to locate those vehicles for further tests (this could be done by trying to spot and stop the vehicle at the test site - if they have passed through the site several times previously, then they will probably continue to use the same route, perhaps even at the same time of day - or by tracing the vehicle through the appropriate vehicle licensing offices).

One of the problems with the collected data is the analysis of the video images of the vehicles - this currently takes a great deal of time to inspect each image and note down the registration number and vehicle details. One days testing takes about 5 man-days of effort to analyse the tapes, which it both expensive and time consuming. This could be automated by the use of a registration number recognition system. This could be integrated with the remote sensing software to allow live number recognition, or used after the test to analyse the collected images.

Another problem with the current system is the use of standard video tapes. These tapes run continuously, independent of the traffic flow, and need replacing every 3 hours. During analysis, the tapes have to be constantly played, paused, rewound, fast forwarded to find the next vehicle on the tape. With the current developments in mass storage devices for PCs, an alternative storage media could be used (eg CD ROM, DVD etc). This would reduce the amount of wasted space (as currently occurs on the video tape when there is a large gap between vehicles), which would make the video image analysis easier and may allow longer time until the storage media is full.

With on-line registration number recognition it would be possible to do away with the need for video image storage - more precise vehicle details could be obtained from a vehicle registration database. Or the video image storage could be selective - only storing the images of vehicles that repeatedly have high emissions.

A further problem with the current system is its high visibility - the source and detector are placed either side of the road surrounded by cones to protect them and a large van is parked at the side of the road. Vehicles often slow down while passing through the site, resulting in invalid readings. The presence of police officers further up the road also causes vehicles to slow down, thinking they are approaching a speed check area. It is possible that the system could be hidden away within normal street ‘furniture’ and be fully automated and secured so that no manning is required.

It is therefore recommended that:

- Remote sensing should be carried out at a site over a few weeks. Modern vehicles with a high number of repeat readings and a high average should be further investigated (initially using a cutpoint of 5% CO, but this could be modified according to the site location and the condition of the local traffic - investigations could be carried out on 5% of the traffic with the highest emissions).
- Further investigation could also be carried out on vehicles that produce high NO readings.
- Registration number recognition software needs to either be built into the remote sensing device or used to analyse the video images, in order to remove the large burden of visually analysing the video images.
- To provide further information about the vehicles and to categorise them according to vehicle technology, a vehicle registration database is needed.
- Speed and acceleration needs to be taken into account with the remote sensing readings - if large accelerations or decelerations are detected, then the remote sensing readings should be rejected as they will be unrepresentative of normal driving.
- After a large amount of remote sensing data has been collected, it might be possible to derive model specific cutpoints. This would prevent specific models that produce high tailpipe concentrations under certain conditions (eg low-powered vehicles that occasionally have to operate under wide open throttle conditions) from being incorrectly identified as high emitters.
- Development of the remote sensing system should allow the device to be hidden within normal street 'furniture', where it can operate unmanned.

In the above usage of remote sensing, the exhaust emissions would be measured without any interference with the traffic flow (unlike the current study which stopped some of the vehicles for a roadside test). There would be no need to carry out an immediate roadside check of the vehicles. Any vehicles over the period that repeatedly exhibit high exhaust emissions could be contacted and advised to have their vehicles checked (as the vehicle registration numbers are known, the owners details could be obtained from a vehicle registration database).

There may be reasons why a suspect vehicle has high remote sensing readings - eg cold start or high load fuel enrichment (although speed and acceleration measurement should account for the latter case). A follow-up test according to the I/M test procedures would therefore be required (and would also allow the repair garages to check that the vehicle has been repaired properly).

The follow-up could be carried out in a number of ways such as:

- the vehicle owner is *instructed* to submit his vehicle for an emission test at a local test centre within a certain time limit.

- The vehicle owner is *advised* that his vehicle has high exhaust emissions and that it should be repaired as soon as possible.

Alternatively, remote sensing could be used in conjunction with roadside tests. A number of countries currently carry our random roadside checks on exhaust emissions. By selecting vehicles that look in a poor condition and vehicles that are know to have high exhaust emissions, a 'hit' rate of 25-35% can be achieved. However, these vehicles with high emissions are predominantly old vehicles without catalysts. Remote sensing could assist these existing roadside checks by selecting modern vehicles with catalysts that appear to be gross emitters (these vehicles are much more important than the old ones as they are likely to cover a much higher annual mileage).

Remote sensing could also be used as a "clean-screen" device before a loaded transient test - in order to reduce the burden of the loaded transient test lanes, vehicles which exhibit low remote sensing readings can be given an immediate pass, while all other vehicles have to be tested over the transient cycle. Pilot studies have been carried out quite successfully within the Ontario IM240 I/M programme, eliminating about one third of the

vehicles for IM240 testing while preserving 88% of the emission reduction potential of a full IM240 programme (Petherick, 1996)

Another use for remote sensing might be to provide an independent means of evaluating the effectiveness of Inspection and Maintenance programmes. Examples of this application with positive results are available for both the US (Stedman et al, 1997) and Sweden (Sjödin et al, 1997). This could also serve as a means of evaluating other road vehicle emission control strategies eg new car emission standards (in-use compliance and penetration of new standards into the fleet), new fuels etc.

6. References

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Stedman D. H., Bishop G. A., Aldrete P., Slott R. S. (1997) On-Road Evaluation of an Automobile Emission Test Program, Environ. Sc. Techn. 31, 927-931.

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APPENDIX A:
Dynamometer versus Remote Sensing Results

The following graphs show the various comparisons of the dynamometer test results (over the NEDC test cycle) with the remote sensing readings.

The following dynamometer results:

--.a. **carbon monoxide (CO)**
--.b. **hydrocarbons (HC)**
--.c. **oxide of nitrogen (NO_X)**
--.d. **carbon dioxide (CO_2)**
--.e **fuel consumption (FC)**

are shown plotted against the following remote sensing readings:

A1. **carbon monoxide (CO)**
A2. **hydrocarbons (HC)**
A3. **nitric oxide (NO)**
A4. **carbon dioxide (CO_2)**

Figure A1.a Dynamometer CO Emissions plotted against Remote Sensing CO Readings

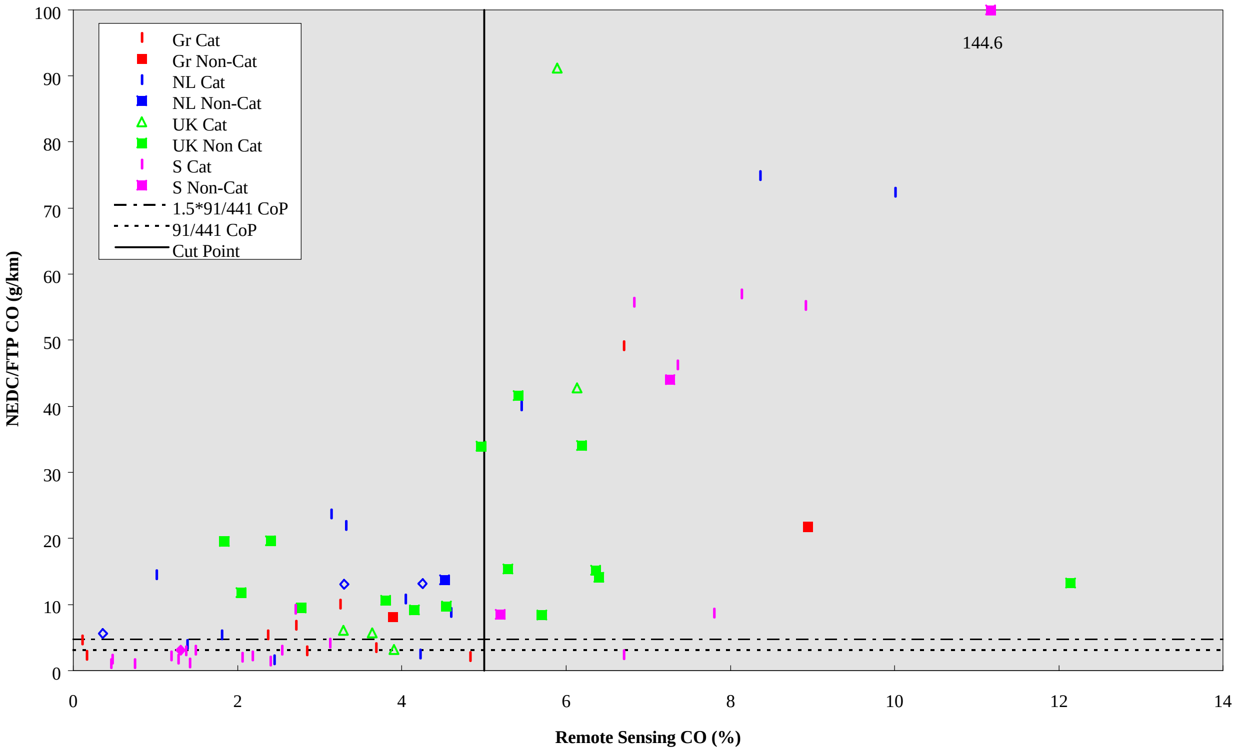

Figure A1.b Dynamometer HC Emissions plotted against Remote Sensing CO Readings

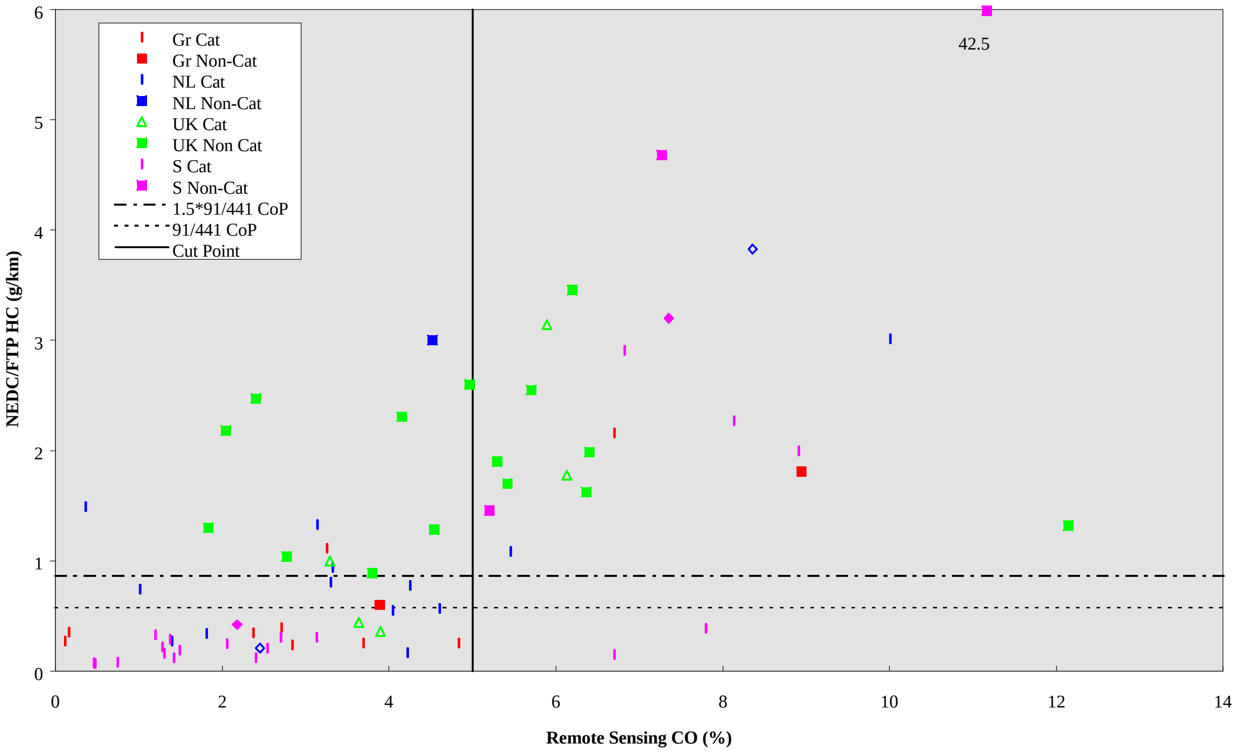

Figure A1.c Dynamometer NO_X Emissions plotted against Remote Sensing CO Readings

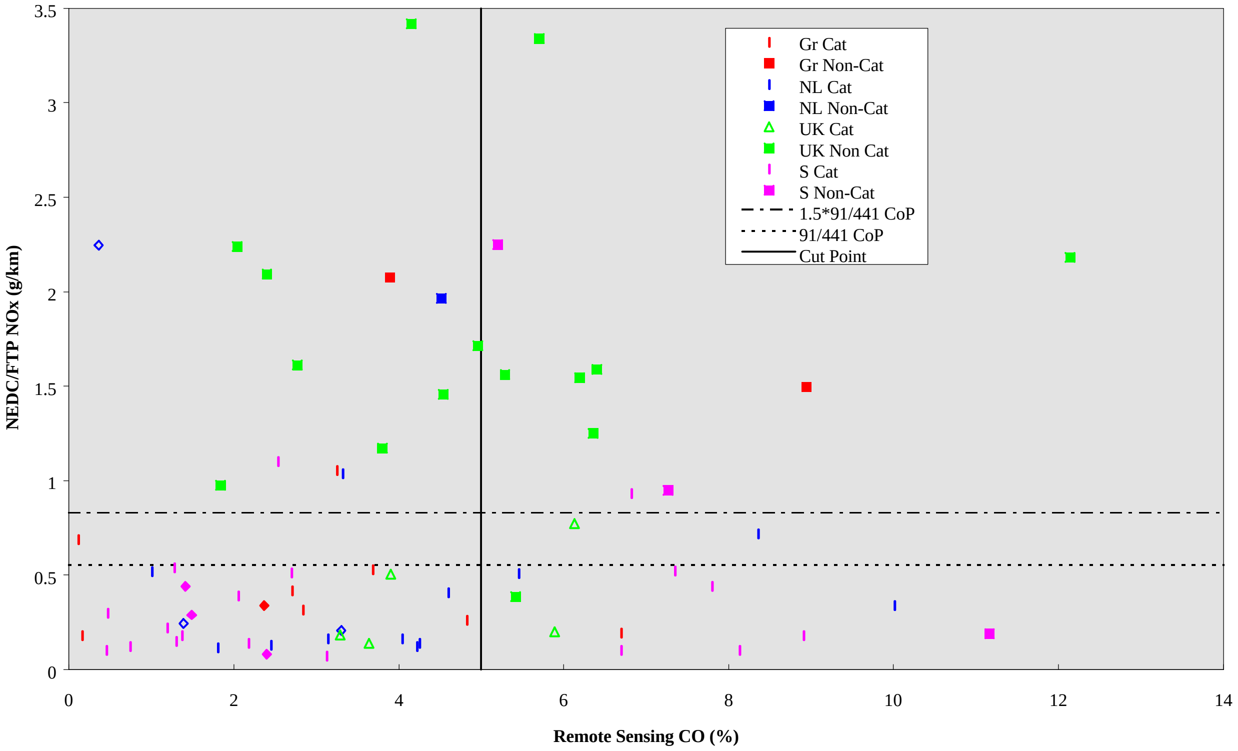

Figure A1.d Dynamometer CO_2 Emissions plotted against Remote Sensing CO Readings

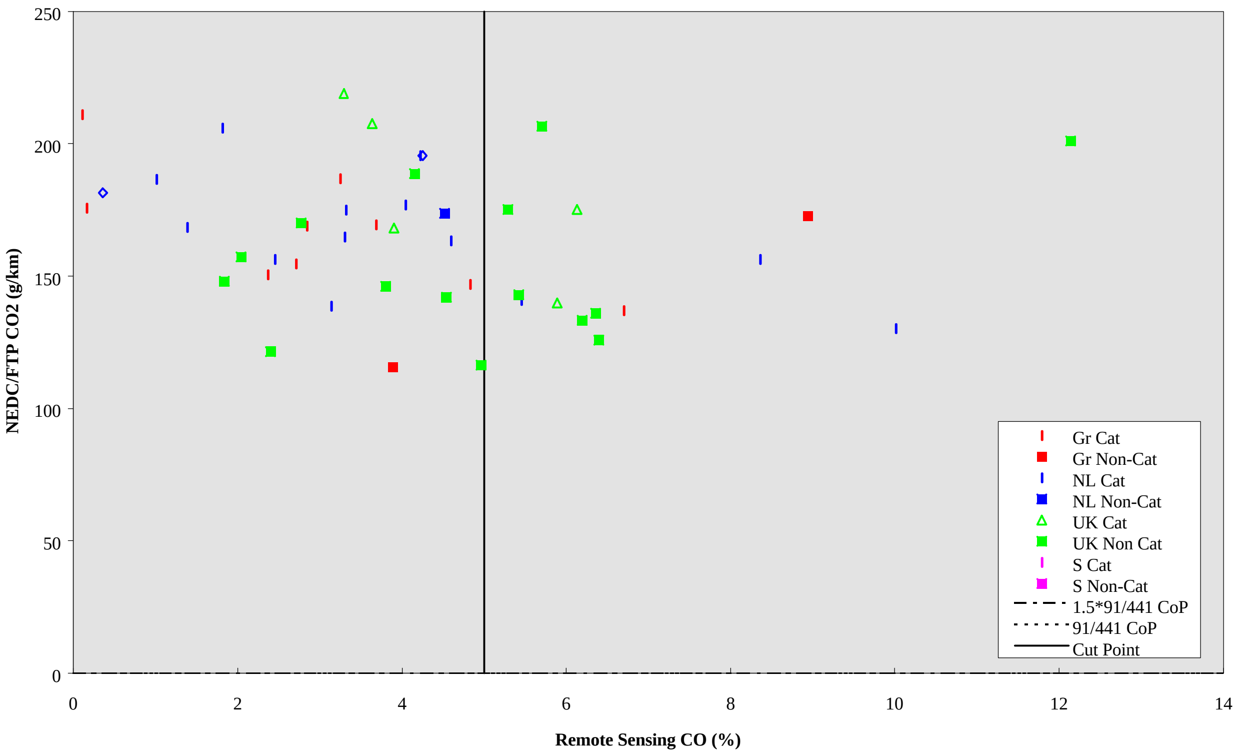

Figure A1.e Dynamometer Fuel Consumption plotted against Remote Sensing CO Readings

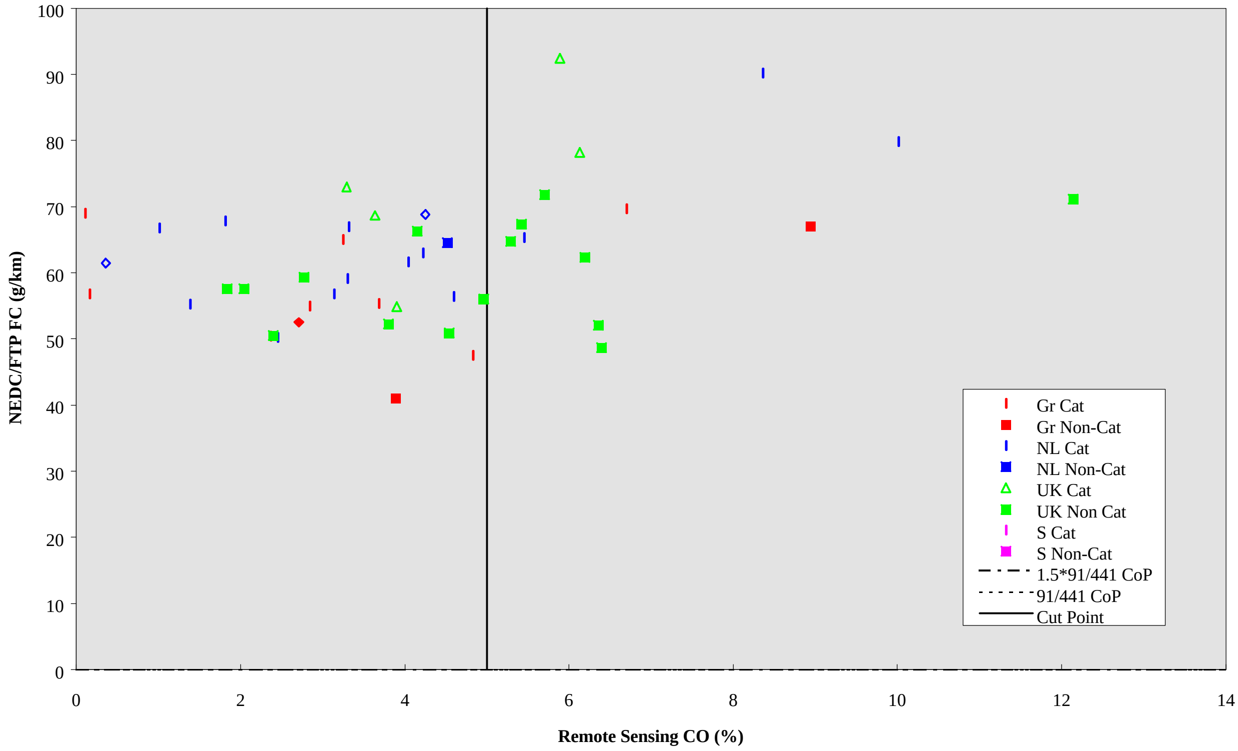

Figure A2.a Dynamometer CO Emissions plotted against Remote Sensing HC Readings

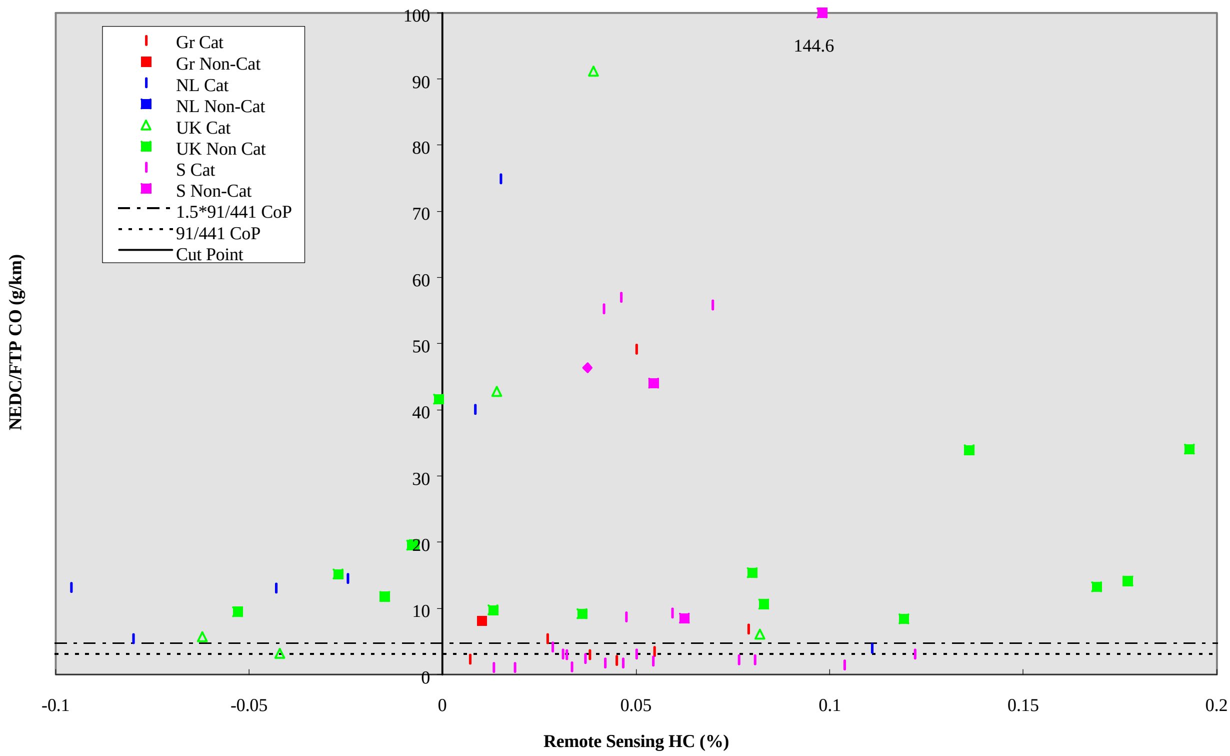

Figure A2.b Dynamometer HC Emissions plotted against Remote Sensing HC Readings

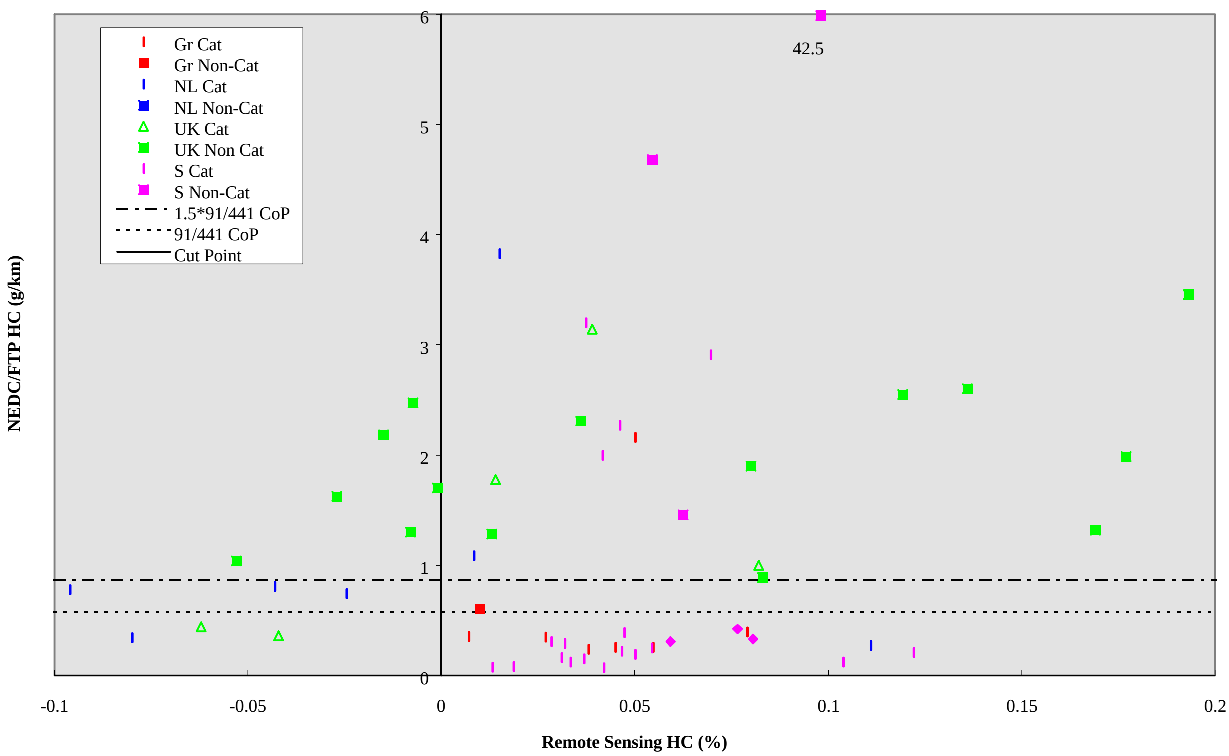

Figure A2.c Dynamometer NO_X Emissions plotted against Remote Sensing HC Readings

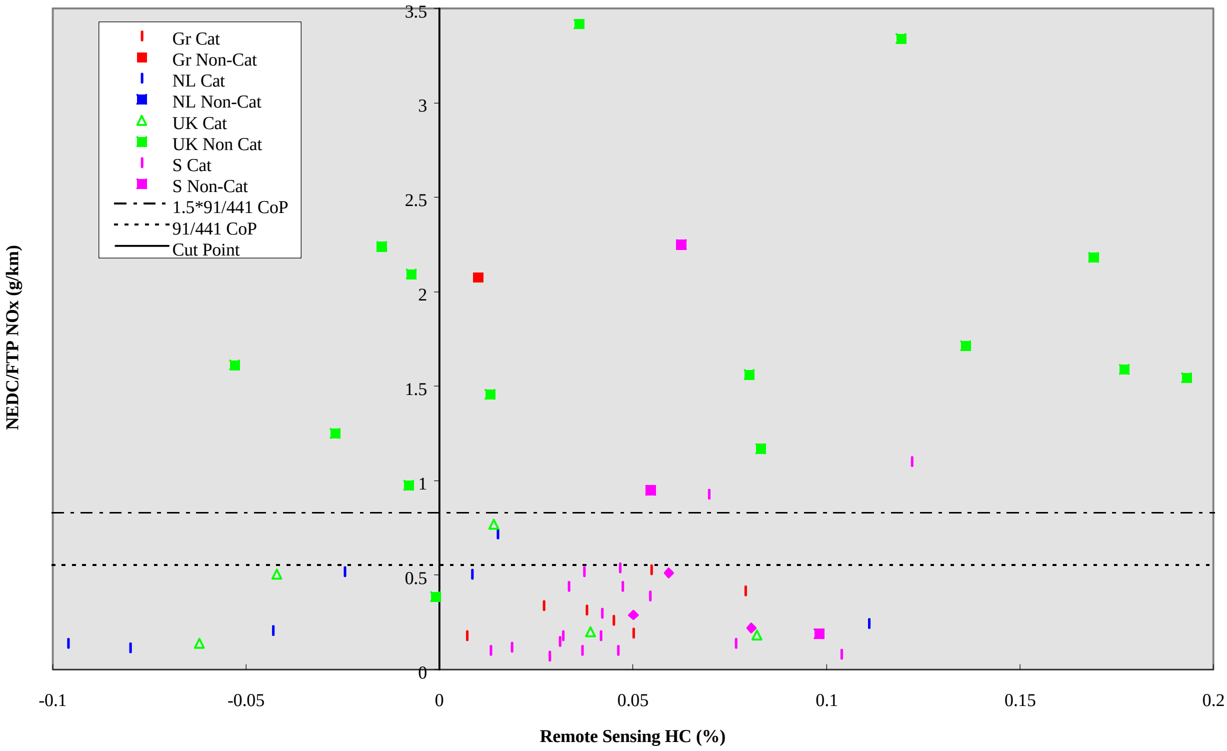

Figure A2.d Dynamometer CO_2 Emissions plotted against Remote Sensing HC Readings

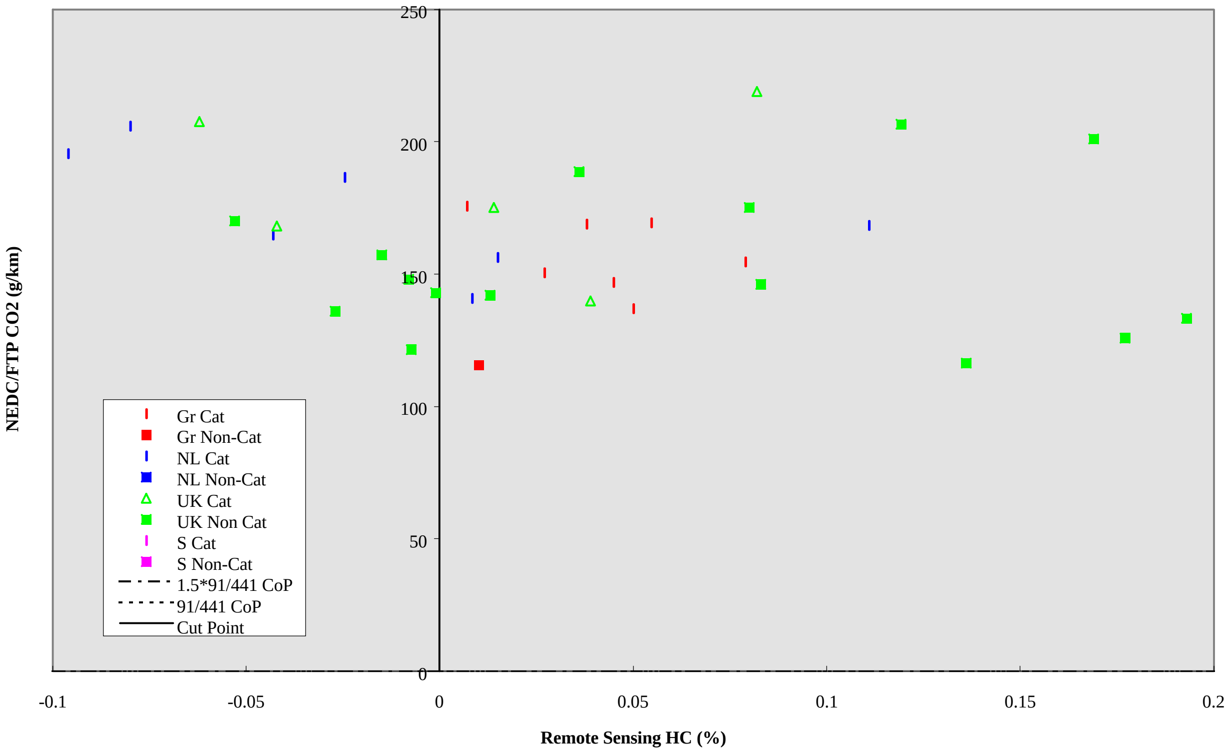

Figure A2.e Dynamometer Fuel Consumption plotted against Remote Sensing HC Readings

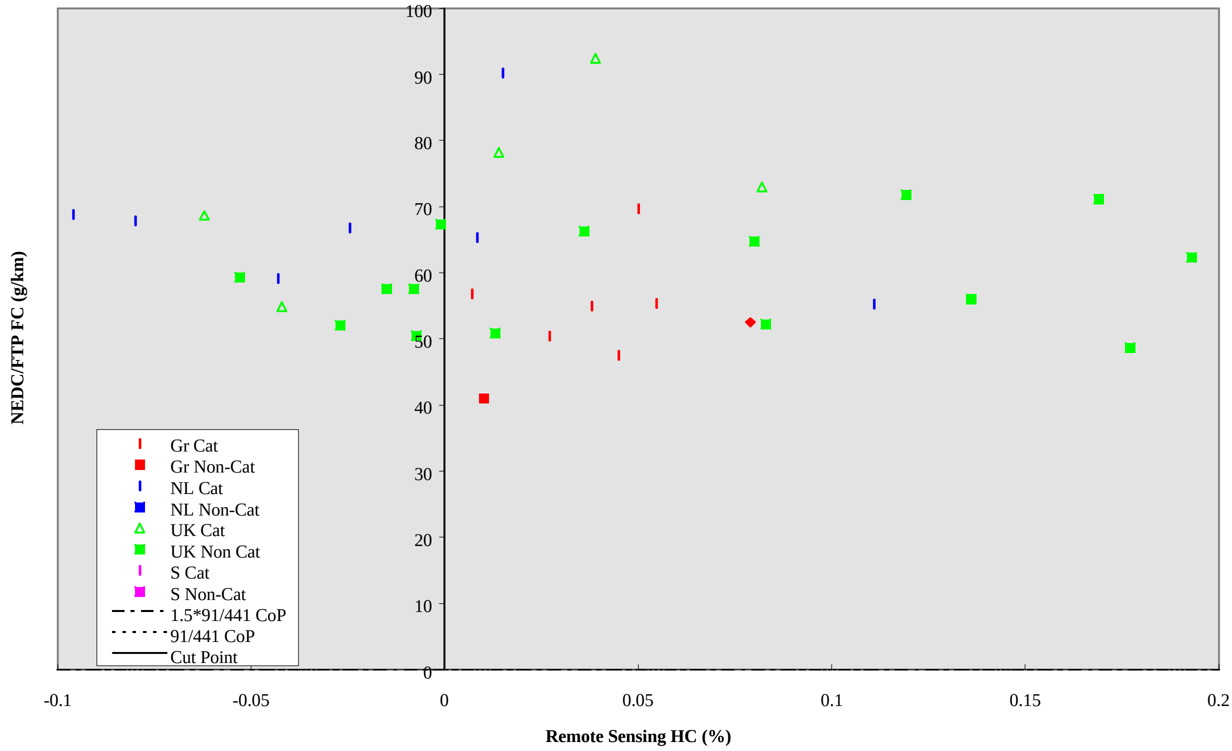

Figure A3.a Dynamometer CO Emissions plotted against Remote Sensing NO Readings

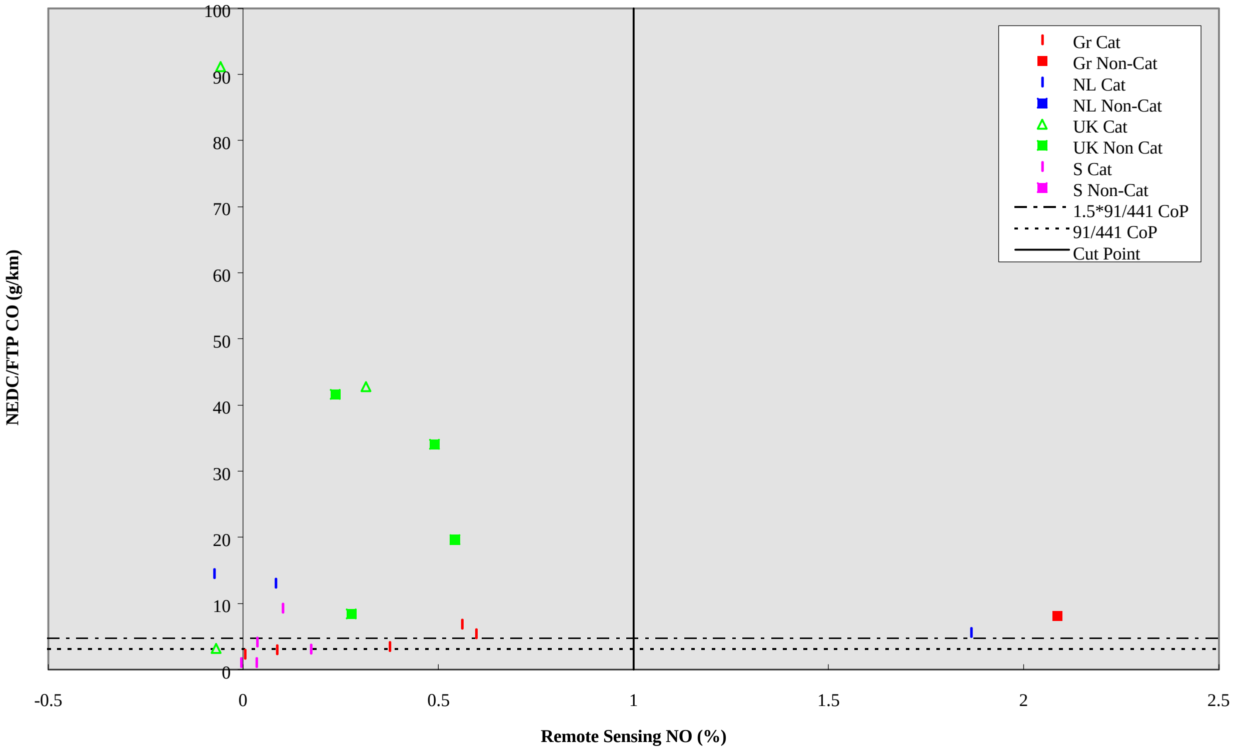

Figure A3.b Dynamometer HC Emissions plotted against Remote Sensing NO Readings

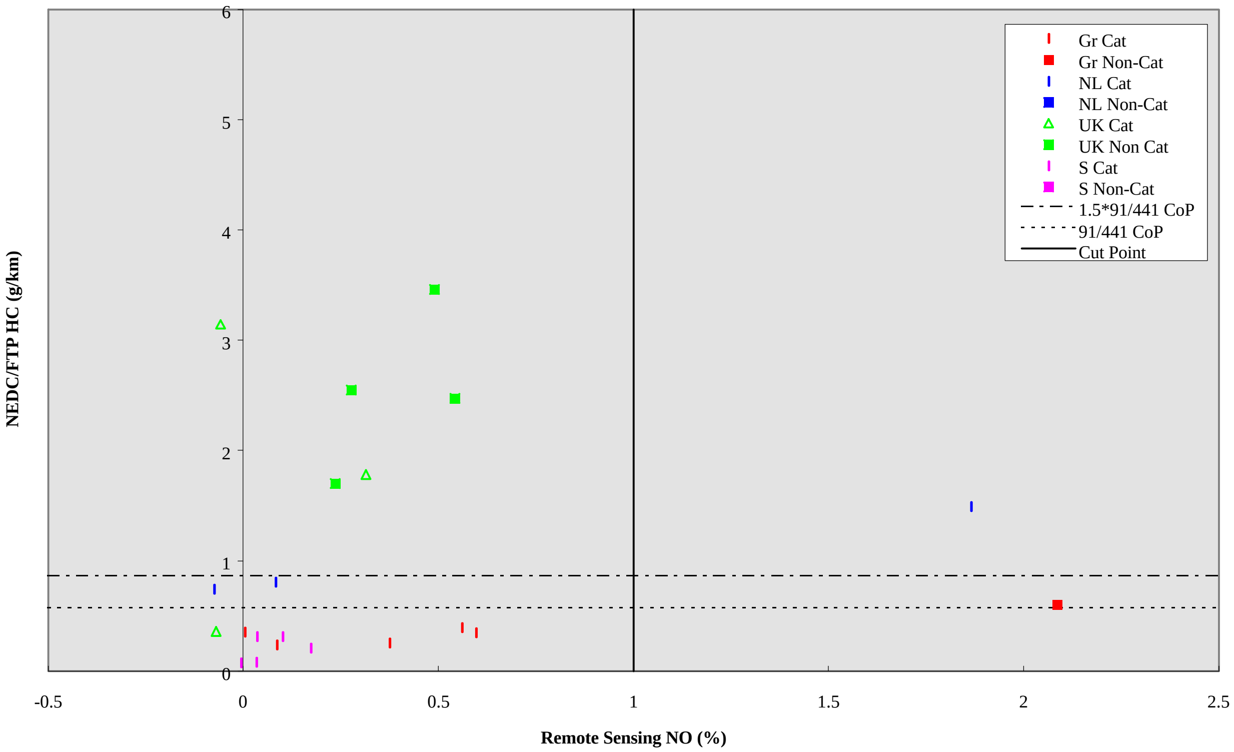

Figure A3.c Dynamometer NO_X Emissions plotted against Remote Sensing NO Readings

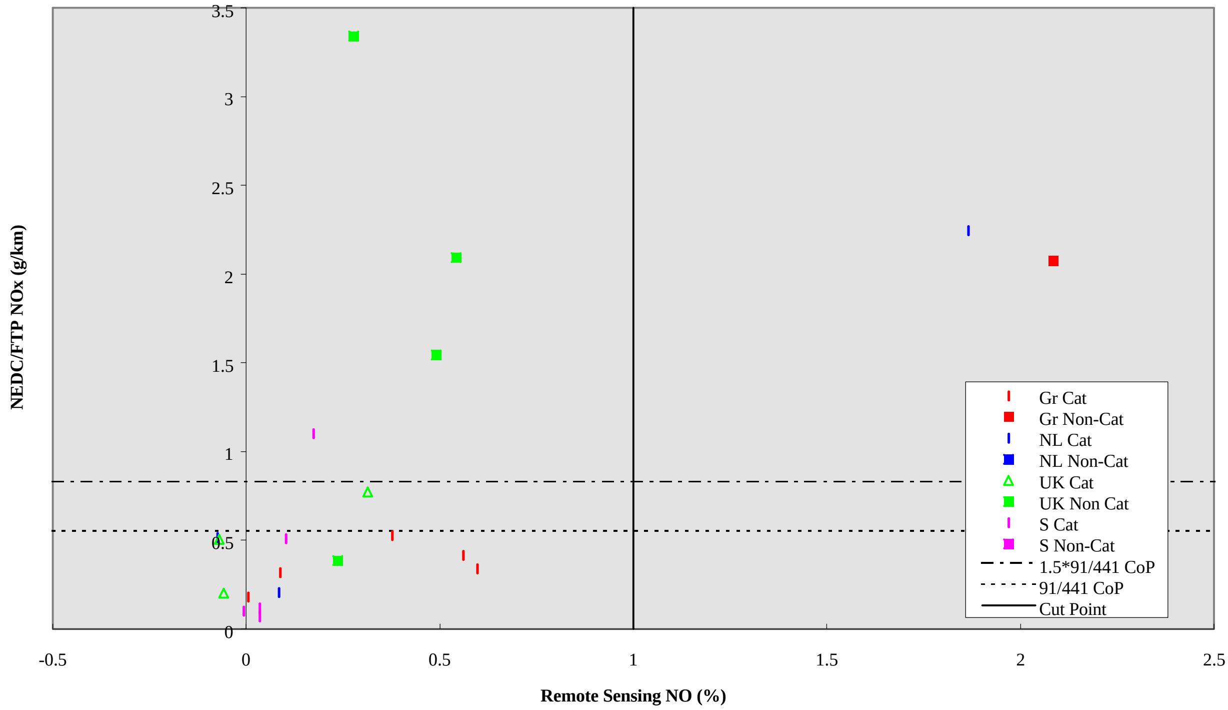

Figure A3.d Dynamometer CO_2 Emissions plotted against Remote Sensing NO Readings

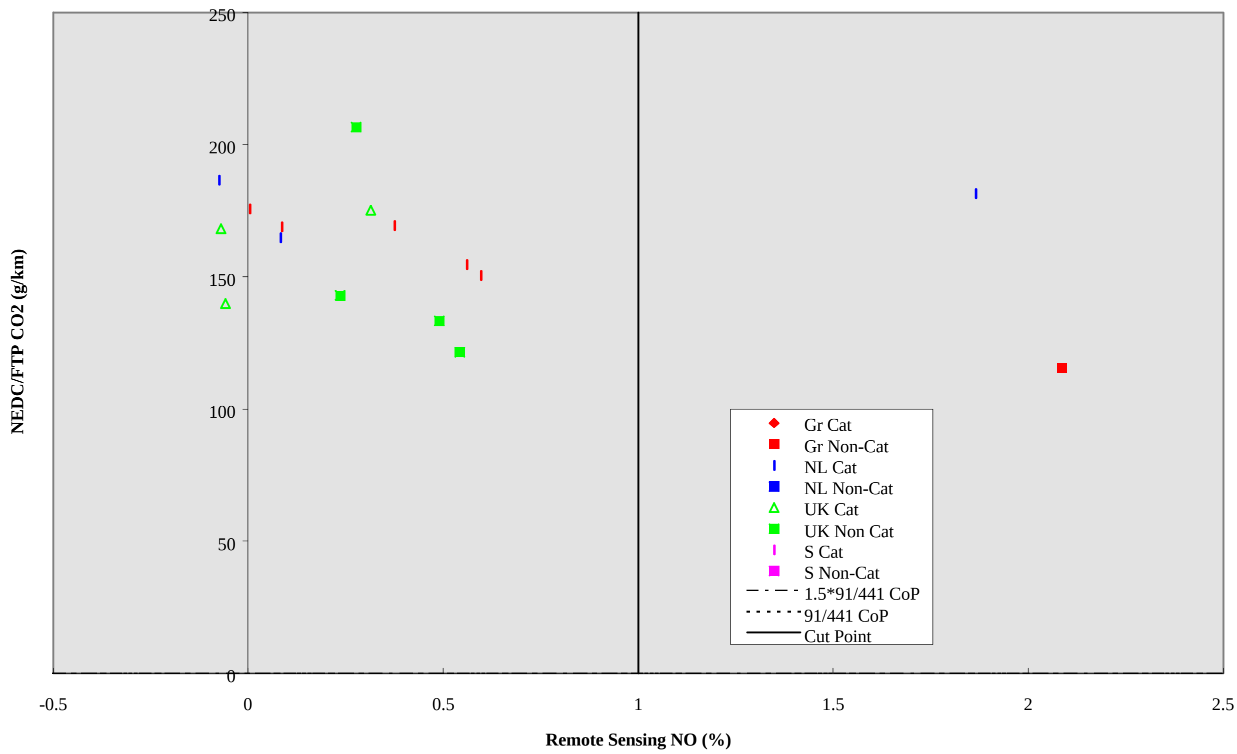

Figure A3.e Dynamometer Fuel Consumption plotted against Remote Sensing NO Readings

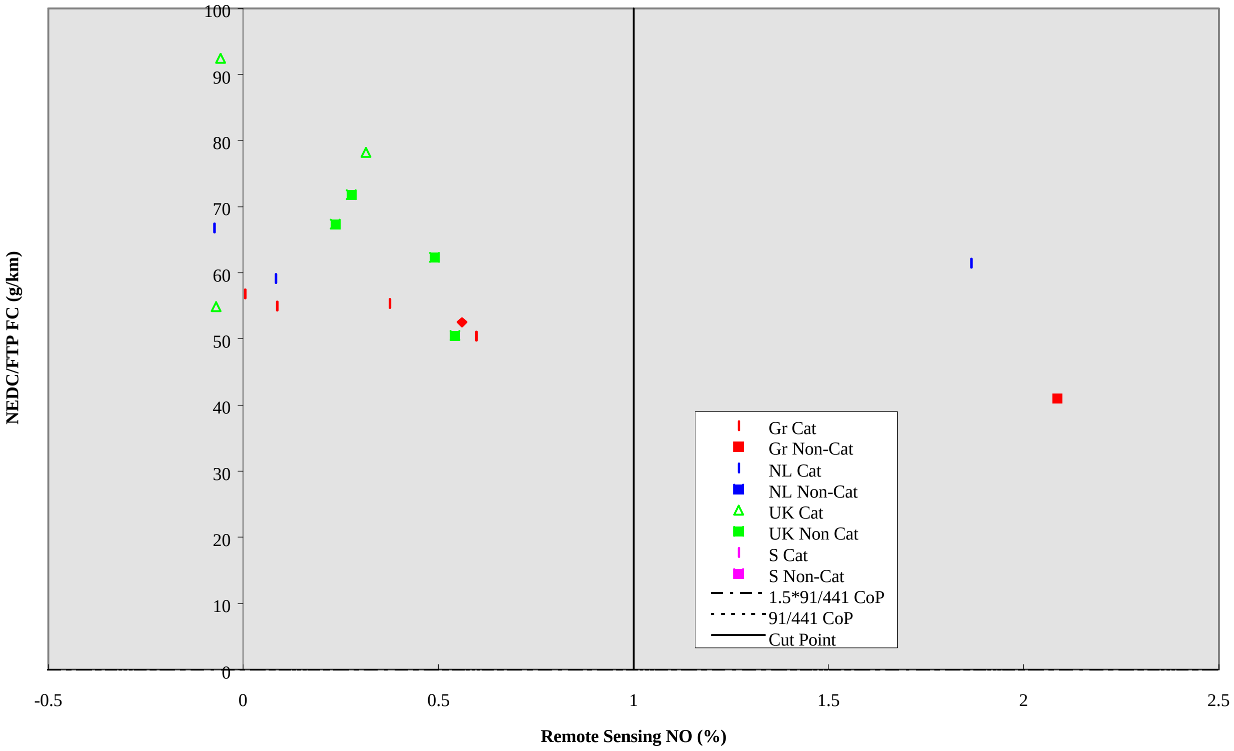

Figure A4.a Dynamometer CO Emissions plotted against Remote Sensing CO_2 Readings

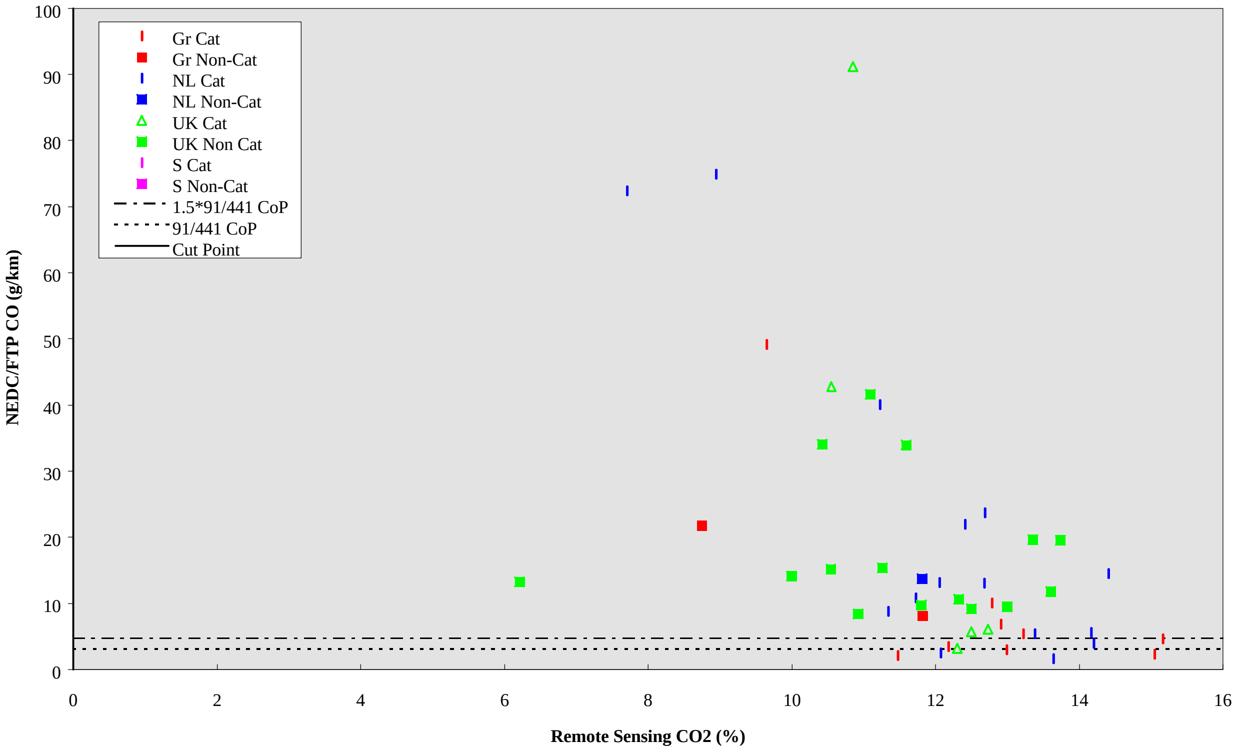

Figure A4.b Dynamometer HC Emissions plotted against Remote Sensing CO_2 Readings

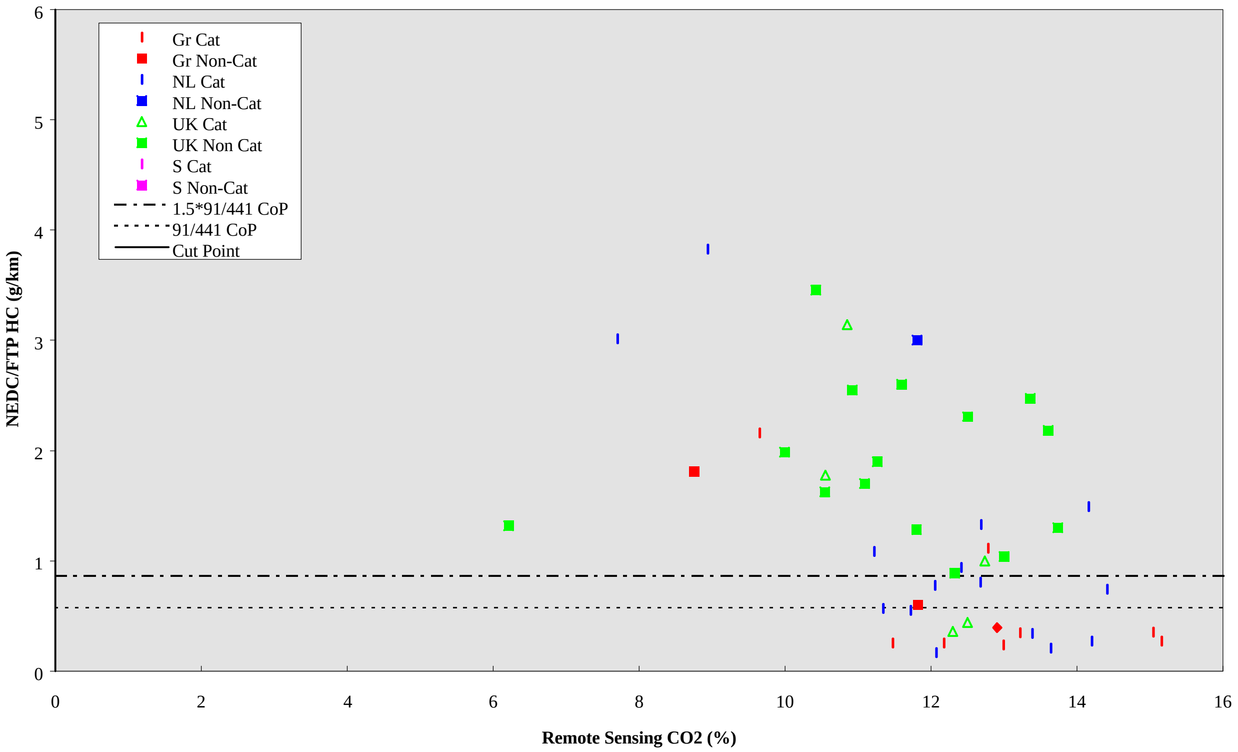

Figure A4.c Dynamometer NO_x Emissions plotted against Remote Sensing CO_2 Readings

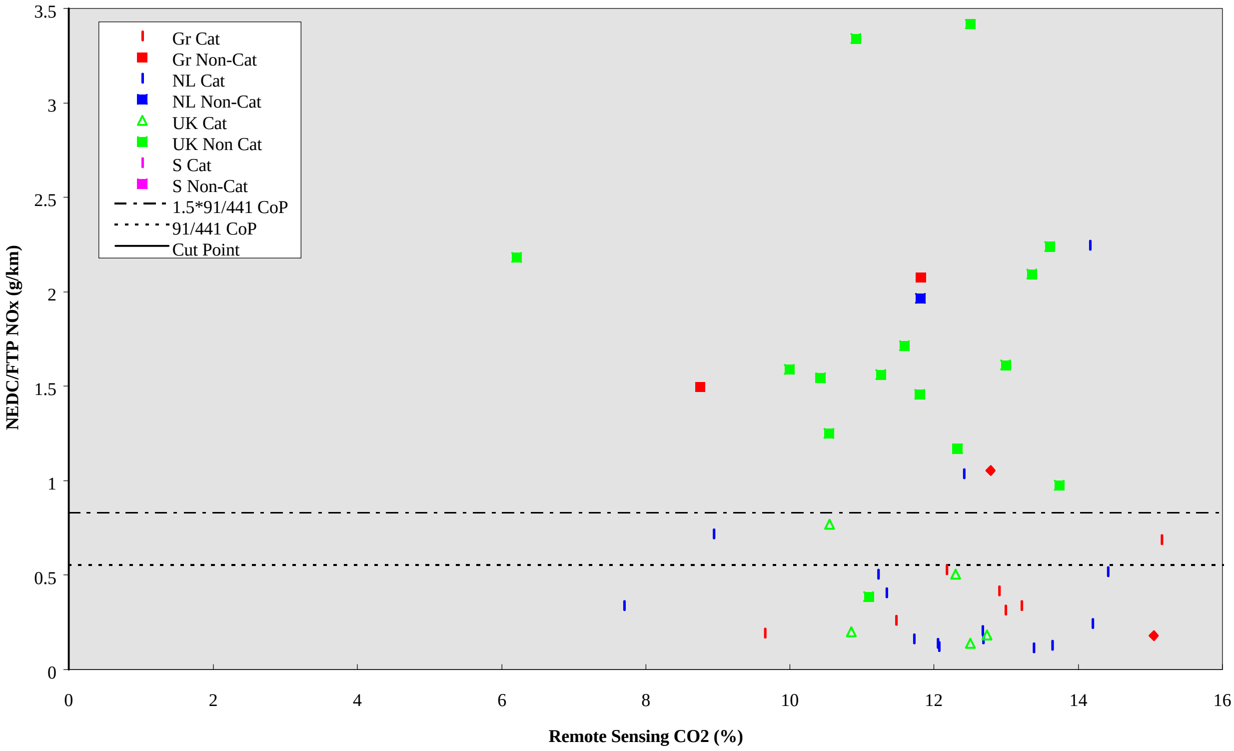

Figure A4.d Dynamometer CO_2 Emissions plotted against Remote Sensing CO_2 Readings

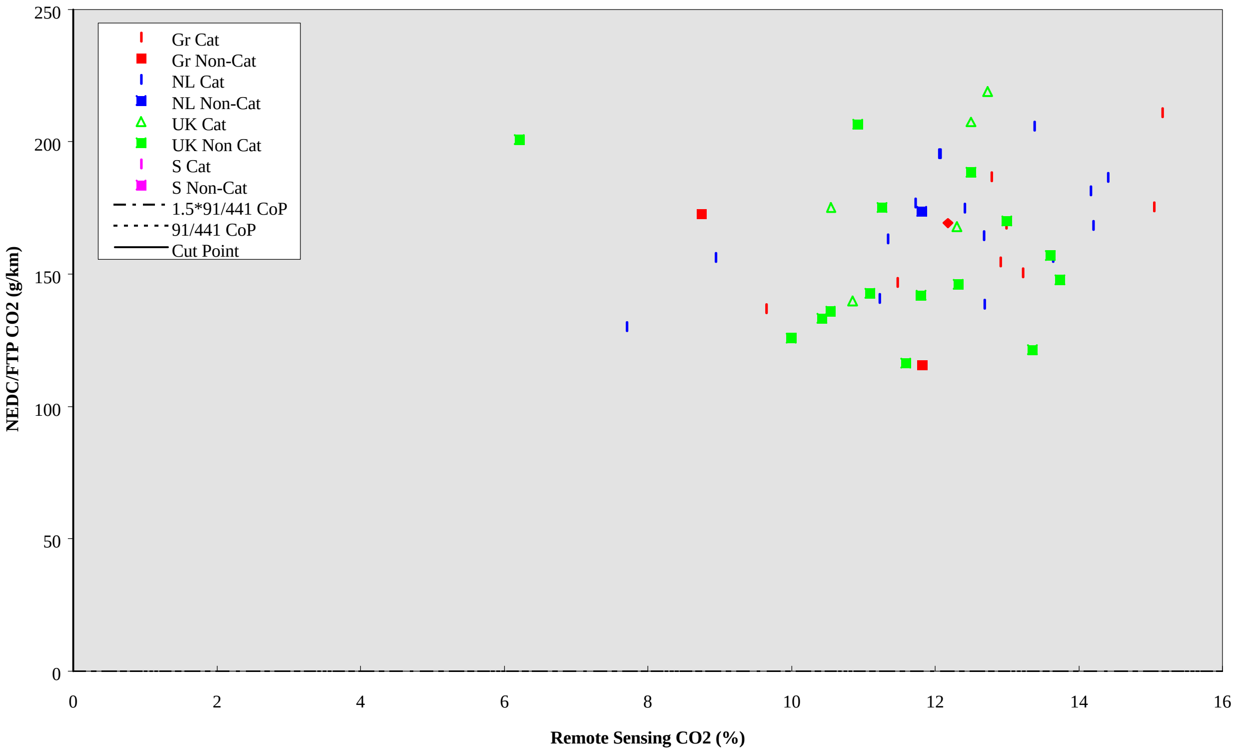

Figure A4.e Dynamometer Fuel Consumption plotted against Remote Sensing CO_2 Readings