UG219 TRAMAQ - cold start emissions. Summary report

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Executive Summary

This work was carried out by AEA Technology on behalf of the Charging and Local Transport Division of the UK Department of the Environment Transport and the Regions (DETR) as a project within the their TRAMAQ Programme. The aim of the TRAMAQ Programme is to provide traffic and environmental planners with information and tools to help them account for traffic management scheme options in their air quality assessments. In this project we were required to develop a planning tool to help Local Authorities (LAs) evaluate the effect of traffic management (particularly parking) schemes on air quality burdens in support of their obligations under the 1995 Environment Act. This Act requires LAs to review and, if necessary, prepare action plans for meeting the Government's air quality objectives for 2005.

The main objective of the research was the development of a model, based on the thermal condition of a vehicle, to predict excess cold start emissions that could be used to assess the effects of cold start on actual vehicle parking control scenarios. The importance of this topic arises from the high proportion of passenger car journeys and vehicle miles that are carried out under cold start conditions and the high excess emissions, at least for some pollutants and vehicle technologies, that result from these conditions of use.

The work programme comprised the following main activities.

- *A study of the literature and available data on cold start emissions*. This led to the confirmation of the proposed modelling approach and the refinement of the experimental programme required for generating the data necessary for model development.
- *A detailed experimental study on three vehicles*. These vehicles were selected as representative of the main passenger car vehicle technologies in the evolving national fleet (gasoline three way catalyst, gasoline direct injection and modern diesel). This measurement programme involved a comprehensive test matrix of ambient temperature, vehicle temperature and vehicle emissions measurements. The results were analysed and used to provide the basis for the development of the model.
- *The establishment of the mathematical basis of a cold start emissions model.*
- *A further experimental measurement campaign*. This involved a reduced test matrix carried out on a further 12 vehicles. It was configured to confirm general applicability of the model and to expand the database within it.
- *A preliminary investigation of selected non-regulated vehicle emissions*. This included assessments of the cold start emissions on a limited range of vehicles of two additional pollutants listed in the National Air Quality Strategy, benzene and 1,3 butadiene, and of size-differentiated particulate number flux, which is a metric of possible future regulatory significance. Both categories of gasoline vehicle exhibited significant cold start excess emissions of benzene and of 20nm particulate flux.
- *The refinement and production of the model*. This involved iterative refinement to take account of both the additional experimental data and our developing awareness, through discussion, of the requirements of different categories of potential users of the model.

The main output of the project is an empirical model capable of predicting cold start excess emissions from different vehicle use scenarios. The model, entitled 'EXEMPT (EXcess

EMissions Planning Tool), has been incorporated into a Microsoft Excel spreadsheet. It has been configured for use either as a simple tool for scheme comparisons involving appropriate default data entries or as a more sophisticated modelling tool where a higher degree of user intervention is required. Detailed operating instructions and worked examples are given in the user guide which accompanies the model. The illustrative worked examples are:

- excess emissions as a function of distance from a car park
- excess emissions as a function of distance from a town centre
- excess emissions as a result of changing the number of available traffic lanes.

The accuracy of the model has been estimated on the basis of the cumulative effect of the uncertainties in the experimental data embedded within it.

In its current form the model's application is limited by the scope of the input data which encompasses emissions data from a relatively restricted sample of current passenger car models. This has the effect of limiting the accuracy of its current predictions, the range of potential applications and the lifetime of its serviceability. These are not limitations of the model itself but of the emissions data embedded within it. These limitations could therefore be overcome by subsequent incorporation of additional emissions data from, for example, other vehicle classes such as PSVs or HGVs, or, at a later date, more modern technology vehicles as they achieve significant penetration of the national vehicle fleet.

This report summarises the main activities undertaken within the project and includes a guide to the use of the arising model. A large body of emissions data was produced during the experimental measurement campaigns. This was used in the development of the model but it may be of value in other applications contexts and can therefore be made available by the authors to other researchers.

The model and its user manual will be made freely available in electonic format to potential users.

Contents

1 Introduction

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The main objective of the research reported here was the development of a model, based on the thermal condition of a vehicle, to predict excess cold start emissions that could be used to assess the effects of cold start on actual vehicle parking control scenarios. The importance of this topic arises from the high proportion of passenger car journeys and vehicle miles which are carried out under cold start conditions and the high excess emissions, at least for some pollutants and vehicle technologies, that result from these conditions of use.

The work programme comprised the following main activities:

- a study of the literature and available data on cold start emissions,
- the selection of vehicles and measurement parameters for the experimental study,
- a detailed experimental study on three vehicles to provide the basis for model development,
- the establishment of the mathematical basis of a cold start emissions model,
- a further experimental campaign, involving a reduced test matrix, to confirm general applicability of the model and expand the database within it,
- refinement of the model and
- illustration of its application.

This report summarises those activities and includes a guide to the use of the arising model. Further detailed results can be obtained from the authors.

(Note. In this report, unless specifically qualified, the term 'cold start' is used in its broadest sense, i.e. vehicle operating range prior to achievement of 'normal' engine temperature conditions).

2 Background

Current environmental planning uses emission factor models to calculate vehicle emissions based on their behaviour at normal operating temperatures. However, most journeys are of short duration (Reference 1) and take place in urban areas. These journeys will start (and most of them end) with the vehicle significantly below its normal operating temperature. Under these conditions the emission of most pollutants will be higher than calculated from the emission factor models. This *excess cold start emission* is therefore of considerable significance for environmental planning. There has however been a relative dearth of both understanding and data relevant to cold start emissions, arguably because of the technical complexity and multiplicity of vehicle technologies involved, coupled with the relatively low profile of this factor historically in the overall regulatory framework. This work seeks to provide a means of calculating this information.

A literature and data review of this subject area is reported in Reference 1. The objective of this literature and data review was to provide a baseline knowledge resource from which the model could draw. It served to identify key gaps in current knowledge, such that the limited associated experimental programme could focus on obtaining key relevant data.

This review identified the key parameters which affect the quantity of *absolute excess cold start emissions*, namely:

- the type of vehicle (including engine size, its fuel and exhaust after treatment fitted),
- the engine and, if appropriate, catalyst, temperature,
- the time interval during which the engine was switched off and the ambient temperature,
- the driving pattern following engine start.

From a review of what is known about cold start emissions and the current state of automotive technology, we initially measured cold start emissions in some detail on vehicles representative of three different engine technologies:

- gasoline fitted with a three way catalyst,
- direct injection gasoline,
- direct injection diesel.

Subsequently, a reduced test matrix was devised for a wider spectrum of vehicles.

The driving pattern will have a significant impact in the amount and time history of excess emission production. The review identified that most journeys are of very short duration and take place within urban environments. In order to make the results of this programme more widely applicable and comparable to previous work, we chose the urban ECE-15 cycle as our basis for measurements.

Earlier studies had shown that the following variables were unlikely to be of major significance for this work:

- the number of miles accumulated by the engine (provided an appropriate level of maintenance has been maintained),
- effects of road gradient or vehicle load,
- effects of altitude,
- degradation of pollution controls.

For the predictions of fleet composition in the year 2005 we used the estimates of UK vehicle fleet composition compiled for the National Atmospheric Emission Inventory Programme of the DETR.

A review of the modelling approaches used by other workers in this field, drawn from the current literature, supported the approaches and techniques employed in this work. It also identified some work that could be built upon and highlighted some of the difficulties and shortcomings of other models.

3 Experimental measurement programme

The experimental measurement programme comprised simultaneous thermal and emissions measurements on vehicles over drive cycles undertaken under controlled ambient temperature conditions in AEA Technology’s vehicle emissions test facility. The main data generation campaign was preceded by a more detailed study on 3 of the total of 15 vehicles investigated.

3.1 CHOICE OF VEHICLES

The choice of 15 vehicles selected for this project was made to reflect the range of vehicle technologies and engine sizes that comprise the current and anticipated 2005 UK vehicle parcs. For example, all vehicles were catalyst-equipped. This has been a requirement for gasoline vehicles sold since 1993, and the likely percentage of pre-1993 vehicles on the road in 2005 can be assumed to be small. Whilst the largest contribution of excess pollutant emissions due to cold start is likely to be from three way catalyst (TWC) equipped gasoline cars, it was considered important to consider other, or emerging alternative, technologies. We therefore used examples of:

- TWC gasoline,
- gasoline direct injection (GDi),
- direct injection (Di) diesel engines equipped with oxidation catalyst, exhaust gas recirculation (EGR) and electronic engine management systems.

Taking the above into consideration, together with the practical issue of availability of hire cars, the following 15 vehicles (Table 1) were chosen for study. All vehicles met EURO II standards. Those shown in bold were subjected to the full test matrix described described in Section 3.2.

Table 1. Project test vehicles.

Vehicle	Fuel	Engine size (cc)	Registration year	Mileage
Vauxhall Corsa	Gasoline	973	1999	3,778
Peugeot 206	Gasoline	1124	2000	7,819
Ford Fiesta	Gasoline	1242	2000	1,513
Skoda Fabia	Gasoline	1390	2000	9,923
Honda Civic	Gasoline	1396	1999	12,001
Mitsubishi Carisma	Gasoline	1597	1998	58,049
Toyota Avensis	Gasoline	1762	1999	55,000
Renault Laguna	Gasoline	1783	1996	56,066
Vauxhall Vectra estate	Gasoline	1796	1999	5,802
Mitsubishi Carisma	Gasoline GDi	1834	1999	8,273
VW Golf TDi	Diesel	1896	1999	9,367
Ford Mondeo	Gasoline	1988	2000	3,422
Peugeot 306 HDi estate	Diesel	1997	1999	18,065
Vauxhall Omega auto	Gasoline	2498	1999	2,744
Jaguar S-type	Gasoline	2967	1998	61,000

3.2 THERMAL AND EMISSIONS MEASUREMENTS

Initially, a representative vehicle of each of the three technology categories was subjected to a comprehensive test matrix of thermal condition and emissions measurements in AEA Technology's controlled temperature chassis dynamometer facility.

The results from the thermal profile investigations and the pollutant emissions measurements on the initial three vehicles were analysed to draw correlations between key indicators and excess emission generation. From these results a test protocol comprising a reduced set of measurements was generated and applied to a further twelve vehicles.

The measurement programme on the three pilot study vehicles included the following stages.

Each vehicle was subjected to safety checks and instrumented to allow second-by-second measurements of key temperature indicators as shown in Table 2.

Table 2. Key temperature indicators

Temperature to be measured	Point of measurement
Oil	In sump, access via dipstick tube.
Engine block	Any convenient threaded hole – vehicle dependent
Coolant	At outlet of engine block to heater [1]
Pre-catalyst exhaust gas	In exhaust pipe in front of the catalyst
Post-catalyst exhaust gas	In exhaust pipe behind the catalyst[2]
Air inlet	In air filter inlet
Fuel – important for diesels only[3]	Via adaptation of return line with a “T” piece.

The emissions laboratory was set up to to allow the following emissions measurements to be made throughout the test programme.

a) Second-by-second (modal) measurements of:
- total hydrocarbons (THC)
- carbon monoxide (CO)
- carbon dioxide (CO_2)
- oxides of nitrogen (NO_x)

using standard automotive emissions analysers.

b) Cumulative sampling of the above emissions over complete drive cycles using regulatory bag analysis procedures.

c) Particulate matter (PM) using standard cumulative filter weighing automotive emissions procedures which yield data approximating to PM_{10} .

d) Nitrogen dioxide (NO_2) by subtraction of NO from NO_x measurements made using chemiluminescence analysis on cumulative bag samples.

Provision was also made for measurements of the following pollutants when required:

- benzene and butadiene via adsorption onto adsorption tubes, followed by off-line analysis

- ultrafine particles particulate number measurements using scanning mobility particle sizer (SMPS) and/or condensation nucleus counter (CNC) instrumentation.

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1 The vehicle’s space heater is fed by hot coolant water from the internal coolant circuit, ie is drawn off before the thermostat. For most vehicles it should be possible to place a thermocouple in this flow on the outer edge of the engine block.

2 The temperature difference between the exhaust gas temperature pre- and post- catalyst will give an indication of the catalyst’s temperature.

3 The temperature dependence of viscosity affects the fuel pump’s characteristics. This is much less of an issue for low viscosity/low injection pressure gasoline fuelled vehicles.

The drive cycles selected were based on the ECE-15 cycle (comprising four identical components), despite its 'stylised' as opposed to 'real world' form. A cycle comprising two ECE-15 cycles was used to ensure that the engine reached its normal operating temperature under cold start conditions. These were preceded by a 9s period during which the engine was started and allowed to idle. Thus the test cycle comprised eight identical components and each component could be treated/analysed separately. This meant more accurate time dependence data could be obtained by integrating the emissions from each of the eight segments.

Additionally, to calculate excess emissions, true hot starts were also performed. The vehicles were driven through the ECE cycles until the engine temperature was stable. At the end of a cycle the engine was then switched off and the actual measurement cycle begun immediately.

Each vehicle was mounted on the chassis dynamometer and matched to its inertia class. All vehicles were preconditioned with the chosen test cycle prior to cold soak. The vehicles were then subjected to cold soak prior to temperature profile monitoring over a range of ambient and engine start temperatures. The temperature matrix that was used is shown in Table 3.

Table 3. Ambient and engine temperature matrix.

Ambient	Engine temperature (°C)						
Temp. (°C)	-7	0	10	20	40	60	Hot
-7	1	1	1	1	1	1	1
0		1	1	1	1	1	1
10			1	1	1	1	1
20				1	1	1	1

The first test of the matrix at a given ambient temperature was a cold start, i.e. the vehicles had been soaked over night. The vehicles were driven over the proposed drive cycle and allowed to cool down to the next "cold start" engine temperature and the process repeated until all "cold start" engine temperatures at that ambient temperature had been completed.

Temperatures were monitored both during testing and during cool-down.

On completion of all tests at one ambient, the test cell temperature was changed to another temperature and the vehicle again soaked until it again reached equilibrium with the new cell temperature.

The output from this work was therefore a comprehensive map of the behaviour of key engine temperature indicators under cold to warm ambient conditions and variable engine start temperatures for a small sample of vehicles representative of the short and longer term vehicle parc.

For the subsequent 12 vehicles the number of tests performed was reduced substantially. The number of tests for the first three vehicles helped to determine accurately the form of the dependencies and allow a good statistical determination of the parameters. For the subsequent vehicles it could be assumed that the form of the functions remains similar, with only their parameters changing. The reduced set of experiments allowed these parameters to be determined, albeit with less statistical significance than for the full tests. The use of eight tests as opposed to the minimum number of three allows some degree of assessment of the statistical significance of the parameters determined for each vehicle. The reduced test matrix was as below in Table 4.

Table 4. Reduced test matrix.

Ambient	Engine start temperature (°C)					
Temp (°C)	-7	0	20	40	60	Hot
-7	1			1		1
0		1			1	1
20			1			1

4 Analysis method

4.1 TOTAL EXCESS EMISSION

The gaseous bag samples and the particulate filters were used to calculate the total emissions from a particular drive cycle. These emissions were then compared to those collected from a cycle when the vehicle was hot, under the same ambient temperature conditions, to obtain the excess emissions from the cold or warm start cycle.

Previous work (Reference 2) suggested that excess emissions are purely a function of engine temperature and independent of ambient temperature. Therefore we assumed a function of the form $Xs = f(T_0)$, where Xs is the excess emission and T_0 is the start engine temperature (whether it be oil, water or engine block). In order to simplify the form of the equation slightly, this equation was modified to $Xs = f(T_h - T_0) = f(\Delta T_0)$ where T_h is the hot engine temperature. This is used so that (0,0) becomes a fixed point on the curve for all vehicles (i.e. when $T_0 = T_h$, $Xs = 0$). We found a weak dependence on ambient temperature in some cases such that $\mathrm{T_h = a + bT_a}$ which has a small impact on the excess emissions.

For the data presented in this report the total excess emissions were empirically modelled using the following curves.

$\Delta \mathrm{T_0 = T_h - T_0}$, and $\mathrm{T_h = a + bT_a}$, where T_h is the hot engine temperature, T_0 the start engine temperature and T_a the ambient temperature.

When $DT_0 < T_{test}$, $\mathrm{Xs = a_0 \Delta T_0^{a_1} + a_2 \Delta T_0^{a_3}}$,

otherwise $Xs = a_4 + a_5 \Delta T_0$,

where a_0, a_1, a_2, a_3, a_4, a_5 and T_{test} are the parameters defined for a given pollutant from a given vehicle for this particular drive cycle. The form has deliberately been made reasonably flexible so that other vehicles and test cycles may subsequently be accommodated.

The "engine temperature" could mean a variety of measures. In this work we investigated using engine oil, block and water temperatures.

4.2 TIME EVOLUTION OF EMISSIONS

As the bag samples were collected, the gaseous pollutant concentrations were also measured in real time (with a time resolution of 0.25s). By their very nature, the accuracy and precision of these real time measurements is not as good as the bag samples, especially under conditions of low overall emissions.

To increase the sensitivity the excess emissions were integrated over each 195s ECE portion in turn for each run. They were then plotted as a function of the end time of each ECE portion. The cumulative sum of the excess emissions as a ratio to the total is then determined. Data where the total excess emission is already small would therefore be unlikely to be reliable. The more extreme conditions are most likely to give useful information.

In order to find an equation that operates under all conditions, the time evolution of the **fraction** of total excess emissions was plotted as a function of time. This leads to an equation of the form

$$F = 1 - \exp(-bt)$$

where F is the fraction of the total excess emissions produced after time t. The parameter b is determined for each pollutant, vehicle, ambient and engine start temperature. For a given vehicle and pollutant b was found to be independent of temperature within experimental uncertainty.

No real time particulate emission data was available so the time evolution parameters determined for THC have been used for particulate as discussed in Section 5.2.

4.3 VEHICLE HEATING PROFILE

The vehicle temperatures were also logged in real time during drive cycles together with the ambient temperature. The main temperatures of interest are the ambient, oil, engine block and water. Pre- and post-catalyst, fuel, and inlet air temperatures were also recorded for reference purposes. This data was used to determine how the temperatures evolve as a function of driving time.

Again, a form of equation had to be determined that could be used over the different test conditions. As the rate of cooling is usually taken to be proportional to the difference from the ambient temperature, this seemed a good variable to use. In other words, equations of the form $T_t - T_a = f(t)$ were investigated, where T_t is the engine temperature at time (t in seconds) elapsed from engine start, and T_a is the ambient temperature.

It is reasonable to hypothesise that a vehicle starting at 40°C with an ambient temperature of 0°C will show the same heating profile as a vehicle starting at 0°C once it reaches 40°C on its warm up. In other words, the effective start time for the 40°C start is delayed relative to that for the 0°C case. Using a polynomial, we obtain an equation of the form

$$T_t - T_a = c_1(t+t') + c_2(t+t')^2 \text{ until } \mathrm{t + t' \geq t_{max}} \text{ or } \mathrm{T_t - T_a > T_{max}} \text{ when } \mathrm{T_t - T_a = T_{max}}.$$

The coefficients c_1 and c_2 are found by fitting a curve to the data when $T_0 = T_a$, for which $t' = 0$. The value of t' is calculated for each T_0 above ambient by setting time t=0, at which point $T_t = T_0$ (i.e. the engine start temperature) which is known, so that t' is found by solving the quadratic equation. This gives

$$\mathrm{t'} = \frac{-\mathrm{c_1} + \sqrt{\mathrm{c_1^2} - 4\mathrm{c_2}(\mathrm{T_a} - \mathrm{T_0})}}{2\mathrm{c_2}}.$$

The parameters c_1, c_2 and T_{max} are determined as a function of ambient temperature and vehicle. The value of t_{max} is determined at each ambient temperature by the turning point of the polynomial. This is found by differentiating the above equation with respect to overall time. The point at which the differential is zero gives the turning point.

$$\frac{\mathrm{dT_t}}{\mathrm{dt_{overall}}} = \mathrm{c_1} + 2\mathrm{c_2 t_{max}} = 0$$

so that

$$t_{\max} = -\frac{c_1}{2c_2}.$$

An alternative form of heating curve was also investigated in the initial test matrix. This took the form of an exponential:-

$$T_t - T_a = c_1\left(1 - \exp\left(c_2(t+t')\right)\right) \text{ until } \mathrm{T_t - T_a \geq T_{max}} \text{ when } \mathrm{T_t - T_a = T_{max}}.$$

The explanation of the parameters is the same as above and the same principles are used to determine the coefficients.

The polynomial version was chosen in preference after the initial test matrix mainly due to its ease of implementation.

4.4 VEHICLE COOLING PROFILE

During cooling of the vehicle the temperatures were logged at one minute intervals.

Newton's law of cooling leads to

$$\frac{dT}{dt} = -k(T_t - T_a).$$

However, this is only true in forced convection (i.e. in a draught). Within the bonnet of a car this is not likely to be the situation. With natural convection we must use the law of Dulong and Petit who found that

$$\frac{dT}{dt} = -k(T_t - T_a)^{5/4}.$$

Integrating this equation leads to the following cooling curve:-

$$(T_t - T_a) = \frac{256}{\left(\frac{4}{(T_0 - T_a)^{1/4}} + kt\right)^4}$$

where T_0 is the temperature at time zero (i.e. at the start of cooling).

The parameter k should be independent of ambient temperature and only dependent on vehicle.

No account has been taken in this work of the effect of wind on the rate of cooling as this would be an extremely complex parameter dependent on the wind strength and direction, degree of shielding from the wind (e.g. by other vehicles), etc.

5 Results

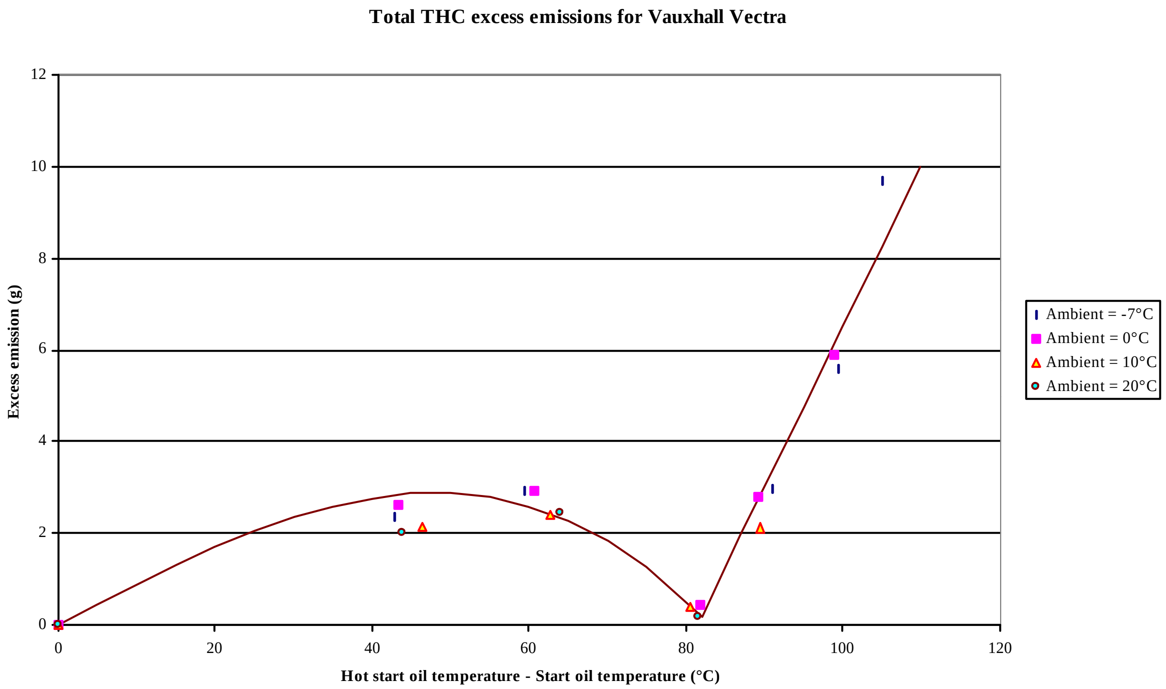
This section contains a brief summary of the data obtained from the measurement campaign. Further details are available from the authors.

For the purposes of determining the behaviour of excess emissions, we investigated the use of oil, coolant and engine block temperatures as measures of engine temperature. The oil and engine block temperatures gave similar data, but the coolant data was not as good – presumably due to effects caused by thermostats. Because of the ease and consistency of measurement, the engine oil temperature has been used as the standard “engine temperature”.

5.1 TOTAL EXCESS EMISSIONS

It was found that consistent data could be obtained by plotting excess emission as a function of the difference between the engine temperature when hot (for that ambient temperature) and its start temperature. Figure 1 shows an example of the data obtained for hydrocarbons for the Vauxhall Vectra. The behaviour is fairly complex but there does not appear to be any significant effect of ambient temperature when the results are plotted in this fashion. The line in the graph is empirically determined.

Figure 1.



Although the form of this curve can be very different dependent on the vehicle and pollutant, the same basic independence of ambient temperature was found. For example, Figure 2 shows the curve for CO excess emissions from the diesel-fuelled VW Golf.

Figure 2

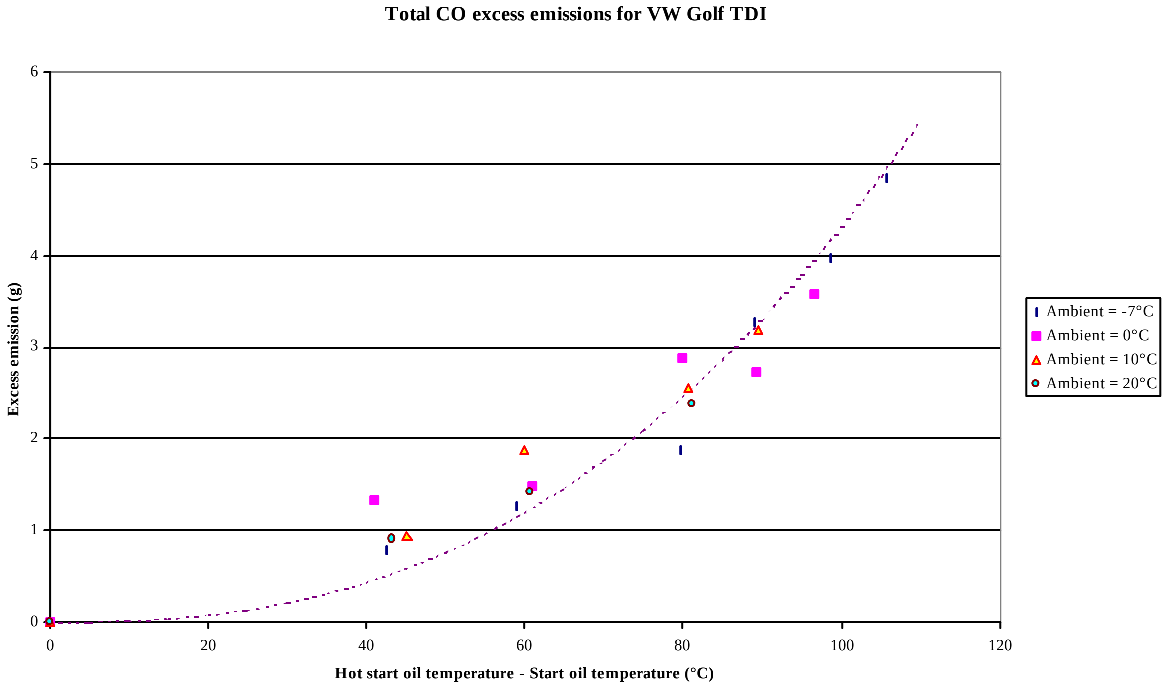
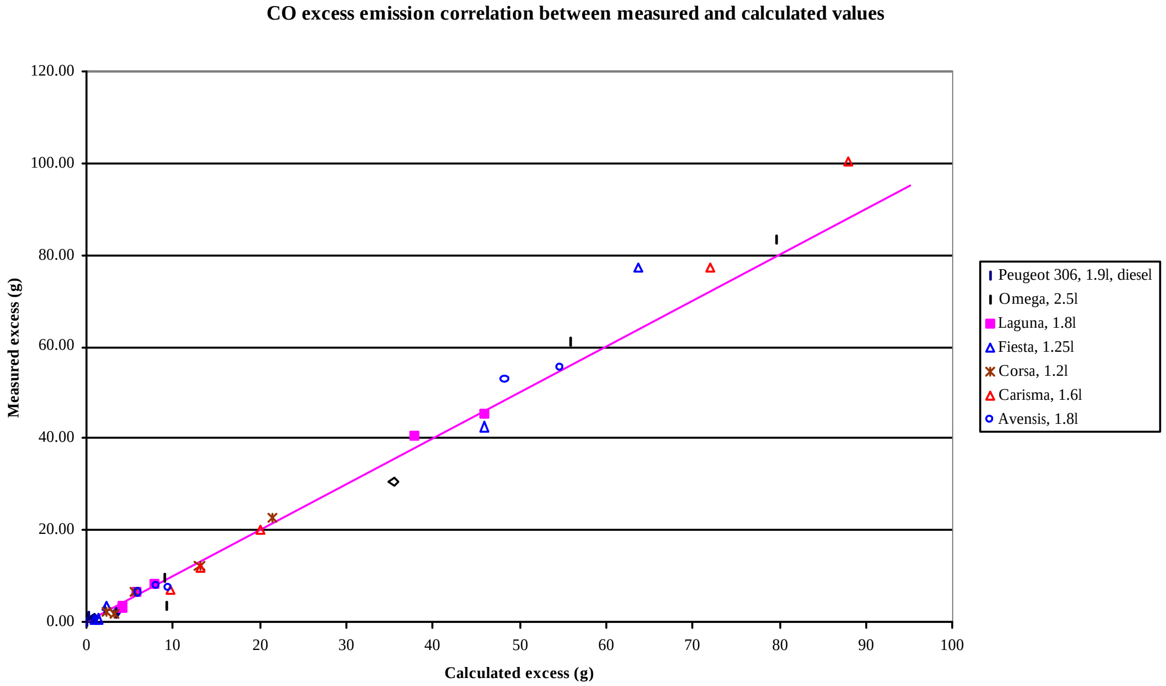


Figure 3 shows an example of the comparison between excess CO emissions calculated from the empirical equations and the experimentally measured values for a range of vehicles, conducted under the reduced test matrix with a range of ambient and starting temperatures. The agreement is very good which shows that the empirical equations represent the actually measured data very well.

Figure 3.



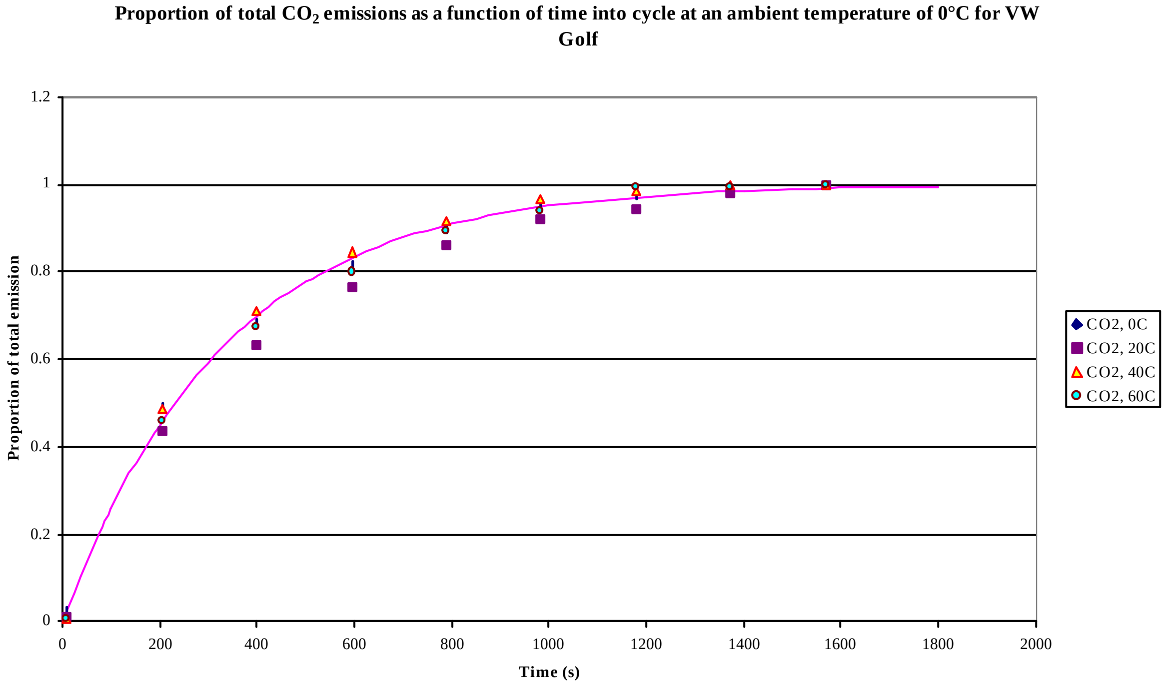
5.2 TIME EVOLUTION OF EXCESS EMISSIONS

The real time data used to assess this is often quite noisy and difficult to analyse due to the low emissions from an individual ECE cycle and the fact that we have to take the difference between two runs. However, where there are significant excess emissions (i.e. with low engine start temperatures) it is usually possible to model the data within the limits of the noise.

Generally, the data for CO_2, CO and THC can be well modelled. The data for NO_x is often very difficult to model. There is no real time data for particulate evolution, so in the model the parameter for THC has been used for particulates as the best estimate available since both pollutants are the result of incomplete combustion.

Figure 4 shows an example of this time dependence for CO_2 for the VW Golf. The parameter was found to be independent of ambient and starting temperatures for all pollutants and vehicles.

Figure 4



5.3 VEHICLE HEATING PROFILES

Figure 5 shows the oil heating curves for the VW Golf plotted directly against the time (corrected for offsets) through the driving cycle for an ambient temperature of 0°C. This shows that the data effectively lie on the same curve. A polynomial and an exponential curve have been fitted to the data. The same form of curve with different parameters can be fitted to the data at each ambient temperature. In other words, the parameters of this heating curve are dependent on ambient temperature.

It was found that the heating curves were similar for all vehicles studied, the equation parameters being different in each case.

5.4 VEHICLE COOLING PROFILES

Figure 6 shows an example cooling profile for the VW Golf at an ambient temperature of 10°C. The uneven fall in measured temperature is due to fluctuations in the measured ambient temperature as the cell conditioning oscillates about its set point. The data is very well fitted by the proposed model.

All vehicles show similar trends with little variation in observed parameter for each vehicle. There is no obvious dependence on ambient temperature. An average value of *k* determined for each vehicle has therefore been used. As an example, the variation in *k* over the different experiments leads to a maximum uncertainty of ~3°C in temperature for the VW Golf.

Figure 5

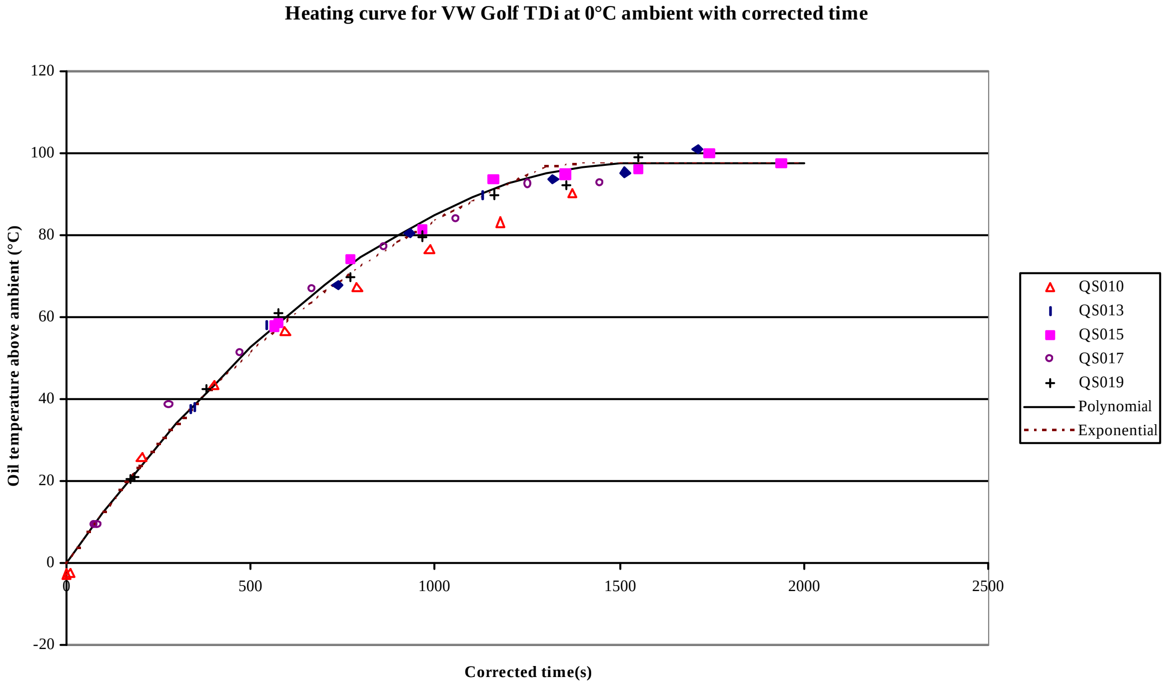
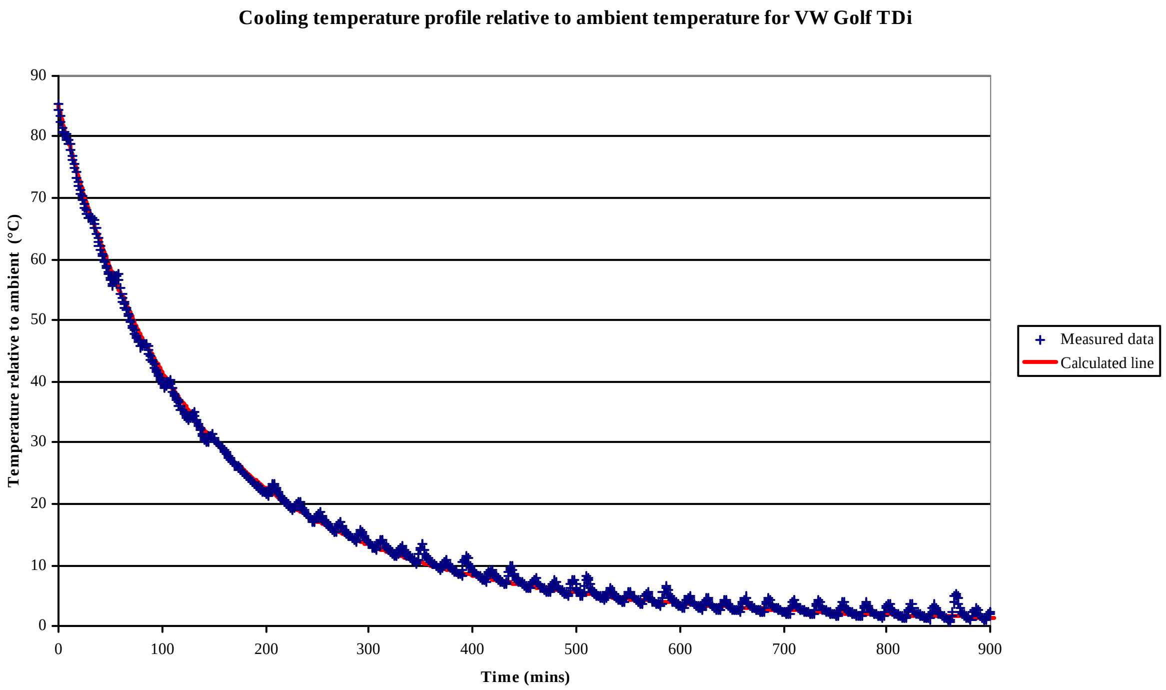


Figure 6



5.5 ADDITIONAL EMISSIONS MEASUREMENTS

.1 5.5.1 Benzene and 1,3-butadiene

Benzene and 1,3-butadiene were monitored in the exhaust gases in a small number of runs. The exhaust was sampled in a controlled manner at the CVS through diffusion tubes. The samples generated were analysed by thermal desorption followed by gas chromatography using mass spectrometry detection.

No 1,3-butadiene was detected, i.e. less than the 5 ng/tube detection limit.

The levels of benzene found are shown in Table 5.

Table 5. Benzene emissions.

Vehicle	Ambient temp. (°C)	Oil start temp. (°C)	Benzene (g/km)
VW Golf TDi	-7	-7	0.001
VW Golf TDi	20	20	0.001
Vauxhall Vectra	-7	-7	0.038
Vauxhall Vectra	20	40	0.017
Misubishi Carisma GDi	-7	-7	0.038
Misubishi Carisma GDi	20	Hot	0.015
Misubishi Carisma GDi	20	Hot	0.006

It can be seen that the benzene levels were very low with the diesel vehicle. The emissions were very similar for the two gasoline technologies. For these a cold start at a -7°C ambient approximately doubled the emissions relative to a hot start at 20°C ambient.

.2 PM and ultrafine particle emissions

As a precursor to ultrafine particulate emissions measurements we analysed the ‘regulatory’ PM emissions data.

The results of regulatory filter paper PM measurements are shown in Table 6 below for a representative vehicle of each technology- diesel, gasoline and gasoline direct injection.

Table 6. PM emissions.

Vehicle	Ambient temperature (°C)	Total hot start emissions (g/test)	Excess cold start emissions (g/test)
VW Golf TDi	-7	0.341	0.193
	20	0.298	0.008
Mitsubishi Carisma GDi	-7	0.034	0.113
	20	0.037	-
Toyota Avensis	-7	0.038	0.051
	20	0.022	0.002

These results suggest that:

- gasoline particulate emissions are about an order of magnitude lower than diesel emissions,
- current GDi vehicles have similar hot start PM emissions to those of conventional gasoline vehicles,
- hot start emissions are relatively unaffected by ambient temperature,
- excess cold start emissions can be increased by more than an order of magnitude by a reduction in ambient temperature from 20°C to -7°C.

Gasoline vehicle emission control technology may be considered relatively mature. At the same time particulate trap technology is now being introduced for diesel vehicles, and might be expected to become standard relatively soon as a a result of tighter regulatory emissions standards. It follows that if gasoline vehicles continue to dominate the vehicle parc, then they will be responsible for the majority of passenger vehicle PM_{10} emissions in the near future. (The National Atmospheric Emissions Inventory predictions suggest that the proportion of PM_{10} emissions due to gasoline vehicles will increase from about 50% in 2000 to about 75% in 2005.)

In view of the potential regulatory interest in size-classified and number-based metrics for ultrafine particulate emissions, we undertook particle number flux measurements on representative ‘conventional’ gasoline and GDi vehicles. The measurements were made using a combination of scanning mobility particle sizer (SMPS) and condensation nucleus counter (CNC) instrumentation. In order to follow the transient cycle with the SMPS, successive scans were undertaken over complete drive cycles (2 x ECE; 8 segments) with the SMPS set to measure the flux of particles with diameters of 20, 50 and 100nm (covering the anticipated range of particle sizes, as determined by steady state tests). Only one cold start measurement could be made each day; the particle flux at 20nm was recorded for this. Both vehicles were tested under both ambient (~25°C) and cold (-7°C) conditions.

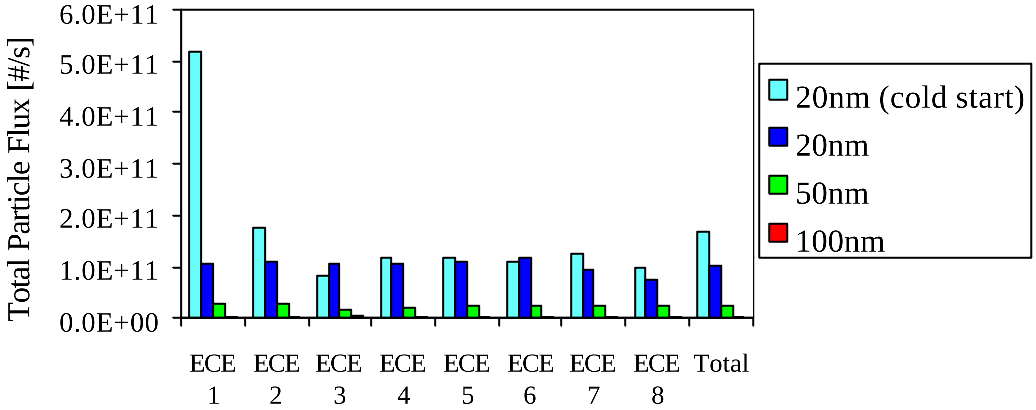
Figure 7 shows the particle flux from the GDi vehicle at -7°C over each of the eight segments of the cycle and the total particle flux. From this it can be seen that:

- the particle size was biased to 20 nm.
- In the first segment the particle flux was five times higher for a cold start than the corresponding hot start.

- Cold start effects were largely confined to the first segment.

Very similar results were obtained at 25°C except that the cold start particle flux in the first segment was only about double that of the hot start.

Figure 7. Ultrafine particle emissions from a Mitsubishi Carisma GDi at -7°C.

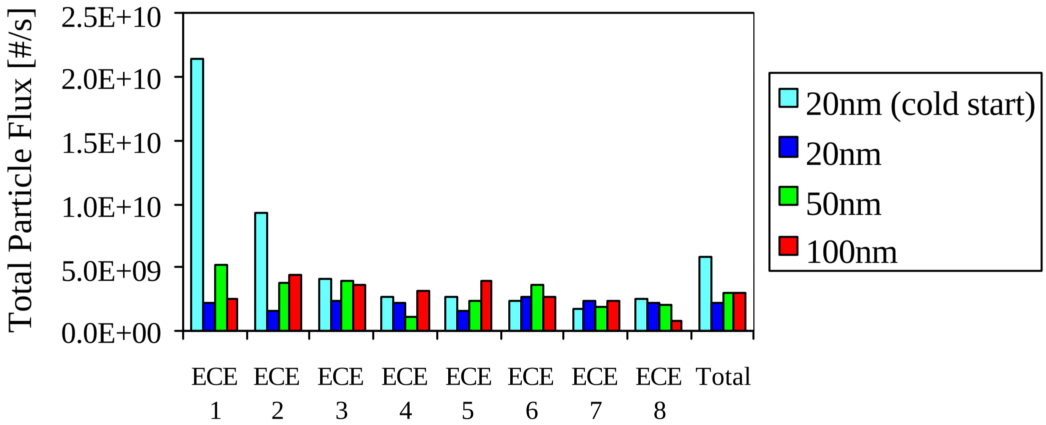


The corresponding results for the gasoline vehicle are shown in Figure 8. In this case it can be seen that:

- The particle size distribution was much wider.
- The particle flux was about two orders of magnitude lower than for the GDi.
- In the first segment the particle flux was again about five times higher for a cold start than a hot start.

At 25°C the particle size distribution was further biased to 100nm and the cold start effects at 20nm were less clear.

Figure 8. Ultrafine particle emissions from a Toyota Avensis at -7°C.



At first sight the significantly higher particle flux from the GDi engine than the conventional gasoline engine is at odds with regulatory filter paper PM measurements which showed broadly similar emissions from both under hot start conditions. However, it must be remembered that particle mass is dependent on the cube of the diameter and that small changes in size distribution can therefore have a major influence on mass (assuming a constant particle density).

6 Discussion

In this section we discuss the results of the experimental programme in terms of their contribution to the predictions of the model and the resultant uncertainties. It must be emphasised that the measured thermal and emissions data from each vehicle tested relate to the specific vehicle tested and are therefore not necessarily representative of the general performance of that vehicle make and model.

6.1 HOT START EMISSIONS

In general it seems that CO_2 emissions increase as the ambient temperature falls. Within experimental uncertainty, there does not appear to be much effect of ambient temperature on hot start CO, THC, NO_x and particulate emissions.

We have also examined the hot start emissions as a function of four vehicle classes as follows,

1. Diesel vehicles (VW Golf and Peugeot 306).
2. Small gasoline vehicles (Ford Fiesta, Vauxhall Corsa, Honda Civic, Skoda Fabia and Peugeot 206).
3. Medium gasoline vehicles (Vauxhall Vectra, Mitsubishi Carisma GDi, Toyota Avensis, Renault Laguna, Mitsubishi Carisma).
4. Large gasoline vehicles (Ford Mondeo, Vauxhall Omega, Jaguar).

The spread of data within a class is acceptable for diesel and small gasoline vehicles. There is a large spread for CO and THC in the medium class. In the large class there is a big uncertainty in NO_x as the Mondeo gave unusually large NO_x emissions.

However, there is a smooth increase in CO_2 emissions from class 1 to 4. CO and THC emissions are similar for all classes except for class 3 (medium vehicles) which has larger emissions. NO_x emissions seem to increase from small to medium sized gasoline vehicles and becoming less for large vehicles, although there is large uncertainty. For PM, all gasoline vehicles give similar emissions which are much lower than the diesel emissions.

6.2 EXCESS EMISSIONS

Trying to split the vehicles into the four categories in Section 0 does not really succeed for excess emissions – the differences within a class being too great.

This makes it important to choose a representative mix of vehicles for the model. In this work we have concentrated on well-maintained, reasonably new vehicles. The effects of age and poor maintenance on the behaviour of excess emissions were not explicitly investigated in this study, as the initial review suggested this should not be of great importance.

This work has also focused on a single drive cycle, representative of urban driving. If other scenarios were to be modelled, further experimental work would be needed in order to determine the new model parameters.

The major parameter in determining excess emissions is the vehicle start temperature. When determining the effects of parking, the cooling curve can therefore have a significant impact on the temperature at which the vehicle will next start. In this work, cooling curves have been obtained within a controlled laboratory environment with air circulation. The effect of wind can have a significant impact in increasing the rate of vehicle cooling. Although this has been noted, the incorporation of the effect of wind has not been included in the model as no systematic study has been done. It is difficult to assess the importance of this, as many vehicles may be sheltered from the effects of wind by buildings or other vehicles.

Assessing the accuracy of the model is not easy. The main problem is that some of the data on which it is based is itself noisy and prone to uncertainty. In many ways the calculated emissions may be more accurate than an individual measurement because the calculations are based on the trends shown by many measurements rather than just one

By observing the spread in the data from the overall trend, we have estimated the uncertainties in individual measurements and the overall uncertainty in the calculation of excess emissions. We have also considered the additional error introduced by the time evolution factor. This will depend on the driving time. For long driving times, where the total excess is produced, no additional uncertainty is added, whereas for intermediate times we have estimated the uncertainty from the spread of measured data about the calculated lines. Similarly we have calculated the uncertainties in excess emissions due to our assumption based on the heating and cooling curve data that each gives rise to uncertainties of 2°C or less.

On the basis of all these uncertainties the cumulative uncertainty in calculated excess emissions can be estimated. Two scenarios were considered. The first involves only one drive cycle whereas the second involves an initial drive cycle followed by cooling and a further drive cycle. The estimated uncertainties for these two cases are presented in Table 7. A second drive cycle has the impact of cumulatively adding uncertainties. The uncertainties in calculating excess emissions arise from the uncertainties in the original measurements on which the model is based. Some vehicles gave very reproducible data whilst others did not.

Table 7. Overall uncertainties in the excess emissions calculations for two scenarios.

Scenario 1 - A straight drive cycle from known starting conditions.
Scenario 2 - Scenario 1 followed by cooling and a further drive cycle.

	Scenario 1 calculation uncertainty (%)	Scenario 2 calculation uncertainty (%)
CO_2	±30%	±70%
CO	±20%	±55%
THC	±25%	±65%
NO_x	±40%	±100%
Particulate	±40%	±100%

The analytical model produced in this work reproduces the experimental data very well on the whole, within the limits of experimental reproducibility. The above estimated uncertainties relate to the absolute values of calculated excess emissions. Their impact on the ranking of different schemes being compared is much less due to the mutually compensating effects of positive and negative errors in the multiple elements of the model calculations.

7 Model implementation

An empirical model (EXEMPT – EXcess EMissions Planning Tool) for calculating excess emissions due to cold start effects has been developed on the basis of analysis of the experimental measurement programme.

The model has been incorporated into a Microsoft Excel spreadsheet. The user uses a mouse to click on menu buttons which run macros to enable access to the different areas of the model. The model calculations are based on the equations outlined in this report. The calculations are hidden from the user and occur instantly when any user input parameter has been changed.

The model has been configured for use either as a simple tool for scheme comparisons involving appropriate default data entries or as a more sophisticated modelling tool where a higher degree of user intervention is required.

Detailed operating instructions and worked examples are given in the user guide which accompanies the model (Reference 3).

The results from this model may be used in conjunction with results from a traffic-based emissions model that calculates mass emissions on a road network from vehicles with their engines at normal operating temperature. These may come from models combining traffic-based emission factors in g/km, (available from the *National Atmospheric Emissions Inventory*, http://www.aeat.co.uk/netcen/airqual/index.html, and the national emission factor database) with vehicle kilometres travelled on the road network. Or they may come from other air quality and emission estimation procedures, for example the Highways Agency DMRB procedure "*Design Manual Roads and Bridges, Volume 11, Section 3, Environmental Assessment Techniques: Part 1 Air Quality, March 2000*", where the user inputs traffic flows on specified road links to calculate emissions and air concentrations near the road side. The user can then add the impact of excess emissions from starting vehicles in an area to the hot exhaust emissions calculated. This might be useful for a scheme appraisal, for example a car-park or out-of-town shopping complex where many cars will start their journeys with cold engines.

The model allows the user to define the percentage of the vehicle parc made up of each vehicle category for which experimental data has been collected. The user specifies the total number of vehicles and the conditions for which the model is to be run. Three stages are defined as follows.

1. The initial driving stage. The user defines ambient and engine start temperatures and the distance driven.
2. The parking stage. The user defines the ambient temperature and parking time – start engine temperature can be specified or calculated from stage 1.
3. A further driving stage. The user defines ambient temperature and driving distance - start engine temperature can be specified or calculated from stage 2.

The total excess emissions of each pollutant is then calculated using this specification. The results can be expressed as the total of each pollutant, or broken down into more detail in terms of the excess from each vehicle type at each stage.

This model can be used as a planning tool for assessing the impact of different car parking schemes, changes in the number of traffic lanes, changing vehicle types that are allowed into city centres, etc. To demonstrate the use of this model, three applications scenarios are presented below.

7.1 EXCESS EMISSIONS AS A FUNCTION OF DISTANCE FROM A CAR PARK

The model can be used to calculate the distribution of excess emissions as a function of distance from a car park. There will be excess emission due to the fact that the vehicle engine temperatures will have cooled during the parking time.

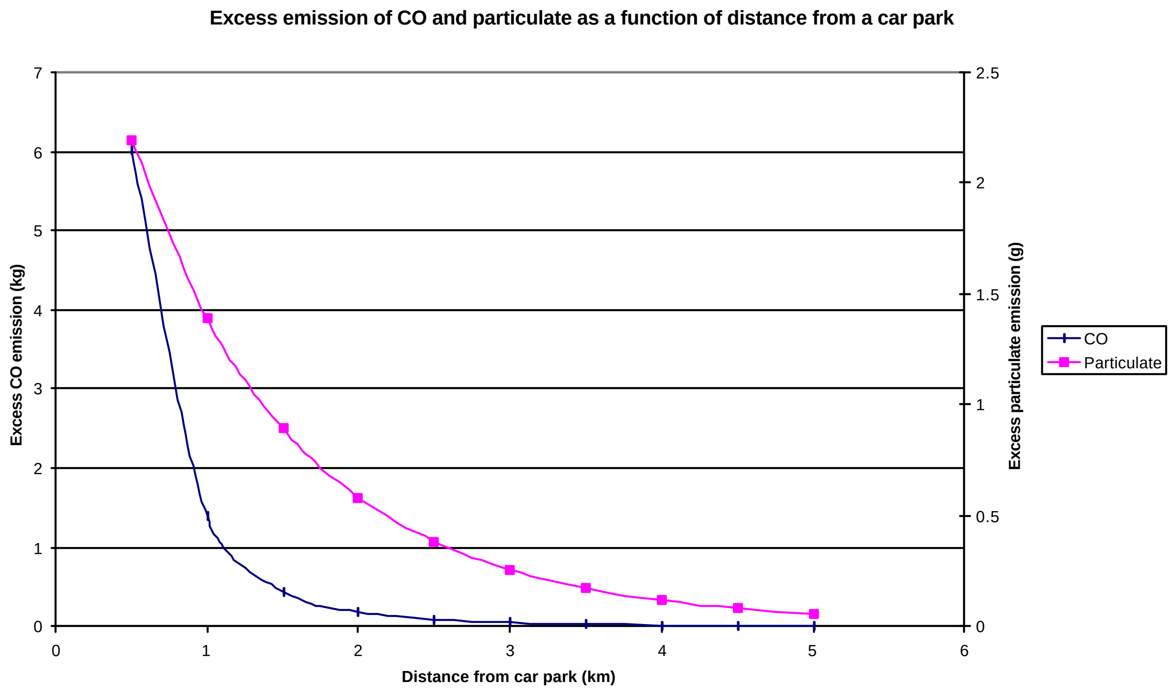
For example, let us assume that all vehicles arrive in the car park with their engines hot, producing no excess emission in the surrounding area on the way to the car park. If the car park was attached to a sports complex, we might assign a parking time of 100 minutes. This time would vary depending on the car park application. We will also assume a total of 1000 parked vehicles during a cold winter's day with an ambient temperature of 0°C.

In order to ensure that the vehicles arrive hot, we set the stage 1 distance to a high value, say 400km, with a start temperature of 50°C and ambient temperature of 0°C. However, this initial stage will produce some excess emission that we do not wish to include in the calculation. Therefore, the distance for stage 3 should initially be set to zero so that the model calculates the excess emission from stage 1. These values should then be subtracted from all subsequent calculated values.

We set the time for parking in stage 2 as 100 minutes and the start of parking temperature as 999 so that the model uses the calculated hot engine temperature from stage 1. The ambient temperature is set to 0°C for all three stages. In stage 3 we set the start engine temperature to 999 so that it is calculated from the rate of cooling in the car park. We then allow the model to calculate the excess emission as a function of distance, for example at 0.5km intervals up to 5km.

The excess emission produced in stage 1 has to be subtracted from all of the data calculated as a function of distance from the car park. The excess emission produced at each distance from the car park is then calculated by subtracting the sum of all the excess produced up to that point. For example, the total excess emission produced at a distance of 3km would be the total excess produced by driving 3km minus that from driving 2.5km. In this way, the distribution shown in Figure 9 is obtained.

Figure 9.



The model can simulate many different car parking arrangements. For example, the parking time might be different if the car park is for a shopping centre (a distribution of parking times could be used). The vehicles may not arrive in a hot condition so that the excess leading to the car park has to be included in the calculation. The vehicles may not all drive beyond 5km from the car park, etc. The change with time of day could be simulated with changes in vehicle number and ambient temperature.

7.2 EXCESS EMISSIONS AS A FUNCTION OF DISTANCE FROM A TOWN CENTRE

The model calculates the total excess emissions produced from a specified set of conditions – there is no information given about the spatial or time distribution of these emissions. However, by careful use of the model, this data can be extracted.

For example, let us consider arbitrary radial zones surrounding a city centre at 0, 1, 2, 3….up to 7km from the city centre as an example, labelled as zones A to H respectively. For simplicity of explanation we will assume that vehicles only drive into the city centre itself. We can calculate the excess emissions produced in each zone on driving into the city by using the following procedure.

We will use just stage 1 and so set the time and distance parameters of stages 2 and 3 to zero. Then, with the appropriate temperatures, we set the distance travelled to 1km and note the excess emissions for 1 vehicle (total vehicles set to one). Calculate the same for each kilometre travelled up to 7km. Then starting at zone H, the total excess produced in G is the total number of vehicles starting in H multiplied by the excess emission from 1km driving. The excess produced in zone F by vehicles starting in H, is the difference in excess between 1 and 2km of driving multiplied by the number of vehicles starting from H and driving 2km. This procedure is repeated all the way into the city centre. The same is then done with the vehicles starting in each zone in turn, until in zone B all vehicles travel 1km into zone A. The total excess in each zone is then integrated from each starting point.

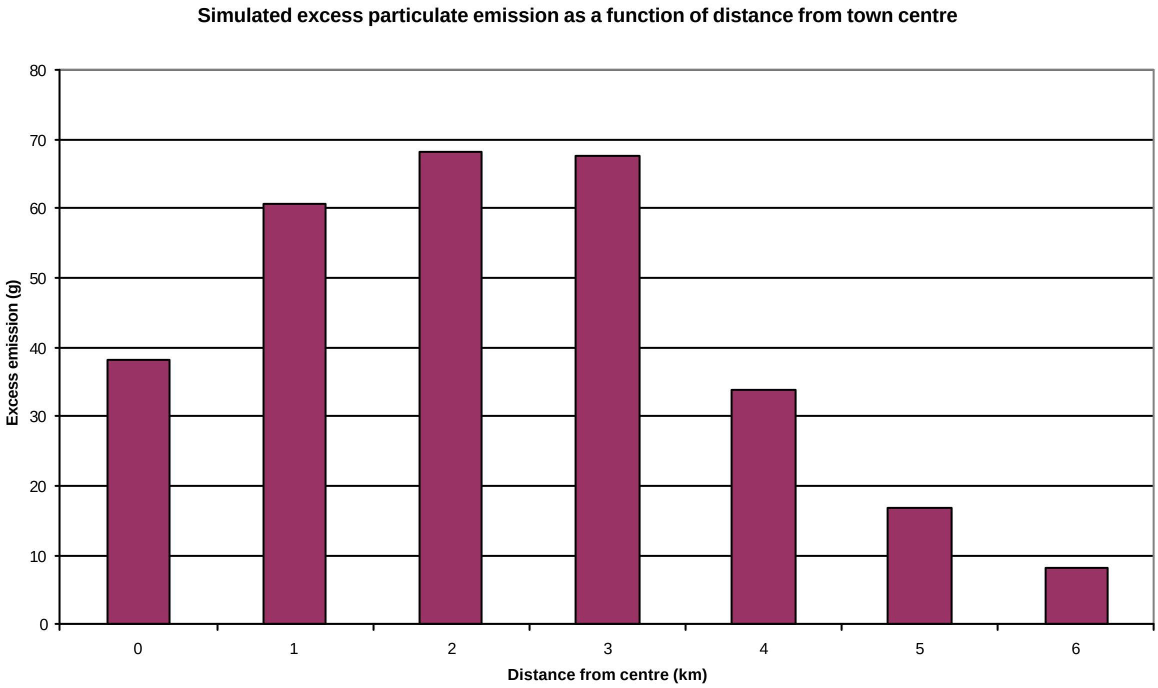
Note that this can be made even more complex by defining different vehicle parc distributions at different zones, perhaps reflecting different wealth in each area. Also, the return journey parameters can also be calculated by initially following the above procedure and then subsequently adding a cooling and driving home stage – the stage 3 excess emissions being calculated from the difference to the above calculation.

As an example we have assumed a vehicle start temperature equal to the ambient temperature of 0°C and that vehicles drive in only one direction into the city centre (i.e. the return journey has not been modelled). The following distribution of vehicles has been assumed as a function of starting point from the city centre.

Zone	Distance from centre (km)	Number of vehicles starting in zone
B	1	500
C	2	1200
D	3	1500
E	4	2000
F	5	1000
G	6	500
H	7	300

The resulting excess particulate emission distribution as a function of distance from the town centre is shown in Figure 10.

Figure 10.



7.3 EFFECT OF CHANGING THE NUMBER OF TRAFFIC LANES

If the number of traffic lanes is changed, the flow of traffic may be affected which will change the time taken to drive a set distance. As the excess emissions are produced as a function of time, for relatively short distances there could be a significant impact on the excess emissions produced. This effect can be estimated using the model.

The model calculates emissions as a function of driving time and not distance. The driving time is calculated from the distance and assuming a constant average speed of the ECE cycle used to measure excess emissions. No real-life situation is going to exactly reflect this drive cycle so the calculated excess emissions are representative of urban-style driving. However, relative changes may be predicted, so that if a lane change produces a 20% increase in average speed, for example, then the journey time decreases by 20%. As the average speed used by the model cannot be changed, the user can simulate this circumstance by reducing the travelled distance by 20% and calculating excess emissions.

For example, consider 1000 vehicles driving 4km along a road at an average speed *x* kph. The journey time for case 1 is then $4/x$ hours. If the number of traffic lanes is reduced we may get a 25% reduction in average speed, which is now $3x/4$, implying a journey time of $16/3x$ for case 2. But for the purposes of the model the speed is unchanged (it actually assumes a constant average speed of 18.4kph) at *x* kph. Therefore, we must adjust the distance travelled in the model to give the correct journey time – i.e. the effective distance travelled is now $16/3$ km. If we assume an ambient temperature of 0°C, a start temperature for stage 1 equal to the ambient temperature, parking for 3 hours and equal drive distances in stages 1 and 3 of the model, we get the following results.

	Excess CO_2 (kg)	Excess CO (kg)	Excess THC (kg)	Excess NO_x (kg)	Excess PM (g)
Case 1	448	57.1	4.67	0.93	63.8
Case 2 (reduced traffic lanes)	475	55.9	4.74	0.98	63.6

There is clearly a substantial increase in excess CO_2 emissions produced by this simulated reduction in traffic lanes, but the other emissions are largely unaffected, with particulate excess actually reducing slightly. This is because although greater excess of particulate will be produced on the stage 1 journey for case 2, as the journey time is longer the engine will get hotter and therefore will be warmer at the start of stage 3 which will produce less excess than for case 1. The overall excess change will therefore be very dependent on parking time and ambient conditions.

7.4 REQUIREMENTS FOR UPDATING AND WIDENING THE RANGE OF APPLICATIONS OF THE MODEL

This project has provided for both the development of a cold start excess emissions model and the generation of input emissions data for light duty vehicles. The model can be used as a simple tool for comparing the vehicle emissions effects of candidate parking schemes and has the potential for use as a more sophisticated emissions modelling tool involving a higher degree of user intervention.

In its current form its application is limited by the scope of the input data which encompasses emissions data from a relatively restricted sample of current passenger car models. This has the effect of limiting the accuracy of its current predictions, the range of potential applications and the lifetime of its serviceability. These are not limitations of the model itself but of the emissions data embedded within it. These limitations could therefore be overcome by subsequent incorporation of additional emissions data from, for example, other vehicle classes such as PSVs or HGVs, or, at a later date, more modern technology vehicles as they achieve significant penetration of the national vehicle fleet.

8 Conclusions

A user-friendly cold start excess emissions model (EXEMPT) has been developed on the basis of analysis of a comprehensive thermal and emissions measurement programme carried out on 15 passenger cars representative of the current UK vehicle fleet. This, together with a user guide which includes illustrative applications, will be made freely available electronically to prospective users. Its range of application is potentially capable of being extended through subsequent incorporation of additional emissions data from, for example, other vehicle classes or, at a later date, more modern technology vehicles as they achieve significant penetration of the national vehicle fleet.

9 References

Reference 1 — *Literature and Data Review. UG219 TRAMAQ - Cold Start Emissions*, J O W Norris, D C W Blaikley and A P Smith. AEA Technology report no. AEAT-5563, May 1999.

Reference 2 — *Methodologies for Estimating Air Pollutant Emissions from Transport - Emission Factors and Traffic Characteristics Data Set*, Deliverable No. 21 of Contract No. ST-96-SC.204, European Commission / DG VII, January 1998.

Reference 3 — *UG219 TRAMAQ. Excess emissions planning tool (EXEMPT) user guide*, AP Smith. AEA Technology report no. AEAT/ENV/R/0639, May 2001.

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