the effects of temperature and fuel volatility on vehicle evaporative emissions

Prepared by the CONCAWE Automotive Emissions Management Group's Special Task Force No.1 (AE/STF-1)

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ABSTRACT

Matched pairs of European vehicles with and without carbon canister evaporative emission control systems have been tested to establish gasoline evaporative emissions, including running losses. Measurements were made over a range of ambient temperatures, fuel volatilities and different driving patterns.

The uncontrolled vehicles exhibited gasoline vapour emissions which increase progressively with ambient temperature and fuel volatility. A 1°C change in ambient temperature was found to have the same effect on evaporative emissions as a 3.8 kPa change in fuel RVP.

Carbon canisters were found to provide effective control of gasoline vapour emissions, capable of reducing total daily emissions by around 95%. Large reductions in benzene emissions were achieved by the canisters, in line with the total emissions. Reducing fuel volatility had no significant effect on emissions from the canister equipped vehicles.

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SUMMARY

Evaporative emissions of gasoline vapours have been measured from five matched pairs of European vehicles, with and without carbon canister evaporative emission control systems. Measurements of hot soak and running losses were made at various ambient temperatures using different fuel volatilities and driving patterns. Measurements of benzene emissions were also made.

Hot-soak losses and running losses from uncontrolled vehicles increased progessively with ambient temperature and fuel volatility (RVP) and have been summarized by simple three-term mathematical models. The response of the emissions to ambient temperature and volatility was found to be similar for all cars and in good agreement with previous studies. A 1°C change in ambient temperature was found to have the same effect on evaporative emissions as a 3.8 kPa change in fuel RVP. Fuel tank temperatures and the consequent hot-soak emissions increased with more severe, i.e. higher speed and longer duration, warm-up of the vehicles, whereas the running losses (per km) were approximately independent of the driving pattern.

Carbon canisters were found to be effective at controlling evaporative emissions to very low levels at all except unrealistically high combinations of ambient temperature and fuel volatility, and total daily emissions were reduced by around 95%.

Running losses could not be detected from canister equipped cars with the procedure used in this programme. Due to the inadequacies of the procedure used to measure running losses, an improved measuring technique is needed to be certain they do not occur.

Reducing fuel RVP had no significant effect on emissions from vehicles equipped with carbon canisters.

Benzene emissions from uncontrolled vehicles varied significantly between vehicles, and the benzene content of the vapour could be more or less than that of the fuel. The carbon canister control system effectively reduced benzene emissions in line with total hydrocarbons.

1. INTRODUCTION

Evaporative emissions of volatile organic compounds (VOCs) from vehicles are known to depend on three major factors:

- o vehicle and fuel system design
- o ambient temperature
- o gasoline volatility

In 1985, CONCAWE set up a task force (AE/STF-1) to study the subject of evaporative emissions from European cars. Their first programme of work (1) determined typical VOC evaporative emission levels from a range of European cars and the effect on them of fuel volatility, vehicle type, and use of carbon canister control systems. The conclusions of this programme were that:

- o vehicle and fuel system design has the greatest influence on evaporative emissions;
- o fuel volatility has a significant but smaller effect;
- o RVP is the only statistically significant fuel parameter affecting evaporative emissions;
- o carbon canisters reduce evaporative emissions by around 85%.

The second programme (2) concerned the conversion of two European vehicles by fitting enlarged carbon canisters which could control emissions from vehicle refuelling as well as evaporative emissions. This work showed that refuelling emissions could be controlled to an efficiency of over 95%. These vehicles have been demonstrated in many European countries and have been tested by the German TÜV who have confirmed CONCAWE's results (3).

Although the first STF-1 programme had shown a significant effect of fuel volatility, and that RVP was the controlling property, the work had all been carried out at a single temperature (28°C specified by the draft CEC PF-11 procedure). Fuel volatility, however, is varied seasonally and regionally throughout Europe depending on the prevailing ambient temperature. Low volatility fuels (~60 kPa) are marketed in southern Europe in the summer months and higher volatility fuels (up to 120 kPa) are marketed in northern Europe in the winter months. At the time of the earlier test programme, a temperature controlled test facility was not available. It was concluded that more information was required on the combined effects of fuel volatility and ambient temperature to assess the influence of these seasonal and regional temperature/volatility variations on evaporative emissions.

Consequently a test programme was devised using a SHED installed in a temperature controlled chassis dynamometer at Shell's Thornton Research Centre where the temperature is controlled to be the same both in the SHED enclosure and on the chassis dynamometer where the vehicle is conditioned.

In this programme, described here, five pairs of cars were tested, one of each pair being equipped with carbon canister evaporative emission control systems. The Opel Ascona and Honda Civic which were equipped with enlarged canisters from the previous programme (2), were matched with a conventional Vauxhall Cavalier and Honda Civic. The three other controlled European cars were equipped with small canisters and comprised a Daimler Benz 190E, Ford Fiesta and Citroen BX19. These were matched with similar conventional cars.

All vehicles were tested at a range of temperatures and fuel volatilities. Both hot-soak losses and running losses were measured. The effect of different conditioning test cycles was determined, and some measurements of benzene emissions were also made.

Within the EC the priority is to control vehicle evaporative rather than refuelling emissions because evaporative emissions are estimated to be more than five times greater. Refuelling emissions were therefore not measured in this programme.

2. EXPERIMENTAL

2.1 TEST FACILITY

All the evaporative emission measurements were carried out in the SHED (Sealed Housing for Evaporative Determination) facility at Shell Research, Thornton Research Centre, England. This SHED is a 33.4 m^3 aluminium enclosure which is located inside a thermostatically controlled chassis dynamometer building. The chassis dynamometer is a single roll unit with capability for full road load and wind speed matching. Temperatures inside the dynamometer building and in the air delivered by the road fan can be controlled between -5 and +40°C to ±1.5°C. The hydrocarbon concentration within the SHED is monitored by a flame ionisation detector (FID). Temperatures of key components are recorded during driving on the dynamometer and while soaking in the SHED using a multipoint temperature recorder.

A simple apparatus (Fig. 1) consisting of a 20 litre fuel reservoir, a metered air supply and a pellister type hydrocarbon detector (an explosimeter) was used for loading carbon canisters off the vehicle. A digital balance with a precision of 0.1 g was used for monitoring canister weights.

2.2 TEST PROCEDURE

There are a number of broadly similar evaporative emissions test procedures in use in different parts of the world but there is currently no agreed standard test procedure for European conditions*. All of the test procedures in current use simulate 'hot-soak' emissions by warming-up the vehicle with a specified driving cycle and then allowing it to soak for a predetermined period in the SHED**. The various test methods differ in the driving cycle, the duration of the soak and the ambient temperature in the SHED. Some of the test procedures also include measurement of diurnal evaporative emissions and/or running losses. Diurnal emissions occur mainly as a result of fuel tank breathing due to changes in ambient temperature and are simulated by heating the fuel in the tank through a prescribed temperature range at a specified rate. Running losses are the evaporative emissions from the vehicle while it is being driven and occur

* During preparation of this report the European Commission has prescribed a legislative evaporative emissions test for Europe based largely on the German UBA procedure. Details of the test may still however be subject to change.

** Some test procedures including the Japanese test, allow carbon traps to be used in place of the SHED to collect the emitted hydrocarbon vapours. But this technique is shown to be less accurate and underestimates evaporative emissions.

mainly as a result of heating of the fuel tank and carburettor. Although some tests specify that running losses should be measured, the techniques for measuring them are not so well established as those for hot-soak and diurnal emissions, especially for vehicles equipped with carbon canister control systems.

In the absence of a standard evaporative emission test method, a procedure was developed specifically for this test programme which was intended to represent severe European driving conditions which would lead to significant evaporative emissions. Earlier CONCAWE work (1) had indicated that, in practice, diurnal emissions represented only a small fraction of the total daily emissions and hence it was decided not to measure diurnal emissions in this study. The programme was thus restricted to the measurement of hot-soak and running losses which can occur every time the vehicle is driven; on average this is 3.4 times a day in Europe. In contrast to all other procedures that are currently used, particular attention was paid in this study to the preconditioning of the carbon canister to ensure that it was in a reproducible condition prior to the test.

An outline of the procedure used is given below and is detailed in Appendix A.

i) Preconditioning
- Load carbon canister to breakthrough (if fitted)
- Drain tank and refill with 10 l of test fuel
- Drive 2 ECE cycles, 80 km/hr for 10 mins, 2 ECE cycles
- Drain and refuel with test fuel to 40% tank capacity
- Soak overnight (12-20 hrs) at test temperature.

ii) Conditioning
- Attach "running loss" carbon canisters to the fuel system vents.
- Drive 90 km/hr for 30 mins (or alternative driving cycle).
- Remove and weigh "running loss" canisters.

iii) Hot-soak
- Push vehicle in SHED and soak for 2 hrs at test temperature
- Record total emissions into SHED
- Sample SHED atmosphere for benzene measurement.

On vehicles fitted with carbon canister evaporative emission control systems the canister is initially loaded to breakthrough off the vehicle by blowing air and gasoline vapour through the canister at a preset flow rate until hydrocarbons are detected at the outlet (Fig. 1). The breakthrough point does not represent a fully laden condition because the carbon continues to adsorb a significant proportion of the hydrocarbon vapour even after the breakthrough point has been reached; it does however represent a well defined condition and one at which the canister fails to give total control of emitted vapours. An adequately designed and properly functioning evaporative control system will purge the canister sufficiently during the test cycle to accommodate all the vehicle evaporative emissions without the canister reaching the breakthrough condition. Starting the test with the canister at the breakthrough condition enables unambiguous identification of the range of temperature and volatility conditions for which the control system works effectively. This canister preconditioning is one of the major improvements over other procedures (e.g. the current US Federal) which allow arbitrary canister loading at the start of test. However, it should be noted that the latest revised draft US Federal procedure also stipulates loading the canister to breakthrough.

After draining and refuelling the tank and refitting the canister, the vehicle is driven through a preconditioning cycle which serves to prime the fuel system with the test fuel and purges the canister in a consistent manner. The vehicle fuel tank is then drained and refuelled with the canister disconnected to avoid unnecessary loading or backpurging and is then soaked overnight at the test temperature with the canister replaced. The evaporative emissions are not measured at this stage but any gain in canister weight is recorded.

On the following day, the vehicle is warmed up by driving on the chassis dynamometer at the appropriate ambient test temperature. It was decided to use a constant speed drive of 30 mins at 90 km/hr because this was found to be a severe driving condition in an earlier CONCAWE study (1). To provide information on relative test severity, two other lower duty cycles were also investigated but in a smaller number of tests. Four ECE-15 cycles as currently used in the European exhaust emissions test, are specified in the draft CEC test procedure and this was used to represent city centre driving. It seemed likely that the mixed low and medium duty test procedure of 4 ECE cycles followed by the extra urban driving cycle (EUDC) would be adopted for the European exhaust and evaporative emissions test and this was therefore investigated as an intermediate driving condition. As in our previous work, a soak period in the SHED of 2 hrs was used. However, the emissions were monitored constantly permitting them to be determined at shorter soak periods if required.

Total running losses from uncontrolled vehicles were measured during the conditioning cycle by attaching purged and weighed 1.5 litre carbon canisters to all fuel vents with the exception of internal carburettor vents. For vehicles with vented fuel caps (and ones where the fuel cap sealing was suspect) a sealing plate was fitted over the filler cap recess and the vapour from this space was piped to the running loss canister (Fig. 2). The difference between the sum of the running loss canister weights at the end and the start of conditioning gives the total running loss. For controlled vehicles the normal mode of venting is through the carbon canister. Attempts at measuring running losses from controlled vehicles by attaching a secondary canister to the vehicle's own canister vent were unsuccessful due to purging of the running loss canister during the driving cycle. There were also the risks that the second canister could impede purging and the increased back pressure could prevent vapour losses from the vehicle canister. Consequently no running losses were measured from the controlled vehicles. Canisters were however fitted to the filler caps as for the uncontrolled vehicles to verify that these were not a source leakage.

Component temperatures were monitored continuously during conditioning and during the hot-soak. Canister weights were monitored at the beginning and end of each phase of the test, preconditioning, conditioning and hot-soak.

2.3 TEST VEHICLE PREPARATION

Ten vehicles were selected for the programme to represent a range of vehicle sizes and manufacturers found in Europe. The vehicles and their important specifications are given in Table 1. There were 5 matched pairs of uncontrolled (no evaporative controls other than fuel tank pressurisation) and controlled (i.e. equipped with carbon canister) vehicles. Two of the controlled vehicles were those equipped for an earlier CONCAWE programme with large carbon canisters for on-board refuelling emission control. The selection contained both carburetted and fuel-injected vehicles.

All vehicles had accumulated a minimum of 4000 km driving prior to testing to allow the carbon canister characteristics and the emissions from plastic materials and underseal etc. to stabilize. The vehicles were checked and reset to manufacturers specifications where necessary and cleaned of any extraneous oil or other hydrocarbons before testing. Each vehicle was equipped with a drain in the fuel tank at the lowest point to facilitate rapid changing of test fuel. Chromel-alumel (type-K) thermocouples were fitted to measure fuel, carburettor (or injector), oil, coolant and underbonnet temperatures. Where appropriate, the carbon canisters were moved to more readily accessible points to allow rapid removal for weighing.

2.4 TEST FUELS

Three test fuels with RVPs of 64, 93 and 123 kPa were blended specially for these tests. These fuels spanned the range of volatilities from those encountered in southern Europe in summer to those in northern Europe in winter. Our earlier work (1) had shown that RVP is the only significant fuel volatility variable to influence evaporative emissions but nonetheless the other variables were kept approximately constant. The fuels contained no oxygenates. The benzene levels of the fuels were all arranged to be similar (~4% v/v).

Table 2 summarizes the inspection properties of the three test fuels.

2.5 TEST PROGRAMME

The programme was designed to map out evaporative emissions the entire range of chosen test temperatures (2,8,15,21,28 & 35°C) for each vehicle using each of the three key test fuels. In the event, some of the planned tests at low temperatures on the controlled vehicles were not carried out because of the very low emission levels observed at intermediate temperatures. Some of the highest temperature and volatility combinations, which represent totally unrealistic conditions as far as the market is concerned, were also not tested due to vapour lock in the vehicle fuel systems. The effect of warm-up driving conditions was investigated at only one condition for each vehicle, the 93kPa fuel at 28°C.

2.6 BENZENE MEASUREMENTS

The CONCAWE "Method for monitoring exposure to gasoline vapour in air", (4) was adapted to analyse the vapour emitted into the SHED for both total hydrocarbon and benzene concentrations. Samples of vapour were drawn from the SHED through a pair of sampling tubes in series, the first containing 200 mg of Chromosorb 106 and the second containing 300 mg of activated charcoal. The hydrocarbons from the SHED atmosphere were adsorbed onto these tubes and then subsequently thermally desorbed into a gas chromatograph which was used to determine the loadings of benzene and total hydrocarbons on the tubes. The flow through the tubes was first calibrated (on the bench) using the actual sampling pump used for the tests. Known volumes of the SHED atmosphere were then drawn through the sample tubes for a known period at this flow rate; concentrations of benzene and total hydrocarbons in the SHED could thus be determined. The sample was drawn from a tube which protruded approximately 200 mm into the SHED to ensure that there were no abnormalities resulting from poor mixing near the wall. This tube was purged prior to each sample.

The sampling period was adjusted from test to test according to the total SHED emissions indicated by the FID; this ensured that an adequate loading of the tubes was achieved to allow accurate determinations. Samples were normally taken in duplicate, one in the last 10 minutes of the 2 hour soak period and one in the 10 minutes immediately after it. In the early tests, background samples were taken from the SHED just before putting the vehicle in to soak but since these indicated very low levels of emissions the FID was used subsequently as an indication of the background level.

2.7 EXHAUST EMISSION MEASUREMENTS

Each of the vehicles was tested prior to the evaporative emissions test to ensure that its exhaust emissions complied with the standard which the vehicle was originally specified to meet.

2.8 ROAD TEMPERATURE MATCHING

The vehicles were driven on an open road for thirty minutes at 90 km/hr whilst simultaneously monitoring the fuel tank and ambient temperatures. This allowed a comparison between the fuel temperature rise on the road with that on the chassis dynamometer.

3. RESULTS

The results from these tests are summarized in Appendix B. The key features of the results are described in the following sections.

3.1 HOT-SOAK LOSS (HSL)

The hot-soak losses, the emissions from the vehicle into the SHED during the two hour soak period, showed distinctly different responses to fuel volatility and ambient temperature for the controlled and the uncontrolled vehicles. The uncontrolled vehicles exhibit steady increases in emissions with both increasing fuel volatility and ambient temperature. The controlled vehicles exhibit a discontinuity at the temperature and volatility where the evaporative loss control system is no longer able to contain the emissions. For this reason it is convenient to consider the two groups of vehicles separately.

3.1.1 Uncontrolled vehicles

Four of the five uncontrolled vehicles, the Honda, Ford, Vauxhall and the Daimler Benz, exhibit very similar responses to temperature and fuel volatility, although the actual emission levels vary from car to car (Figs. 3a-6a). There is an approximately exponential increase in evaporative emissions with both temperature and volatility; temperature has the greatest influence over the ranges studied.

The fifth vehicle, the Citroen BX, shows distinctly different behaviour from the other four for reasons that could not be identified (Fig. 7a). There appears to be a background emission level of approximately 10 g which is insensitive to fuel volatility and only slightly sensitive to ambient temperature at all conditions except combinations of high temperature and high fuel volatility. This behaviour would be expected if there was a small leak on the fuel system but close inspection of the vehicle did not reveal one. This anomalous behaviour may be a characteristic of some particular design feature of this vehicle, an undetected leak or other fault. The results from this vehicle have therefore been excluded from the data analysis.

A more quantitative description of these results is presented in Section 4 where statistical models are applied to describe the data.

3.1.2 Controlled vehicles

As expected, the controlled vehicles show typically much lower levels of hot-soak emissions over most of the range of temperatures and volatilities studied (Figs. 3b-7b). At all except the high volatility and high ambient temperature combinations, the emissions are almost independent of temperature and volatility. Over this range, the canister capacity, which is dictated by the purging characteristics of the vehicle and the size of the canister, is sufficient to adsorb all emissions from the vehicle tank and carburettor. The small background emission of typically 1 g is believed to result from small leaks, fuel line porosity, plastics and lubricants. At high temperatures and volatilities, the vapour emissions generated by the vehicle exceed the canister capacity and there is a step change in the emissions into the SHED; we refer to this as breakthrough (Fig. 8). All of the vehicles exhibit breakthrough at approximately the same combinations of temperature and volatility, but once breakthrough has occurred the emission results are somewhat erratic. The occurrence of breakthrough can easily be identified by the canister reaching or exceeding its breakthrough weight, Fig. 8. However, because of the relatively coarse grid of conditions used for the tests it is not possible to accurately define the breakthrough conditions from our results. The dashed lines on Figs. 3b-7b indicate the approximate conditions for the onset of breakthrough which in every case represent higher temperature/volatility combinations than those normally encountered in the European market as shown in Table 3.

The total hot-soak emissions from a controlled vehicle are the sum of the emissions into the SHED plus the weight gain by the canister during the hot-soak. The total emissions are similar to those of the corresponding uncontrolled vehicles with similar dependencies on temperature and RVP.

3.2 RUNNING LOSSES

All of the uncontrolled vehicles showed significant running losses at combinations of high ambient temperature and fuel volatility (Figs. 9-13). The running losses are more sensitive to temperature and volatility than are the hot-soak losses under the conditions used for these tests. At low temperatures and volatilities the running losses are less than the hot-soak losses while at high temperatures and volatilities they exceed them. It is also important to remember that running losses are dependent on the distance driven, which in the case of these tests is 45 km. The relative importance of the running losses and hot-soak losses will depend on the number of kilometres driven and on the number of hot-soaks per day. Time resolved studies of the running losses were not made but it is reasonable to assume that the rate of running loss emission increases with time as the fuel tank warms up. The length of individual journeys as well as the total distance driven is therefore likely to be important.

As described in Section 2.2, running losses were measured by fitting carbon canister traps to the vehicle's fuel tank vents. 'Running loss' canisters were also fitted to the purge vents of the canisters of the controlled vehicles but no weight gains were recorded. In fact, in some cases these running loss canisters lost weight as they were purged in tandem with the vehicles' own canister. Due to the inadequacies of the procedure used to measure running losses, we cannot say definitively from these results that there were no running losses from the controlled vehicles. An improved method of measuring running losses from vehicles fitted with carbon canisters needs to be developed.

3.3 FUEL TANK TEMPERATURES

The emissions from the fuel tank occur mainly as a result of the rise in fuel tank temperature which occurs as the vehicle is driven. For all the vehicles the tank is heated by the exhaust system. For vehicles with fuel recirculation systems, there is additional heat input from the recirculation of the fuel through the hot engine compartment. It is important that the rise in temperature on the dynamometer is consistent and that it also approximates closely to that on the road.

For each of the vehicles, the fuel tank temperature after conditioning on the dynamometer increases almost linearly with ambient temperature and, as expected, is independent of the test fuel volatility (Fig.14). The average fuel tank temperatures at the various ambient temperatures are summarized in Figs. 15 and 16 and are remarkably similar for all 10 vehicles. Typically, the fuel tank temperature is about 7 or 8°C above ambient, the difference being slightly higher at lower ambient temperatures than at higher ambient temperatures.

The fuel tank temperatures on the road were measured at the prevailing ambient temperature and are consequently different for each vehicle. We have therefore compared the temperature rise (DT) above ambient for each vehicle when comparing the temperature rise on the road and dynamometer, as in Table 4. There is reasonably good agreement between fuel temperatures measured on the road and dynamometer. The temperatures on the dynamometer are on average slightly higher than on the road probably as a result of less efficient cooling by the air flow around the vehicle.

3.4 EFFECT OF CONDITIONING/"WARM-UP" DRIVE CYCLE

The effect of vehicle conditioning prior to the hot-soak was examined for only one fuel and ambient temperature combination, the 93 kPa fuel at 28°C. This particular volatility and ambient temperature combination was chosen because it is close to the 'breakthrough' conditions for all of the canister vehicles with the standard 90 km/hr warm-up conditioning. It thus provided a stringent test of the response of controlled vehicles to the conditioning cycle used.

The 90 km/hr warm-up was chosen on the basis of an earlier study of uncontrolled vehicles which showed it to be a fairly severe conditioning procedure. As indicated above, this conditioning produced typically a 7°C rise in fuel temperature at 28°C. The other warm-up driving conditions examined in the study, the ECE cycle (actually 4 repeated cycles) and the ECE cycle followed by the new Extra Urban Driving Cycle (EUDC), involve shorter distances, times and average speed as shown in Table 5.

As expected, the ECE and ECE+EUDC cycles produced significantly lower fuel tank temperatures on all cars (Fig. 17) and, for the uncontrolled cars, lower emissions. (Figs. 18 & 19). The ECE cycles alone produced on average a 2°C rise in tank temperature whereas the addition of the EUDC cycle increases this to approximately 3.5°C. The average hot-soak emissions from the uncontrolled cars increase in line with the fuel tank temperatures (Fig. 18). The running losses appear to increase much more rapidly with the severity of the warm-up driving cycle as shown in Table 6 and Fig. 19; they are less than the hot-soak emissions for the ECE cycle warm-up and many times more than the hot-soak emissions for the 90 km/hr warm-up. Running losses depend not only on the peak fuel tank temperature achieved but also on the duration of the warm-up cycle which is related also to the distance driven. It is more appropriate therefore to consider the running loss emissions in terms of g/km. On this basis the running losses for this particular fuel and temperature combination (93 kPa and 28°C) are approximately constant at around 1 g/km. (Table 6).

For controlled vehicles the increase in hot-soak emissions with the severity of the driving cycle is offset by the increased canister purge during longer and higher speed driving. This is illustrated clearly by the results from the Ford Fiesta, Fig. 20. In this instance the increased canister purge more than compensates for the increased emissions from the vehicle. Paradoxically, this makes the ECE cycle the most severe in this case. Nonetheless, the controlled vehicles (with the exception of the Citroen BX which shows anomalous behaviour) show excellent control of the hot-soak emissions for all three cycles, the average emissions being approximately 1 g per test in each case, as shown in Fig. 21.

3.5 BENZENE EMISSIONS

Measurements of the mass of emitted benzene during the hot soak were obtained for four of the five pairs of vehicles (Figs. 22-23). The data from the Fiestas were found to be unreliable due to problems with the analytical equipment. Benzene samples were not obtained from every test and hence the data are less extensive than for the other variables, for example, the hot-soak losses.

For the uncontrolled vehicles, the mass of emitted benzene increased with ambient temperature broadly in line with the total hydrocarbon emissions. The benzene emissions however do not appear to increase significantly with increasing RVP of the fuel except in the case of the Daimler Benz.

The actual mass of benzene emissions is substantially reduced by the carbon canister control systems more or less in line with the reduction in total hydrocarbons (Figs. 22 and 23).

4. STATISTICAL MODEL FITTING

Statistical models have been fitted to the data presented in Section 3 in order to provide a concise summary of the data that can be conveniently incorporated into global emissions models for Europe. For the uncontrolled cars, models were fitted to describe hot-soak loss (HSL), running loss (RL) and total daily loss (TDL = 3.4 HSL + 35 x RL/45) emissions. The total loss is expressed in grammes per day and is based on 35 km driving and 3.4 hot-soaks per day which represents the average European driving pattern (1); diurnal emissions are not included. For the controlled vehicles, models were fitted to describe the total emissions from the vehicle to the SHED and the canister which we have called HSLGAIN. HSLGAIN is broadly equivalent to the HSL for uncontrolled vehicles since it represents the emissions that would occur from that vehicle if the canister were not fitted. For controlled vehicles, the sharp discontinuity in the emissions levels that occurs once the canister has broken through precludes any sensible modelling of the true hot-soak losses.

Based on inspection of the data, a number of different empirical models with various combinations of linear and exponential terms in RVP and ambient temperature were considered. Overall, models with exponential terms in both RVP and temperature were found to give the best description of the data:

$$\ln\ (\text{HSL or RL, HSLGAIN or TDL})\ (g) = a + b.\text{RVP(kPa)} + c.\text{T(°C)}$$

A second type of model, developed by Esso Research and based on theoretical considerations, was also fitted to the data:

$$\ln\ (\text{HSL or RL, HSLGAIN or TDL})\ (g) = a + \ln\ (\text{RVP(kPa)}/(\text{T(°C)}+B)) - (C - d.\text{RVP(kPa)}/(\text{T(°C)}+273)$$

This model is used in their global emissions computer model. However, despite its additional adjustable parameter it did not provide a better description of the data than the simple exponential model which we conclude provides the best summary of these data.

As a first step, the data from each vehicle except the Citroen (which was omitted because of its abnormally high background emissions) were modelled independently, i.e. each vehicle had its own constants a, b, c. For the HSL (uncontrolled cars) and HSLGAIN (controlled cars) there was no significant difference between the ambient temperature coefficients of the different car models, and only a small difference between the RVP coefficients. The absolute levels of emissions (characterized by coefficient a) did vary significantly from car to car. For the running loss (RL) and total loss (TDL) emissions there were small significant differences in the coefficients c and b, respectively, but nonetheless a model incorporating common b and c coefficients for all vehicles provided a reasonably good summary of the data. One virtue of this simple model is that the ratio of coefficients b and c indicates the relative influence of ambient temperature and RVP on evaporative emissions. In every case an increase of 1°C in ambient temperature has approximately the same effect on evaporative emissions (HSL, RL, HSLGAIN and TDL) as an increase of 4 kPa in fuel RVP. This is discussed further in Section 5.

For use in statistical emission models, evaporative emission models based on individual vehicles are of little use; it is necessary to use an average emission model for the whole car park or a small number of models to represent a few particular categories e.g. small, medium and large vehicles. With the small number of vehicles tested in this programme it was impractical to divide the models into subgroups and therefore a single model was fitted to all the vehicles. The following models were derived:

Uncontrolled cars

$$\ln (HSL(g) + 0.01) = -1.644 + 0.0199 . RVP(kPa) + 0.0752 . T(°C)$$
$$\ln (RL(g) + 0.01) = -5.967 + 0.0426 . RVP(kPa) + 0.1773 . T(°C)$$
$$\ln (TDL(g) + 0.01) = -0.609 + 0.0227 . RVP(kPa) + 0.0928 . T(°C)$$

Controlled cars

$$\ln (HSLGAIN(g) + 0.01) = -2.410 + 0.0230 . RVP(kPa) + 0.09408 . T(°C)$$

The errors (RMS values) in these models are significantly greater than those for the individual car models because of the widely different emission levels from the different vehicles. Care must therefore be exercised when using these models especially in view of the small number of car models on which they are based.

Full details of the statistical analysis including models for individual cars and the Esso models are given in Appendix C.

5. DISCUSSION OF RESULTS

The main objective of the programme was to obtain detailed up-to-date information on how evaporative emissions, hot-soak loss (HSL) and running loss (RL) vary with ambient temperature and gasoline volatility. As expected from previous studies (1,4) the HSLs and RLs from uncontrolled cars (except the Citroen which showed anomalous behaviour) varied exponentially with both RVP and temperature, and could be described by a simple three-term exponential model. The temperature coefficients of this model were essentially the same for all four cars but the RVP coefficients varied slightly from car to car. Fig. 24 shows the variation of HSL with RVP at 28°C for the four cars whose data were fitted to the model. Three of these vehicles produce similar HSLs but the fourth shows significantly higher emissions.

Despite the differences between the cars in their evaporative emissions, equations have been developed to summarize the emissions from the group of four cars as a whole. The application of these "overall" models must be treated with caution for the reasons described in Section 4 but they do provide a convenient summary of the data which can be compared readily with previous work. The results from the earlier CONCAWE study (1), which was carried out at 28°C using three vehicles, were summarized by the following two equations:

$$\ln HSL(g) = 1.1 + 0.02 . RVP\ (kPa)$$
$$\ln RL\ (g) = 0.4 + 0.03 . RVP\ (kPa)$$

It must be stressed however that the data used in making this comparison was that obtained using 90 km/hr conditioning; the data obtained from the earlier study using a less severe conditioning procedure showed a different response to RVP. At 28°C, and after similar rounding of the coefficients, the "overall" models from this study reduce to:

$$\ln HSL(g) = 0.5 + 0.02 . RVP\ (kPa)$$
$$\ln RL\ (g) = -1.0 + 0.04 . RVP\ (kPa)$$

(Note that the 0.01 offsets used in Section 4 have been omitted here for clarity). The effect of RVP on HSL was identical in both studies although the actual level of emissions in the earlier study was approximately twice that found in the current programme. For the running losses, we have found a slightly larger effect of RVP in the current work than in the previous study, although because of the small number of vehicles tested this difference is probably not significant. Overall we conclude that there is excellent agreement between the two studies regarding the effect of RVP on evaporative emissions.

The only comparable data on the effect of ambient temperature on evaporative emissions is that of Eccleston and Hurn (5), Fig. 25.

These data were obtained as total emissions, i.e. the sum of running and hot-soak losses, using the 1968 FTP emissions cycle for conditioning. In order to make as direct a comparison as possible with these results, we have used the sum of our measurements of HSL plus the RL that would have occurred over the 11.2 km of that cycle, i.e. 11.2/45ths of the 90 km/hr running losses, also shown in Fig. 25. The levels of the emissions and response to ambient temperature are very similar to those from compact US cars tested by Eccleston and Hurn.

The fuel tank temperature at the end of vehicle conditioning shows an approximately linear dependence on ambient temperature (Figs. 15 and 16). The influence of test temperature on evaporative emissions is due primarily to this change in the fuel temperature which alters the vapour pressure of the fuel in the tank. Thus it is the temperature at which the vehicle is conditioned which influences evaporative emissions and not just the temperature of the "hot-soak" in the SHED

Emission levels from uncontrolled cars are shown in Table 7 for a range of RVPs and ambient temperatures typical of those seen in Europe. The figures in this table were calculated using the three "overall" equations given in Section 4. At temperatures below 10°C, all evaporative emissions, and especially the running losses, are very low irrespective of the RVP of the fuel. This suggests that evaporative emissions are not a serious problem in winter, even at high fuel volatility levels. At higher temperatures the emissions are significantly greater, and over the range of temperature/RVP combinations predominantly found in Europe (120 kPa at 15°C to 60 kPa at 35°C), average total daily emissions are highest (55 g/day) at 35°C with the 60 kPa fuel.

The exponential dependence of evaporative emissions on ambient temperature and volatility means that for a given change in RVP or temperature, the percentage change in emissions is constant, Table 8. The 20% reduction in average total daily emissions for a 10 kPa reduction in RVP is in very good agreement with the 23% reduction observed in the earlier study (1).

A further important conclusion from this study is that a 1°C change in ambient temperature produces the same change in evaporative emissions as a 3.8 kPa change in RVP. Based on this result it is informative to plot lines of constant evaporative emissions over a range of temperatures and RVPs. Fig. 26 presents the line of constant evaporative emissions (TDL) which pass through the point 35°C, 60 kPa. This point is representative of conditions in southern Europe during the summer and, as described above, gives highest emission levels. Control systems that are capable of controlling emissions throughout Europe must therefore be designed to cope with the emission levels represented by this line. For certification testing of evaporative control systems it is appropriate therefore to test at any combination of RVP and ambient temperature represented by this line. For example, at the temperature of the original CEC draft procedure, 28°C, an 86 kPa fuel is appropriate. At lower temperatures higher volatility test fuels should be used to ensure that evaporative emission control systems are effective under all European conditions.

The second main objective of the programme was to assess the efficacy of carbon canister evaporative control systems over a range of RVPs and temperatures. No running losses were detected, although we cannot state conclusively that they did not occur because an appropriate test method is yet to be developed for measuring running losses from controlled vehicles. Hot-soak emissions from controlled cars were also very low, generally below the US limit of 2 g/test for all combinations of temperature and RVP normally found in Europe. Canister breakthrough only occurred at unrealistic combinations of ambient temperature and RVP, for example at 28°C with the 123 kPa fuel. In the regime where the canister controls the emissions effectively, the effects of ambient temperature and RVP on the emissions were negligible. We conclude that modern vehicles with well designed evaporative emission control systems can contain evaporative losses under all realistic conditions and that, for these vehicles, a reduction in RVP of the fuel gives no significant additional reduction in emissions.

A high-speed test cycle was deliberately chosen for this programme to represent severe driving conditions. The use of less severe conditioning cycles produced significantly lower fuel tank temperatures and, for the uncontrolled cars, they resulted in lower hot-soak and running losses. However, the EC now plans to adopt a new European Exhaust Emissions driving cycle (ECE-15 plus an Extra Urban Driving Cycle, EUDC) which will also be used for the European Evaporative Emissions Test. As shown in Fig. 18, hot-soak emissions from uncontrolled cars for the new cycle are midway between those for the ECE-15 cycle and the 90 km/hr conditioning for 30 mins. Running losses, as shown in Fig. 19, appear to be much higher for the 90 km/hr conditioning. However, when expressed on a g/km basis (see Section 3.4) they are approximately independent of the conditioning cycle used and for a 93 kPa RVP at an ambient temperature of 28°C, unrepresentative of European conditions, running losses are approximately 1 g/km. For the uncontrolled cars, the average total daily losses (TDLs) for the EUDC and 90 km/hr driving modes, for this temperature and RVP are:

$$\begin{aligned} & \quad\ \ \underline{HS} \qquad\ \ \underline{RL} \\ TDL_{(EUDC)} &= 27.2\ g + 37.0\ g = 64.2\ g/day \\ TDL_{(90)} &= 40.8\ g + 32.5\ g = 73.3\ g/day \end{aligned}$$

Under these conditions the hot soak and running losses make roughly equal contributions to the TDL which are only about 10% lower using the EUDC cycle. For the controlled cars, assuming no running losses, the TDLs for the equivalent conditions are as follows:

$$\begin{aligned} TDL_{(EUDC)} &= 3.1\ g + 0.0\ g = 3.1\ g/day \\ TDL_{(90)} &= 4.4\ g + 0.0\ g = 4.4\ g/day \end{aligned}$$

This corresponds to 95% and 94% reductions in hydrocarbon emissions for the EUDC and 90 km/hr driving modes, respectively.

The control of benzene emissions is an area of growing interest. This study has shown that the composition of the vapours emitted by an uncontrolled vehicle can vary significantly from vehicle to vehicle and that the percentages of benzene can differ by a factor of four. However, carbon canisters have been found to reduce substantially evaporative emissions of benzene broadly in line with the reduction in total hydrocarbon emissions.

6. CONCLUSIONS

The evaporative hot-soak and running losses increased progressively with both temperature and RVP and could be described by a simple three-term exponential model.

Temperature coefficients for the four cars were not significantly different, and the variation in RVP coefficients was minor. "Overall" models were therefore developed to describe average hot-soak, running loss and total daily emissions from all cars. These models were in good agreement with previous work.

The exponential dependence in the equations means that a fixed change in RVP or temperature causes a constant percentage change in emissions. A 1°C change in temperature has the same effect on evaporative emissions as a 3.8 kPa change in RVP. For example a 10 kPa reduction in RVP or a 2.6°C reduction in temperature will reduce hot soak and running loss emissions by 20%.

At temperatures below 10°C emissions are low regardless of RVP.

To generate the same emissions at a 28°C test temperature as a combination of 35°C and 60 kPa (typical southern Europe summer), a test fuel volatility of 86 kPa is required.

Running losses expressed on a g/km basis were similar for all conditioning cycles at aproximately 1 g/km for all test cycles when using a severe temperature/RVP combination unrepresentative of European conditions

Vehicles equipped with carbon canisters controlled hot-soak losses to below 2 g/test at all realistic temperature/RVP combinations. Canister breakthrough was only observed at unrealistic combinations, i.e. 123 kPa fuel at 28°C or higher.

Running losses could not be detected from canister equipped cars with the procedure used in this programme. Due to the inadequacies of the procedure used to measure running losses, an improved measuring technique is needed to be certain they do not occur.

At the severe test combinations of 28°C and 93 kPa, total daily emissions (excluding diurnal) from uncontrolled cars were estimated to be 64-73 g/day, depending on driving conditions. For the controlled cars this was reduced to 3-4 g/day, a reduction of 95%.

Carbon canisters substantially reduced benzene emissions in line with the reduction of other total hydrocarbon emissions.

7. REFERENCES

1. CONCAWE (1987) An investigation into evaporative hydrocarbon emissions from European vehicles. Report No. 87/60. Brussels: CONCAWE

2. CONCAWE (1988) The control of vehicle evaporative and refuelling emissions - the on-board system. Report No. 88/62. Brussels: CONCAWE

3. Preliminary TÜV report following the 2nd November, 1989 Berlin refuelling workshop). Vergleichende Untersuchung von Tankstellen und fahrzeugseitigen Techniken zur Verminderung der Emissionen bei der Betankung von Fahrzeugen mit Ottokraftstoff. Zwischenbericht, Köln, November 1989.

4. CONCAWE (1986) Method for monitoring exposure to gasoline vapour in air. Report No. 8/86. Brussels: CONCAWE

5. Eccleston, B.H., Hurn, R.W. (1972) Effect of fuel front-end and midrange volatility on automobile emissions. U.S. Bureau of Mines Report Rl 7707

Table 1

Test Vehicle Specifications

	A	B	C	D	E
Make	Honda	Honda	Mercedes(DB)	Mercedes (DB)	Opel
Model	Civic	Civic	190E	190E	Ascona 1.8i
Displacement, cc	1342	1342	2276	2299	1796
Comp. Ratio	8.7:1	8.7:1	10.5:1	10.5:1	8.9:1
Rated power kW/rpm	52/6000	45/5500	125/6000	130/6000	73.5/5800
Fuel system type	Carb	Carb	MPI	MPI	MPI
Fuel recirculation	Yes	Yes	Yes	Yes	Yes
Fuel tank capacity, l	45	46	69	69	61
Pressurized tank	No	No	Yes	Yes	No
Evap. control system	No	Yes (LCC)	Yes	No	Yes (LCC)
Approx. canister size, l	-	3	1.5	-	4.7
Exhaust gas catalyst	No	No	3-way	No	3-way

Table 1 (continued)

Test Vehicle Specifications

	F	G	H	I	J
Make	Vauxhall	Citroen	Citroen	Ford	Ford
Model	Cavalier GLI	BX 19 TRI	BX 19 TRS	Fiesta	Fiesta 1.4
Displacement, cc	1796	1905	1905	1392	1392
Comp. Ratio	9.5:1	8.4:1	9.3:1	8.5:1	9.5:1
Rated power kW/rpm	87/5800	75/6000	75/5600	52/5500	55/5600
Fuel system type	MPI	MPI	Carb	SPI	Carb
Fuel recirculation	Yes	Yes	Yes	Yes	Yes
Fuel tank capacity, l	61	66	66	40	40
Pressurized tank	No	No	No	No	No
Evap. control system	No	Yes	No	Yes	No
Approx. canister size, l	-	1.0	-	1	No
Exhaust gas catalyst	No	3-way	No	Yes	No

Table 2

Properties of the test fuels

	FUEL		
	1	2	3
RVP (ASTM D 323) kPa	64	93	123
Distillation (ASTM D:86):			
IBP, °C	35	25	23
* E70 (%v)	37.5	33	32
E100 (%v)	53.5	53.5	52
E120 (%v)	64	68.5	73
E150 (%v)	83	86.5	89
E180 (%v)	98	98	97
FBP, °C	191	190	194
RON (ASTM D2699)	97.5	97.3	97.0
MON (ASTM D2700)	85.0	85.3	85.2
Density @ 15°C (PARR) g/cc	0.798	0.751	0.730
Benzene, %v	4.1	3.4	3.0
Benzene, %wt	4.5	4.0	3.6

* % Gasoline evaporated at 70°C, 100°C, 120°C, etc.

Table 3

Typical ambient temperature and volatility combinations for canister breakthrough in the SHED tests

Ambient Temperature °C	Breakthrough Volatility, kPa
36	~ 90
24	~120
20	>120

Table 4

Comparison of fuel tank temperature rise on the road and on chassis dynamometer as a result of driving for 30 mins at 90 km/hr

Uncontrolled vehicles	Ambient Temp. °C	Temperature Rise T, °C	
		On road	On Dyno.
Ford Fiesta	10	6	11
Honda Civic	12	7	7
Daimler Benz	13	7	7
Citroen BX 14	9	7	8
Vauxhall Cavalier	-	-	11
Controlled vehicles			
Ford Fiesta	-	-	9
Honda Civic	13	6	8
Daimler Benz	7	6	7
Citroen BX 14	7	14	9
Opel	9	7	-

Table 5

Comparison of different conditioning driving cycles used

Driving Mode	Distance Km	Time s	Ave. Speed km/hr
ECE	4.1	800	18
ECE + EUDC	10.8	1200	32
90 km/hr for 30 mins	45.0	1800	90

Table 6

Running losses from uncontrolled vehicles

Driving mode	Average* running losses	
	g/test	g/km
ECE	3.2	0.78
ECE + EUDC	11.4	1.06
90 km/hr for 30 mins	42.1	0.93

* Data from 4 cars used - Citroen Data omitted

Table 7

Mean emission levels from uncontrolled cars

	HOT SOAK LOSS EVAPORATIVE EMISSIONS - GRAMS/TEST						
RVP, kPa	60	70	80	90	100	110	120
Temp. °C							
0	0.6	0.8	0.9	1.2	1.4	1.7	2.1
5	0.9	1.1	1.4	1.7	2.1	2.5	3.1
10	1.4	1.7	2.0	2.5	3.0	3.7	4.5
15	2.0	2.4	2.9	3.6	4.4	5.3	6.5
20	2.9	3.5	4.3	5.2	6.4	7.8	9.5
25	4.2	5.1	6.2	7.6	9.3	11.3	13.8
30	6.1	7.4	9.1	11.1	13.5	16.5	20.1
35	8.9	10.8	13.2	16.1	19.6	24.0	29.3

	RUNNING LOSS EVAPORATIVE EMISSIONS - GRAMS/TEST						
RVP, kPa	60	70	80	90	100	110	120
Temp. °C							
0	0.0	0.1	0.1	0.1	0.2	0.3	0.4
5	0.1	0.1	0.2	0.3	0.4	0.7	1.0
10	0.2	0.3	0.5	0.7	1.1	1.6	2.5
15	0.5	0.7	1.1	1.7	2.6	4.0	6.1
20	1.1	1.8	2.7	4.1	6.3	9.6	14.7
25	2.8	4.3	6.5	10.0	15.3	23.4	35.8
30	6.7	10.3	15.8	24.2	37.0	56.7	86.8
35	16.4	25.0	38.3	58.7	89.9	137.6	210.7

	TOTAL DAILY EVAPORATIVE EMISSIONS - GRAMS/DAY						
RVP, kPa	60	70	80	90	100	110	120
Temp. °C							
0	2.1	2.7	3.3	4.2	5.3	6.6	8.3
5	3.4	4.2	5.3	6.7	8.4	10.5	13.2
10	5.4	6.7	8.5	10.6	13.3	16.7	21.0
15	8.5	10.7	13.5	16.9	21.2	26.6	33.3
20	13.6	17.0	21.4	26.8	33.7	42.3	53.0
25	21.6	27.1	34.0	42.7	53.6	67.2	84.4
30	34.4	43.1	54.1	67.9	85.2	106.9	134.2
35	54.7	68.6	86.1	108.0	135.5	170.0	213.4

Table 8

Effect of RVP and Temperature on Emissions

Reduction of:	Percentage reduction in emissions		
	HSL	RL	TOTAL DAILY
10 kPa RVP	18%	35%	20%
5°C Temp.	31%	59%	38%

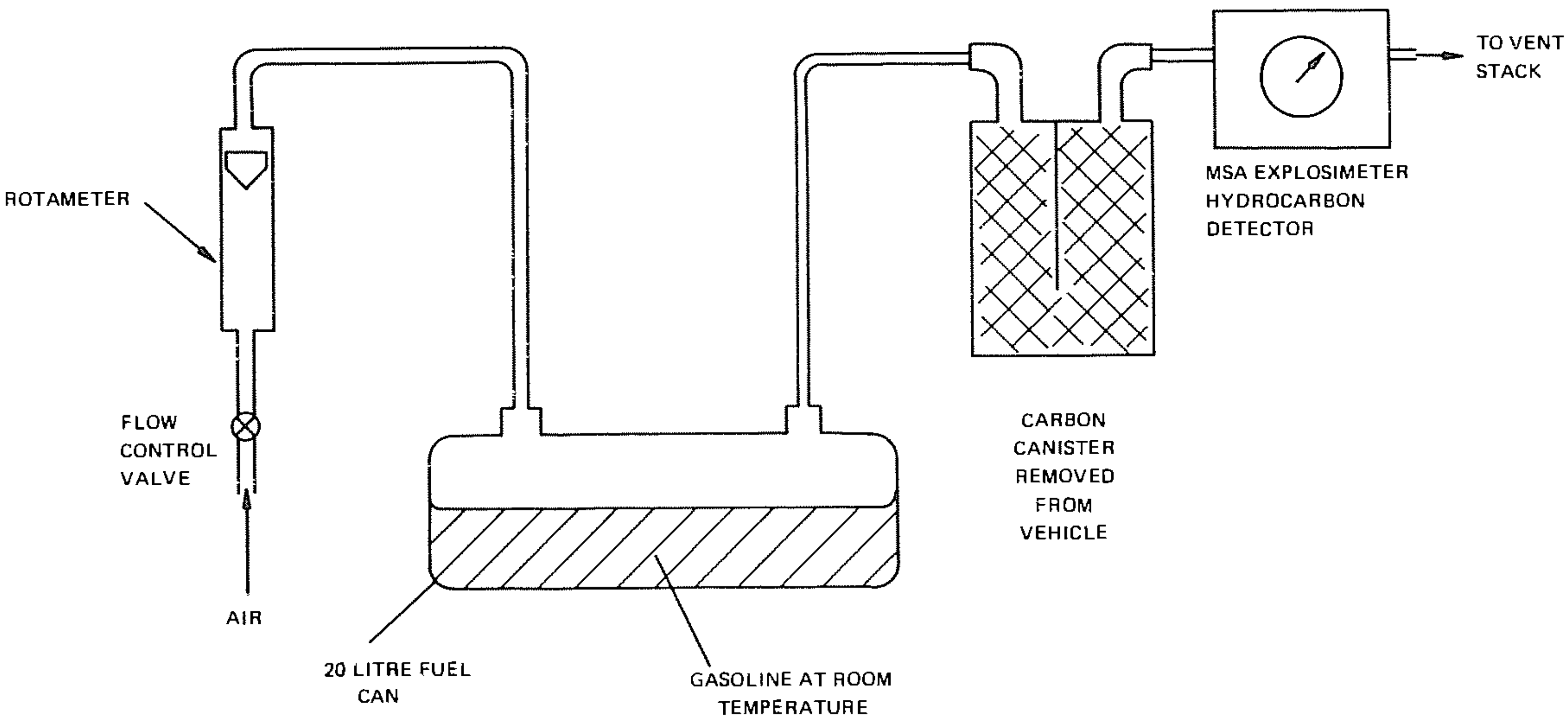


FIG. 1 – Schematic diagram of apparatus used to load carbon canisters to breakthrough.

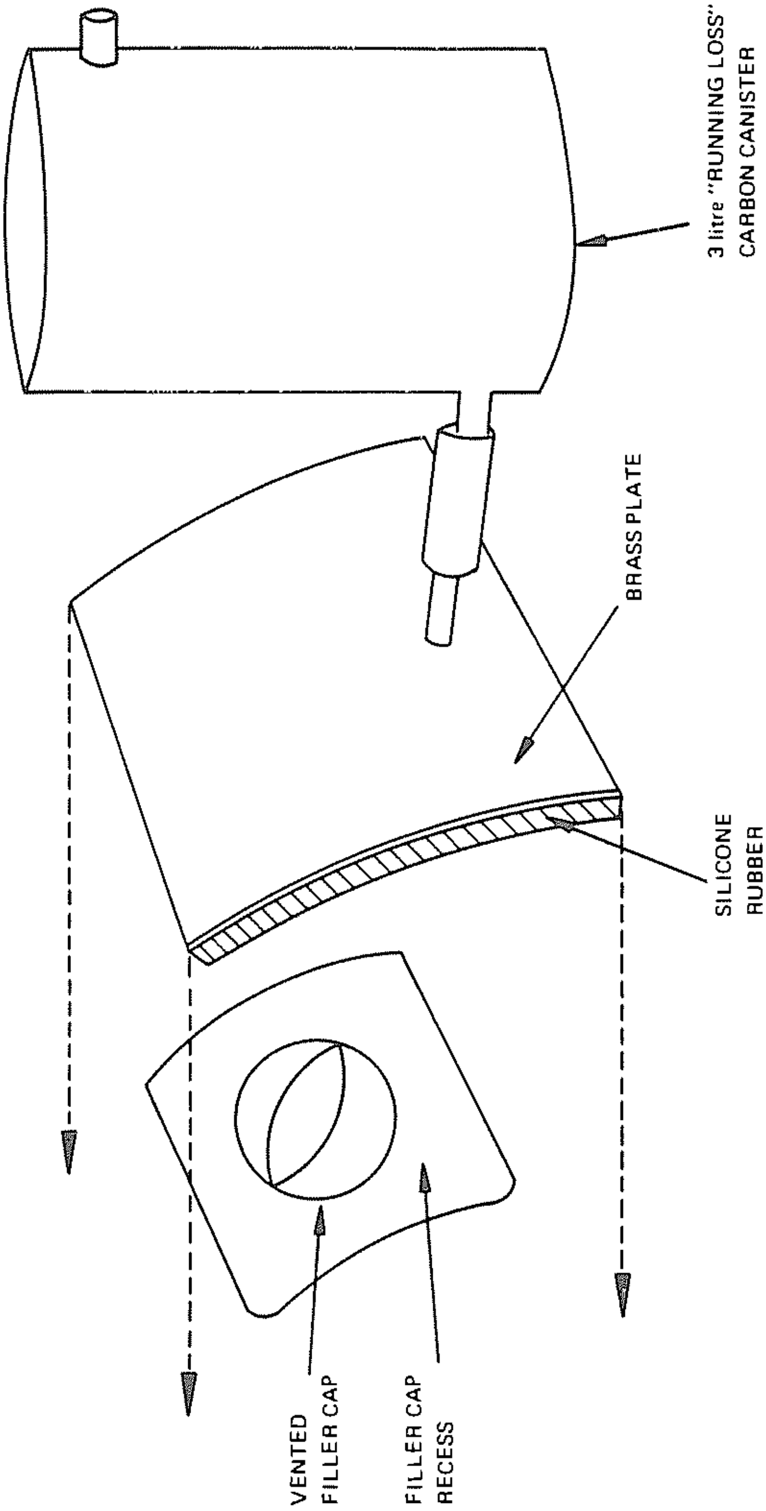
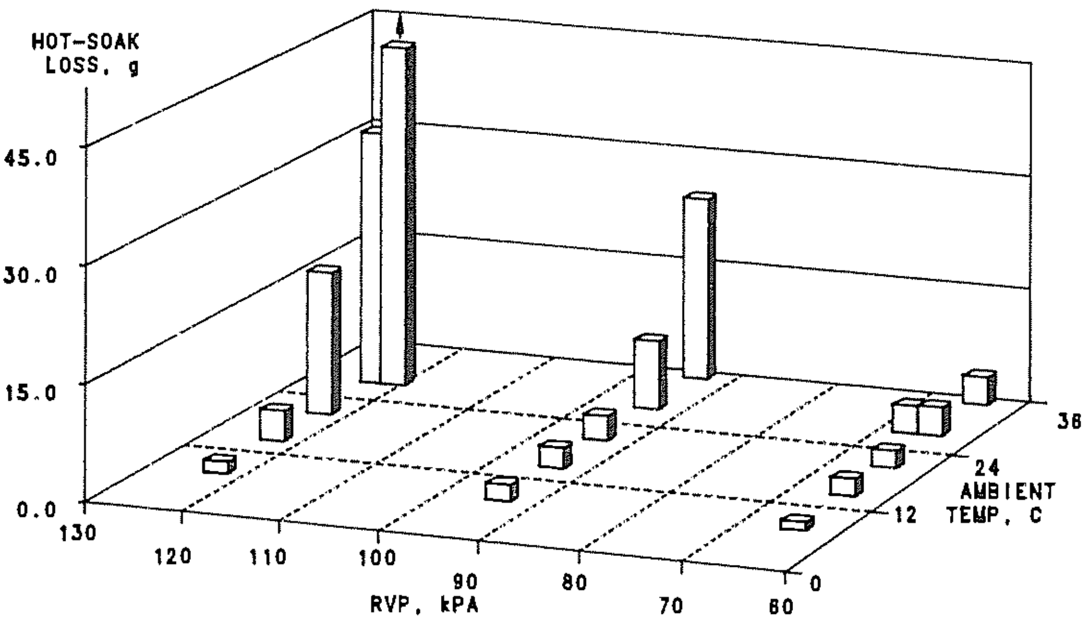


FIG. 2 — Filler cap attachment for the measurement of running losses.

FIG. 3 – Hot-soak losses from the Ford Fiestas.

(a) Uncontrolled



(b) With Small Canister

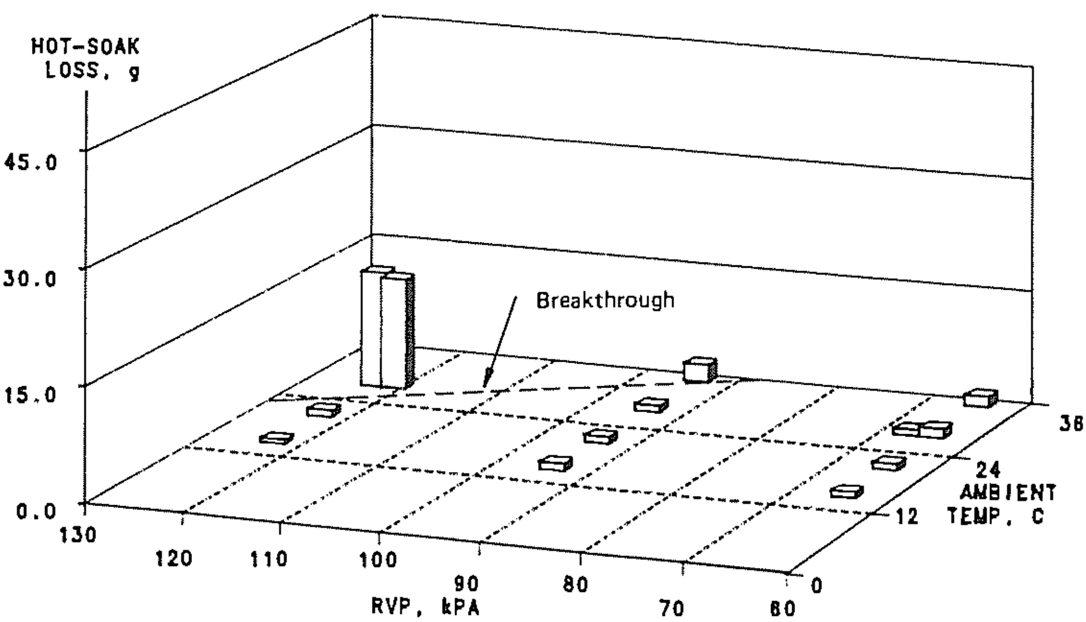
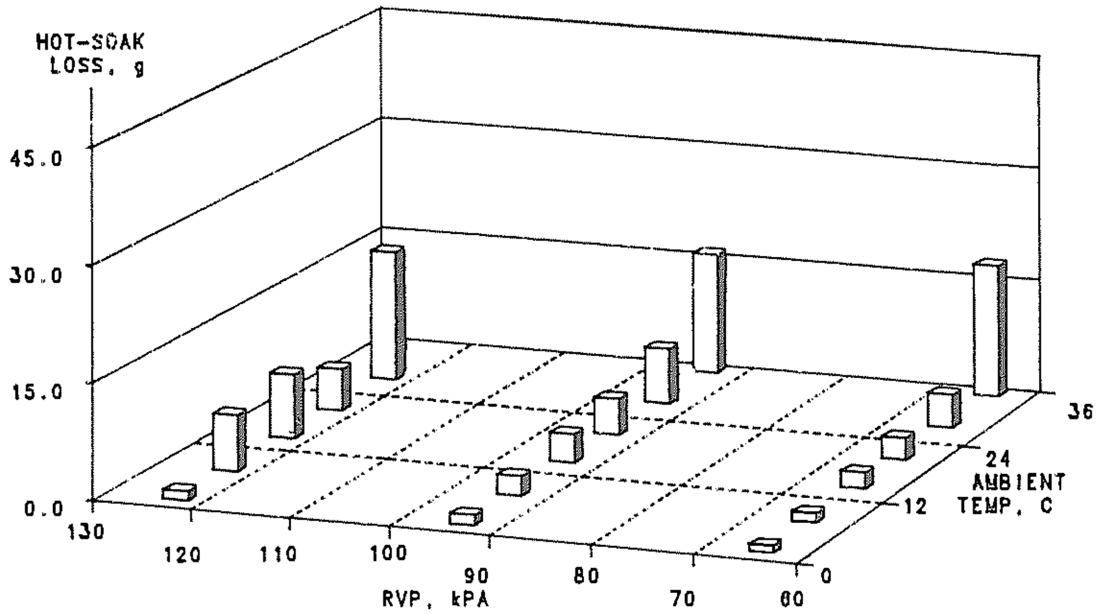


FIG. 4 – Hot-soak losses from the Honda Civics

(a) Uncontrolled



(b) With Large Canister

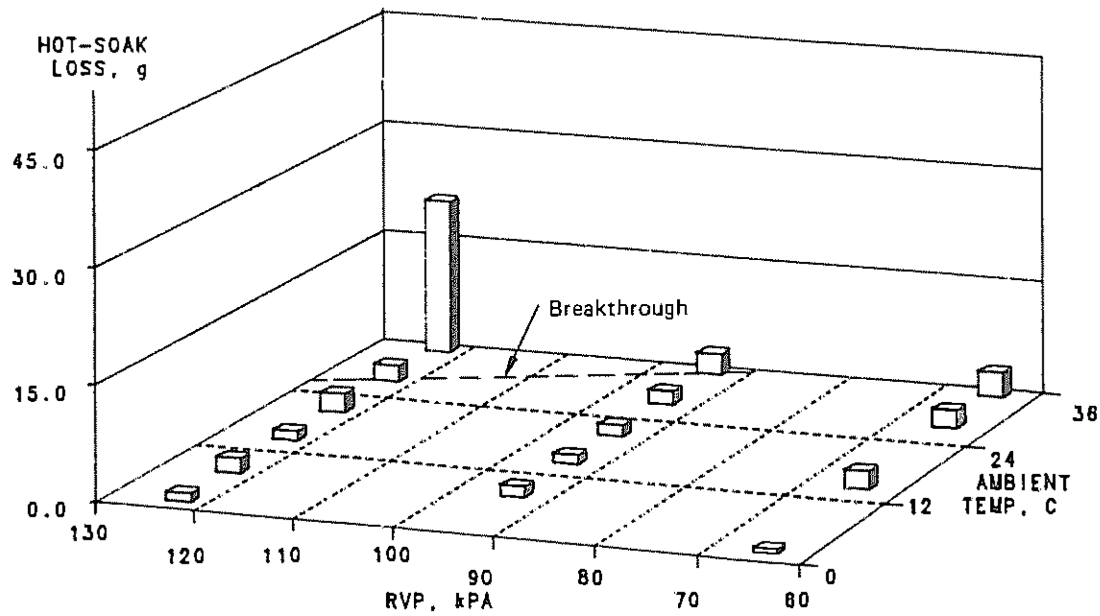
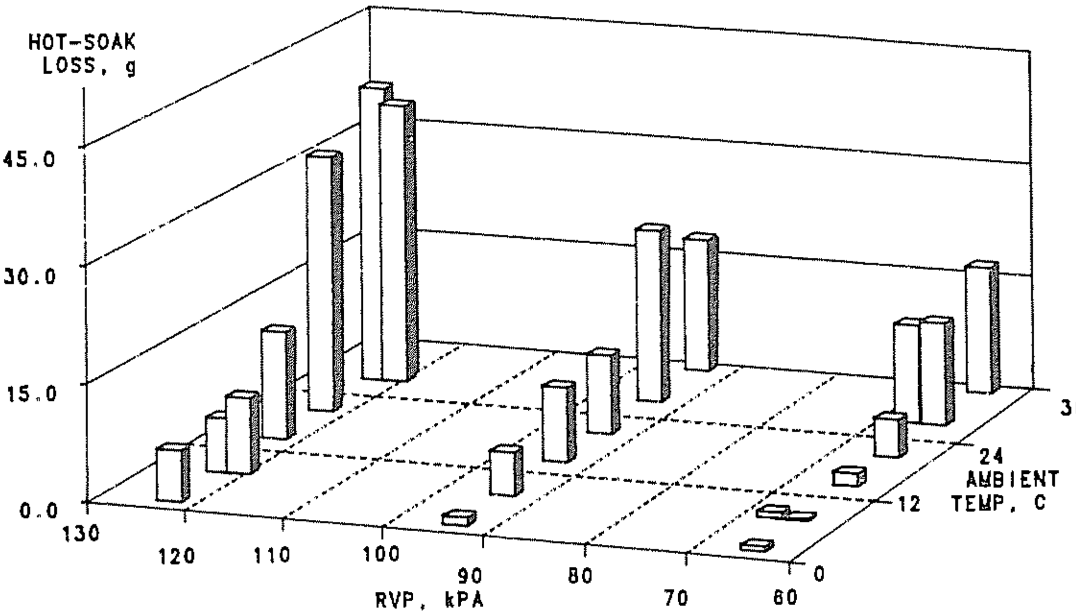


FIG. 5 – Hot-soak losses from the Daimler Benz.

(a) Uncontrolled



(b) With small canister

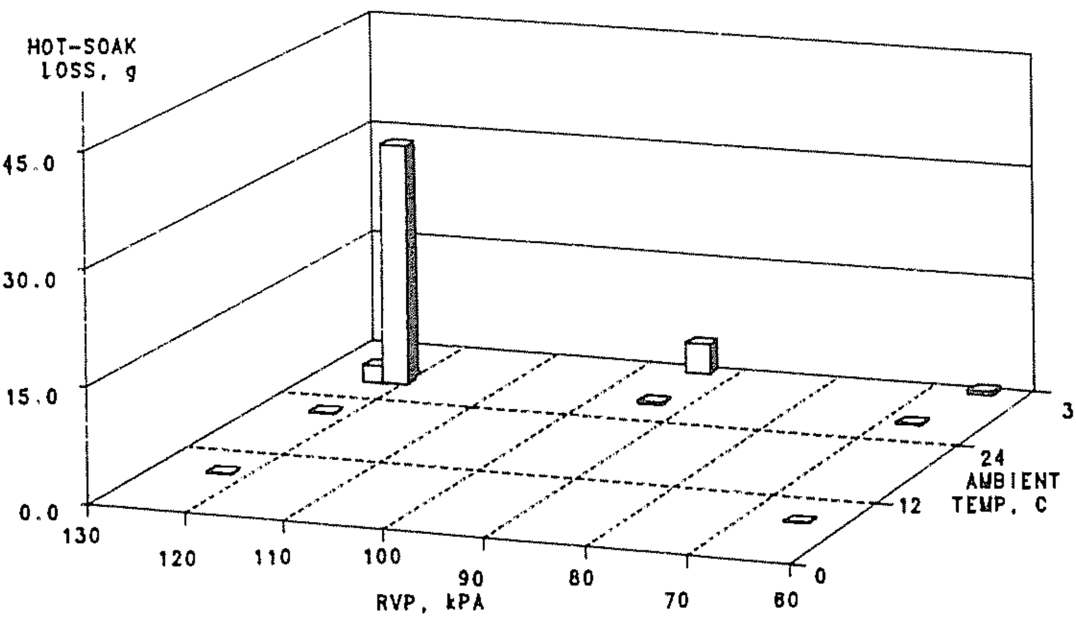
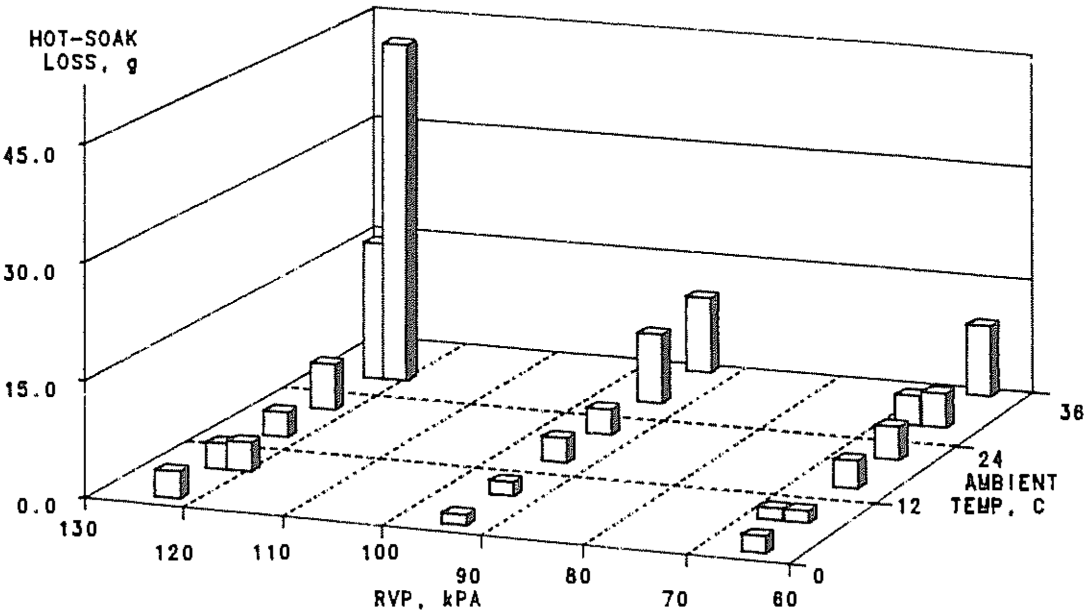


FIG. 6 — Hot-soak losses from the Vauxhall Cavalier and Opel Ascona.

(a) Vauxhall Cavalier Uncontrolled



(b) Opel Ascona with large canister

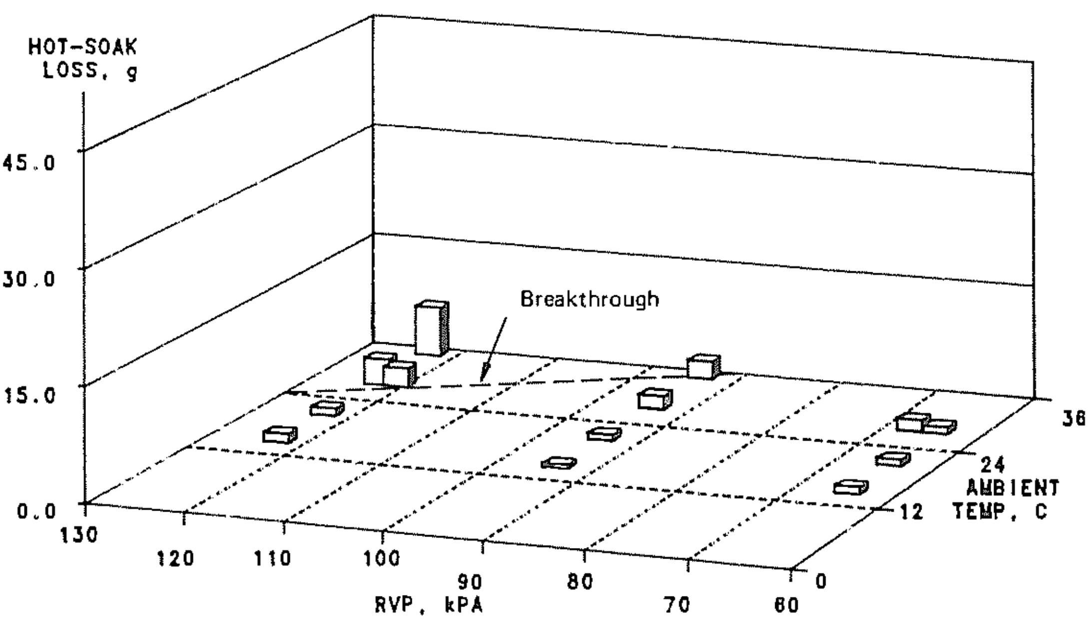
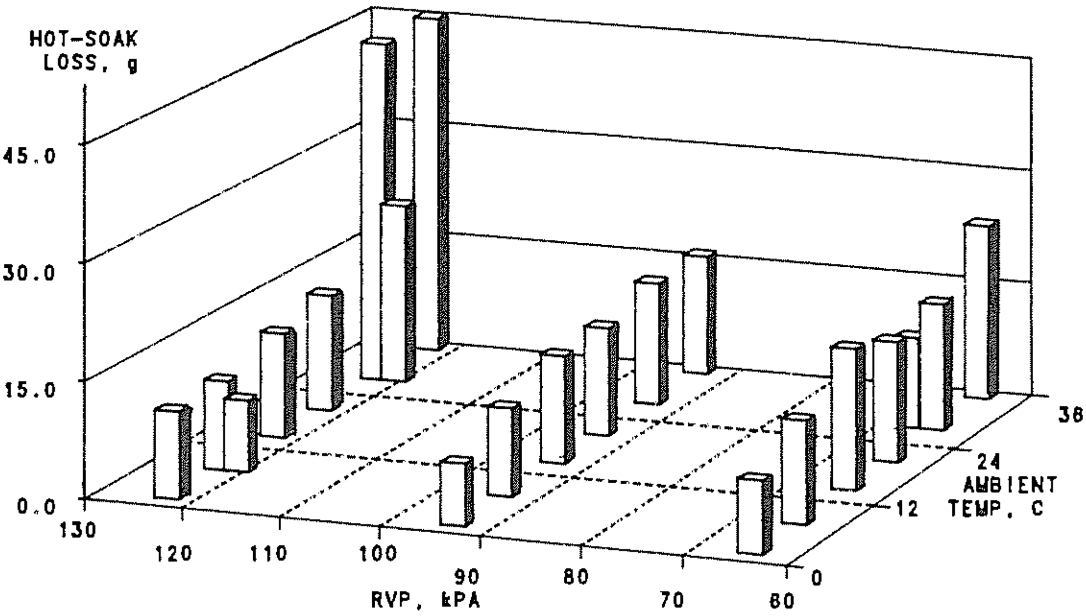


FIG. 7 — Hot-soak losses from the Citroen BX19s.

(a) Uncontrolled



(b) With small canister

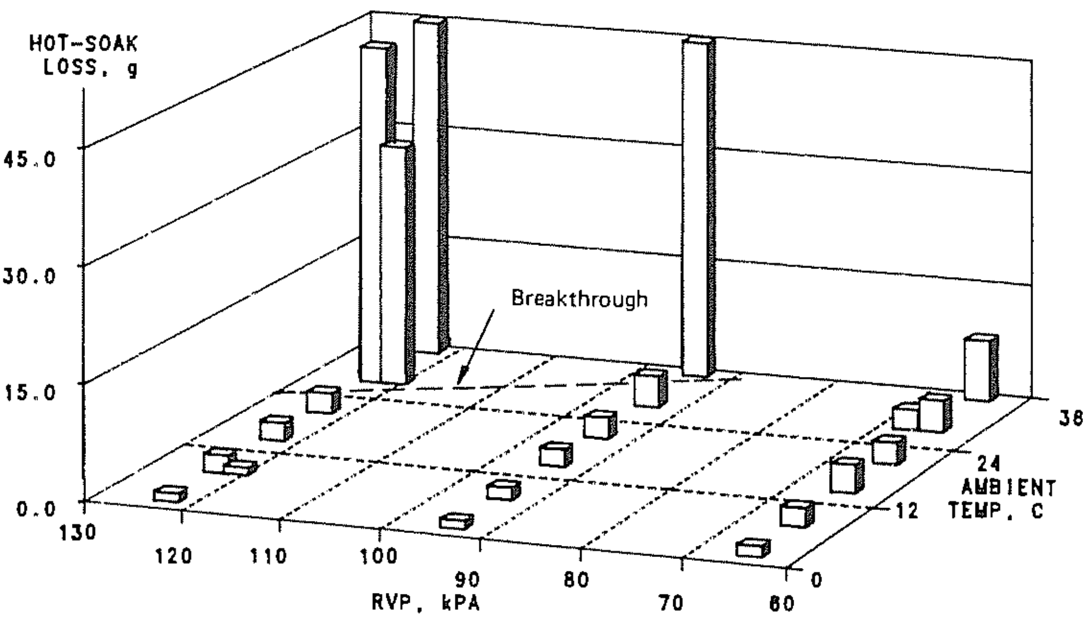


FIG. 8 – Schematic representation illustrating the influence of ambient temperature (or fuel volatility) on carbon canister weight and hot-soak loss from a controlled car.

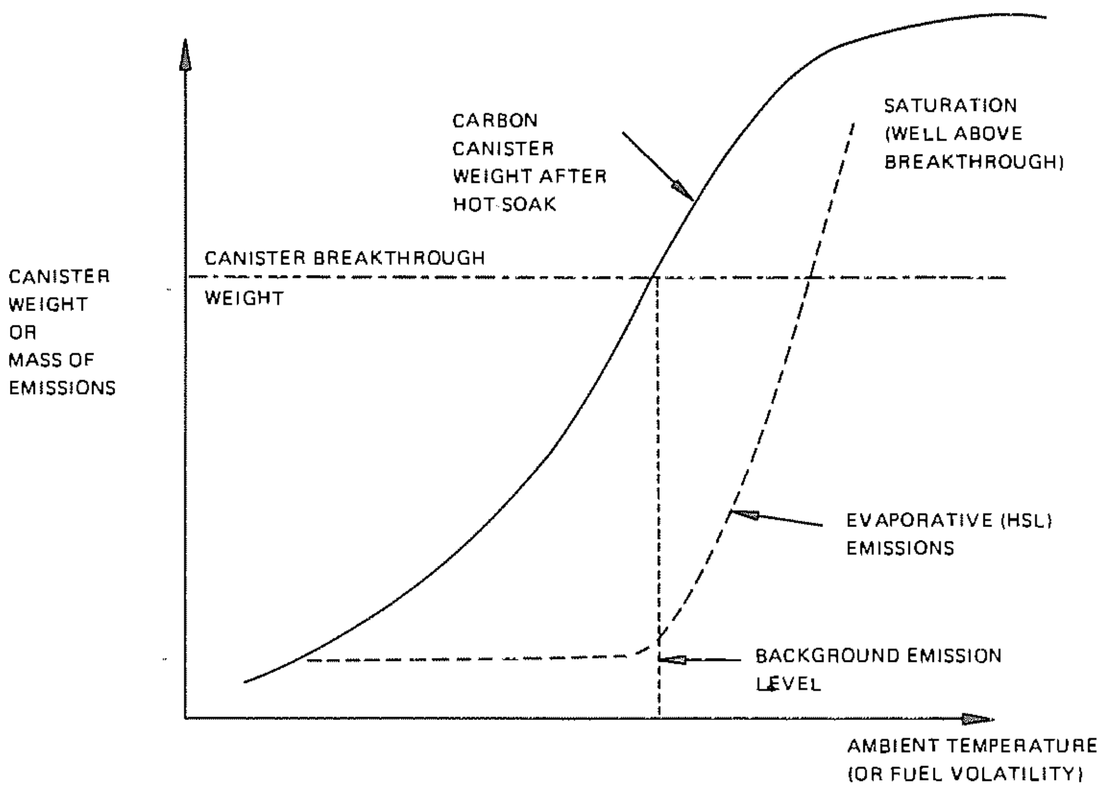


FIG. 9 — Running losses from the uncontrolled Ford Fiesta.

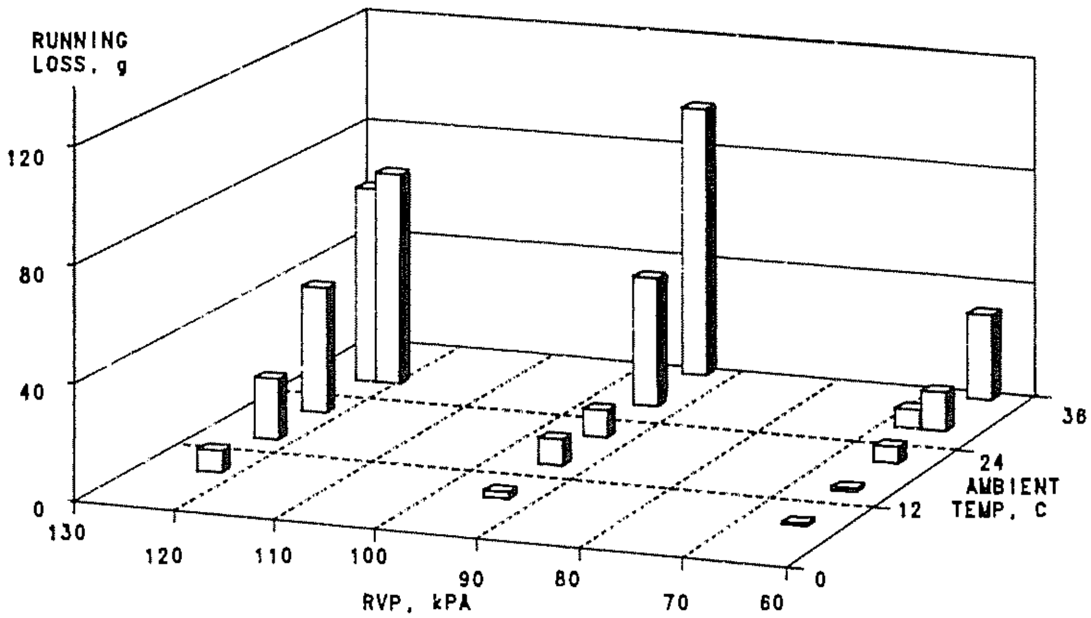


FIG. 10 — Running losses from the uncontrolled Honda Civic.

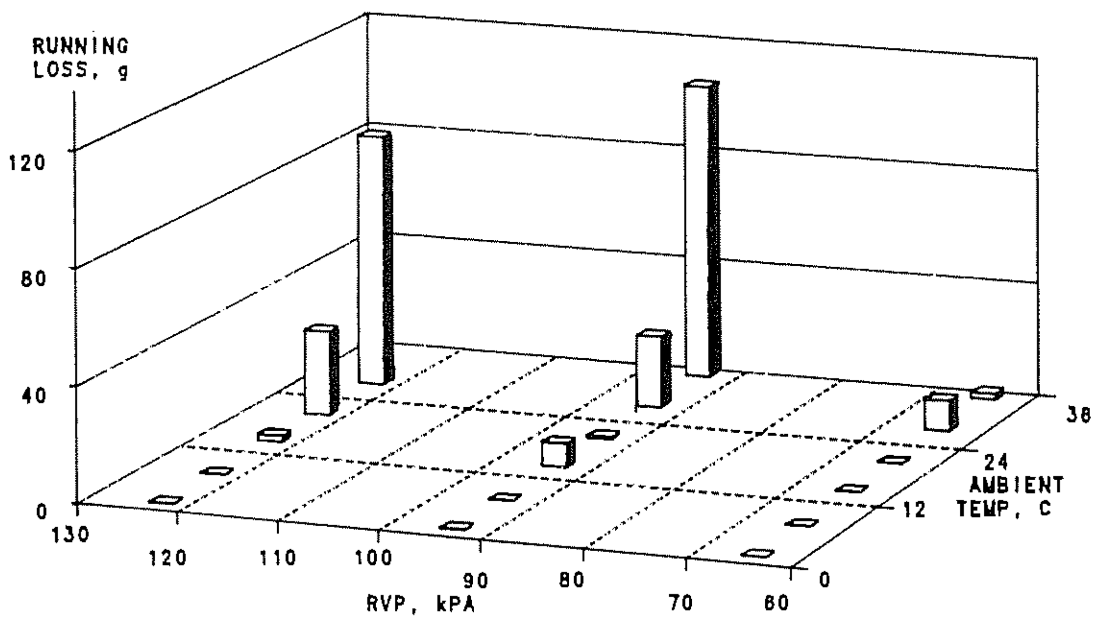


FIG. 11 – Running losses from the uncontrolled Daimler Benz.

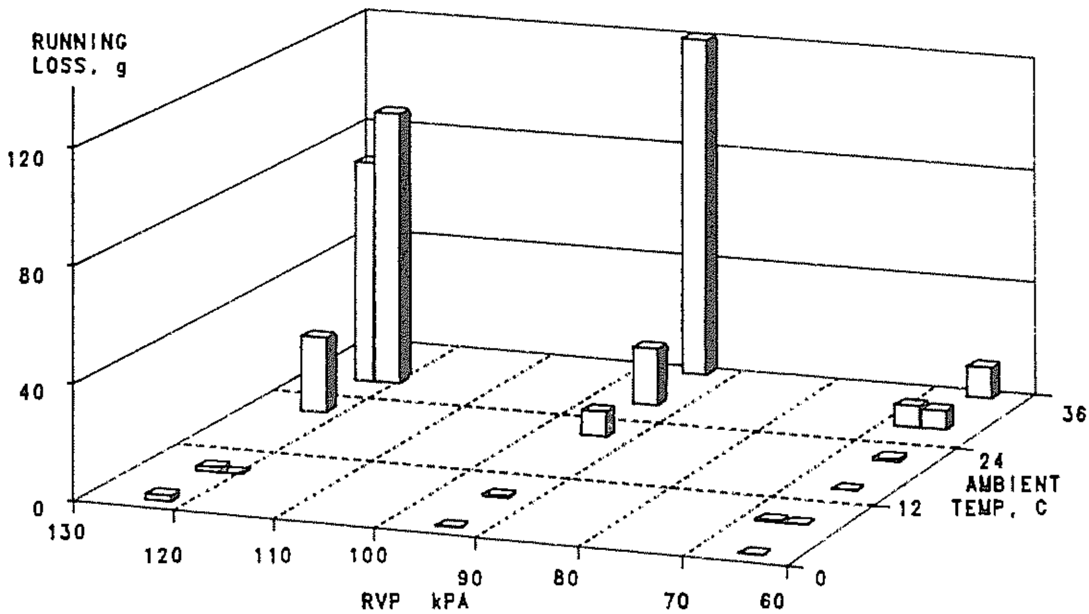


FIG. 12 – Running losses from the uncontrolled Vauxhall Cavalier.

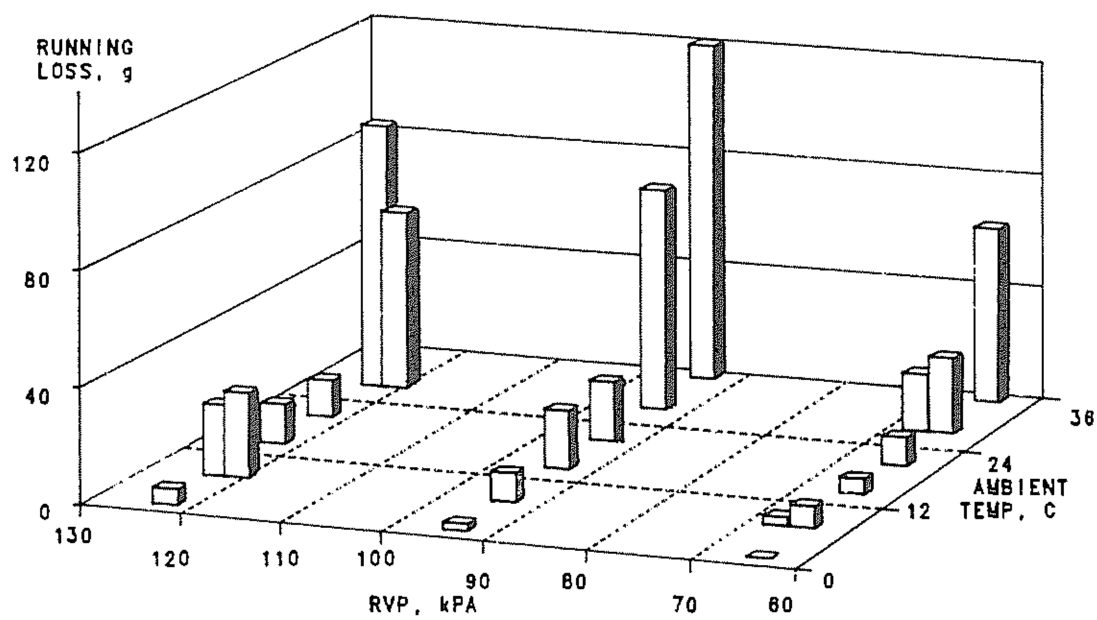


FIG. 13 – Running losses from the uncontrolled Citroen BX19.

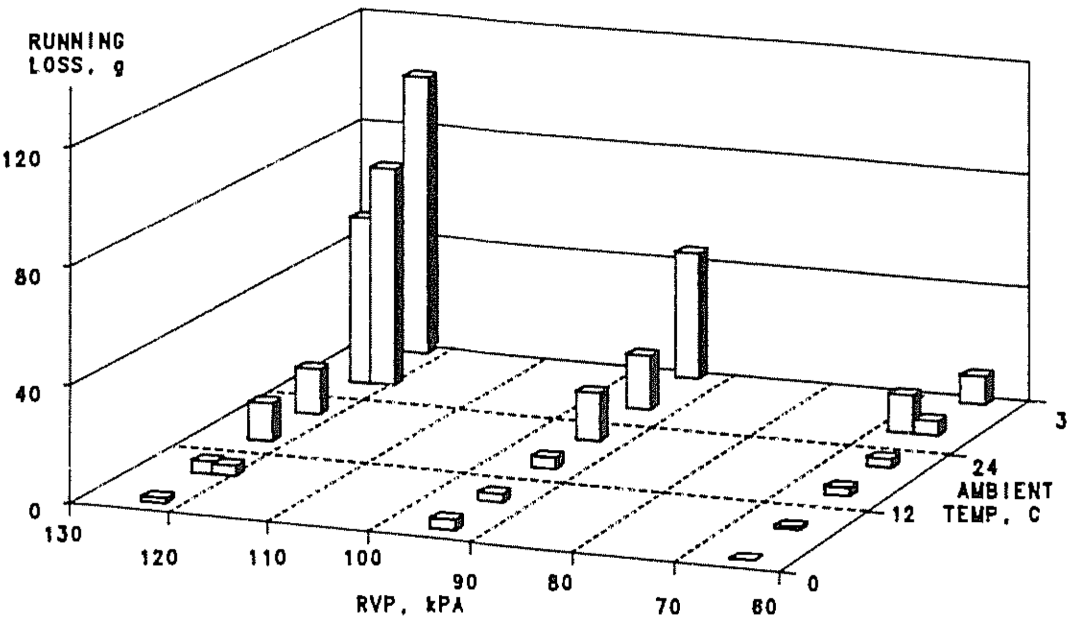
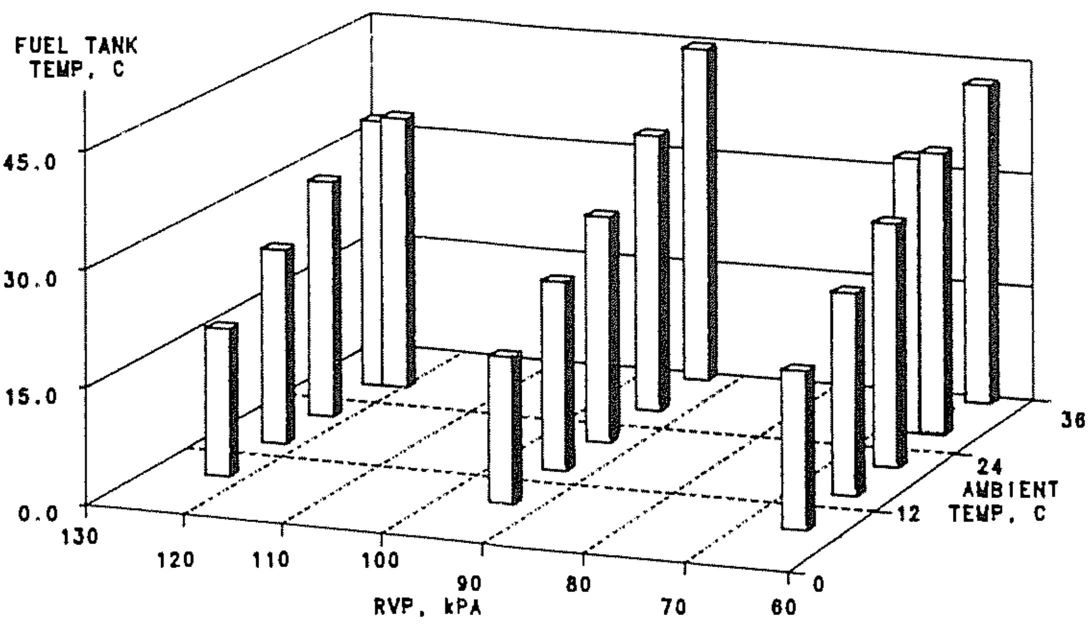


FIG. 14 – Fuel tank temperatures after conditioning for the uncontrolled Ford Fiesta.



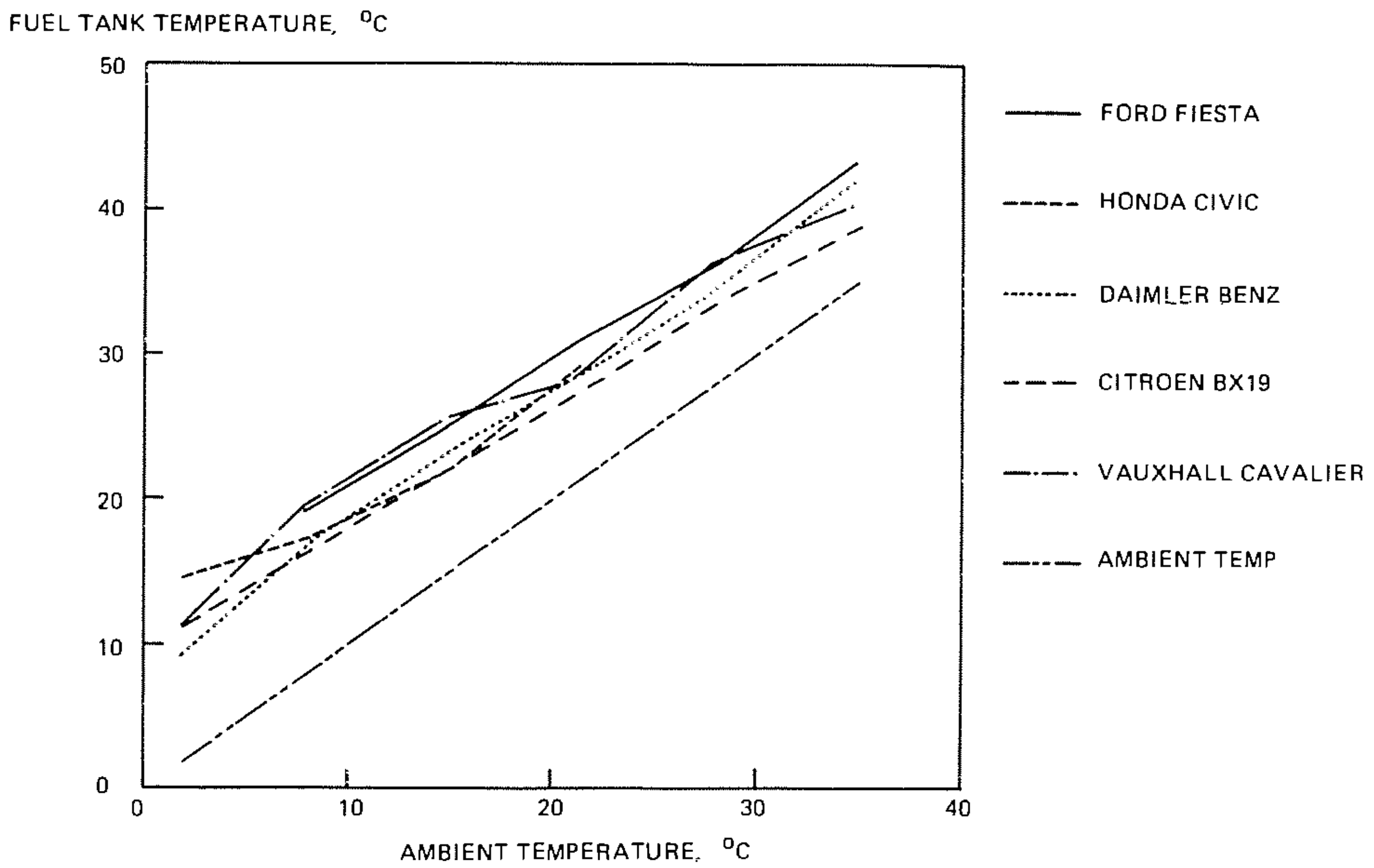


FIG. 15 – Fuel tank temperatures at the end of conditioning (30 mins/90 kph) for the uncontrolled vehicles

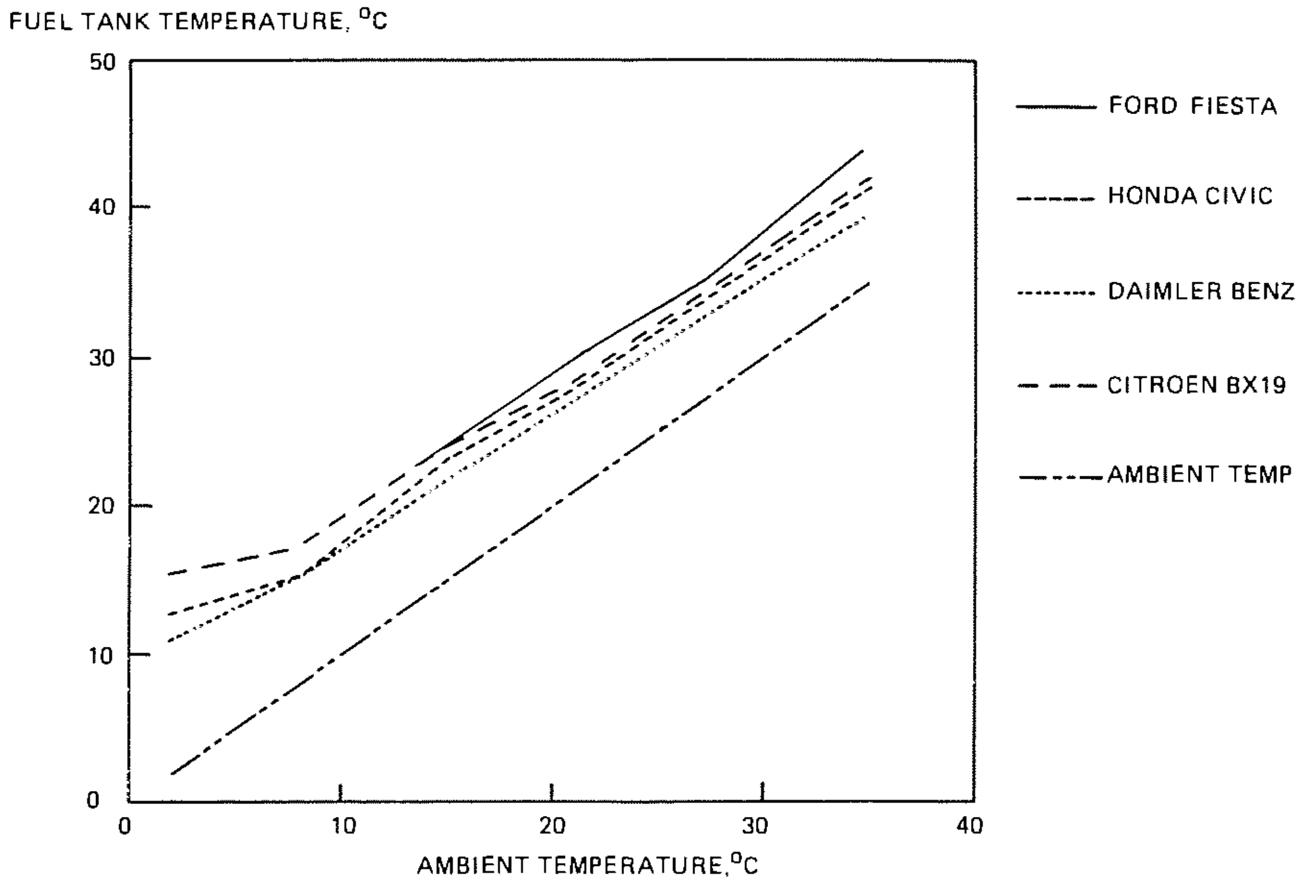


FIG. 16 – Fuel tank temperatures at end of conditioning (30 mins/90 kph) for the vehicles equipped with carbon canisters

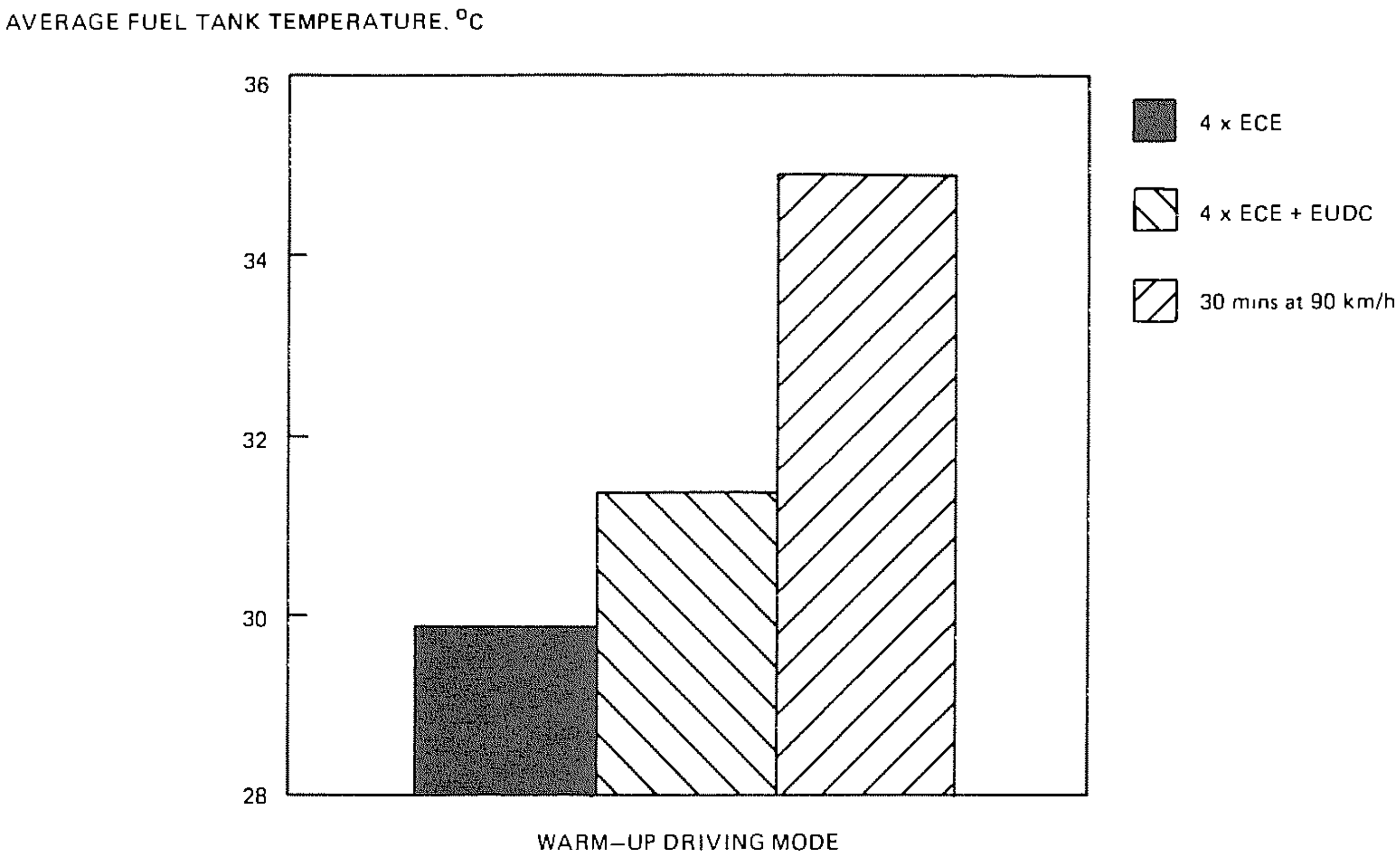


FIG. 17 – Effect of the driving cycle on the fuel tank temperature at the end of conditioning.

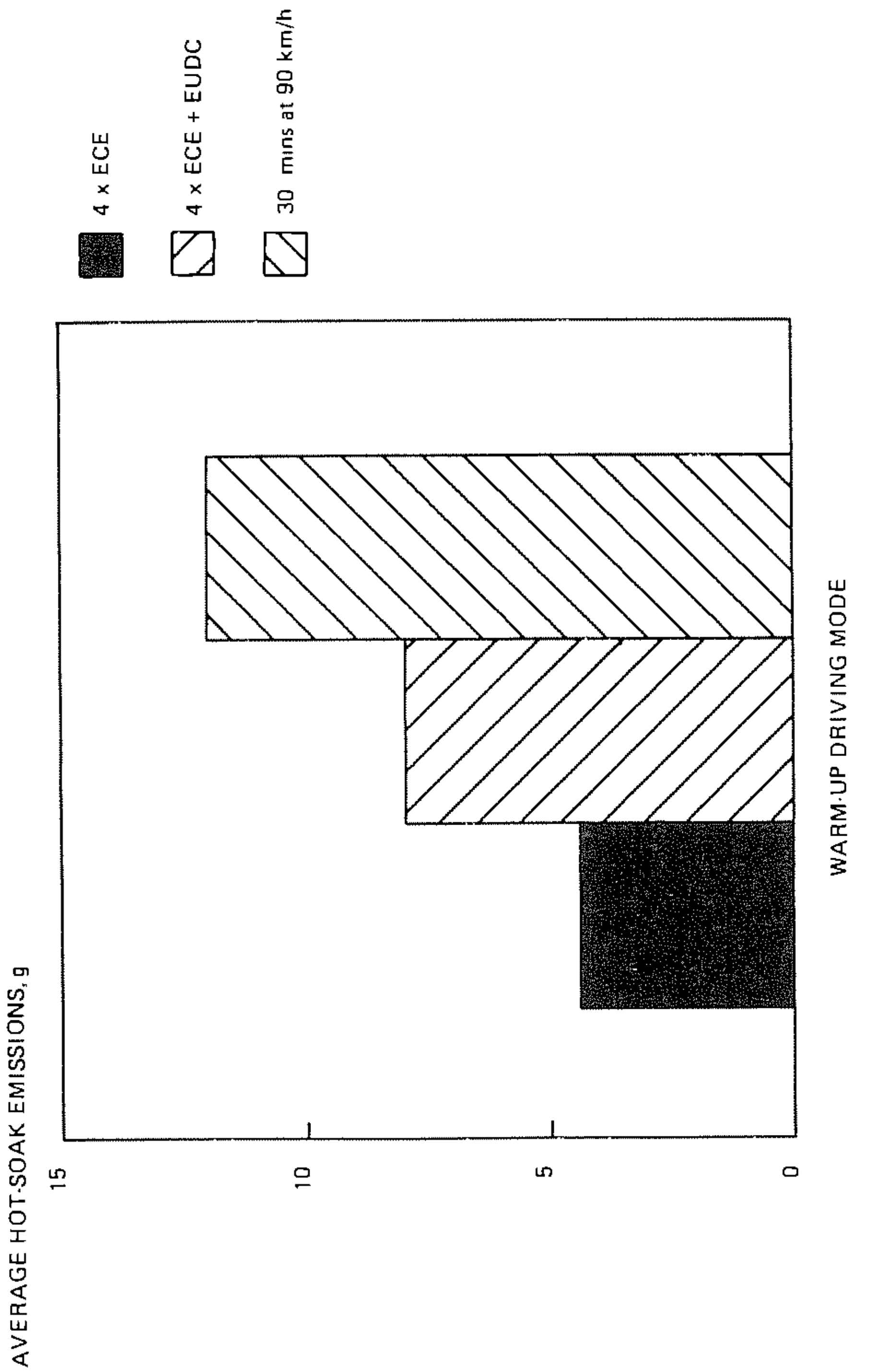


FIG. 18 – Effect of the conditioning cycle on the hot-soak losses from uncontrolled vehicles.

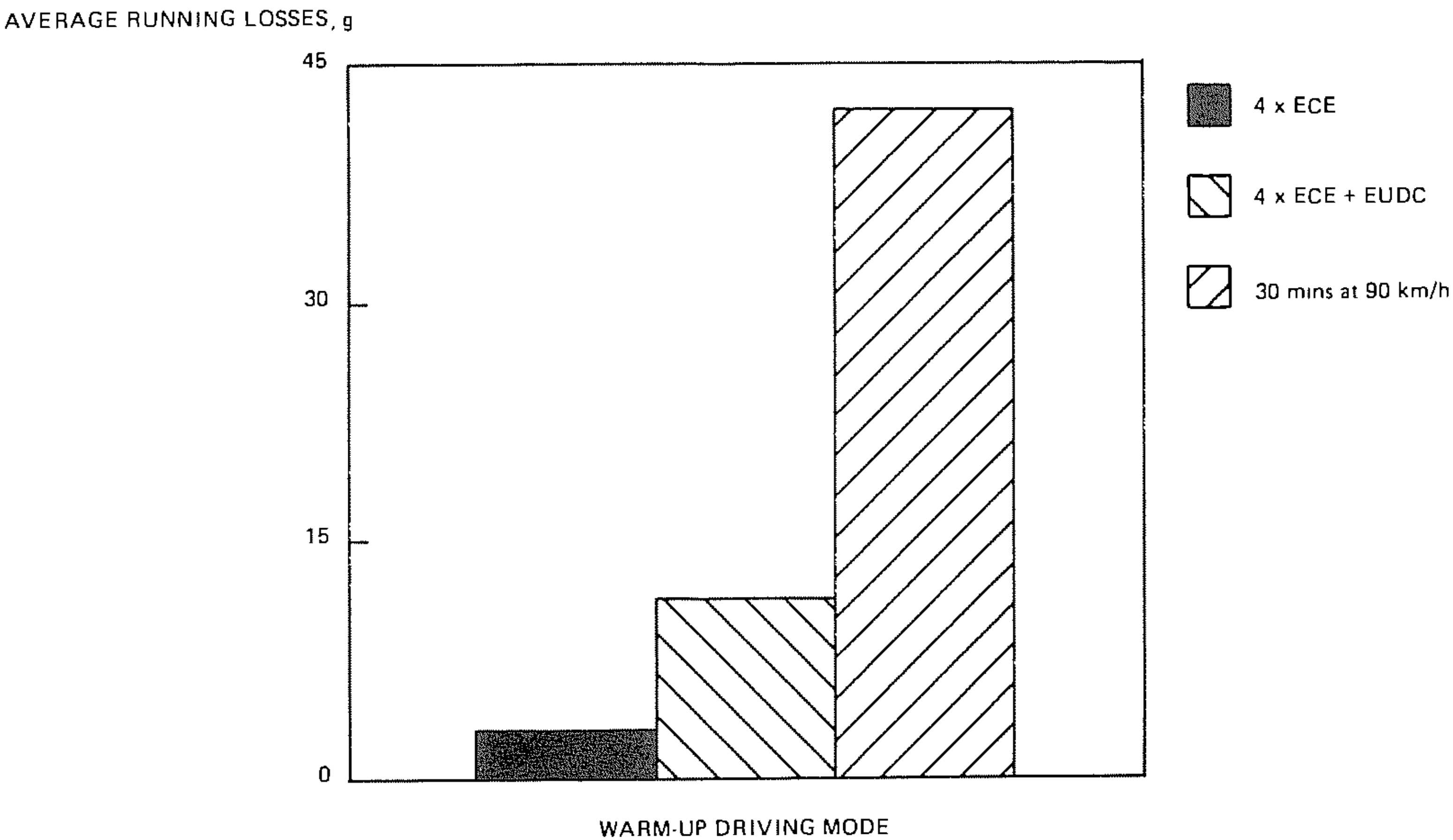


FIG. 19 – Effect of the conditioning cycle on the running losses from uncontrolled vehicles.

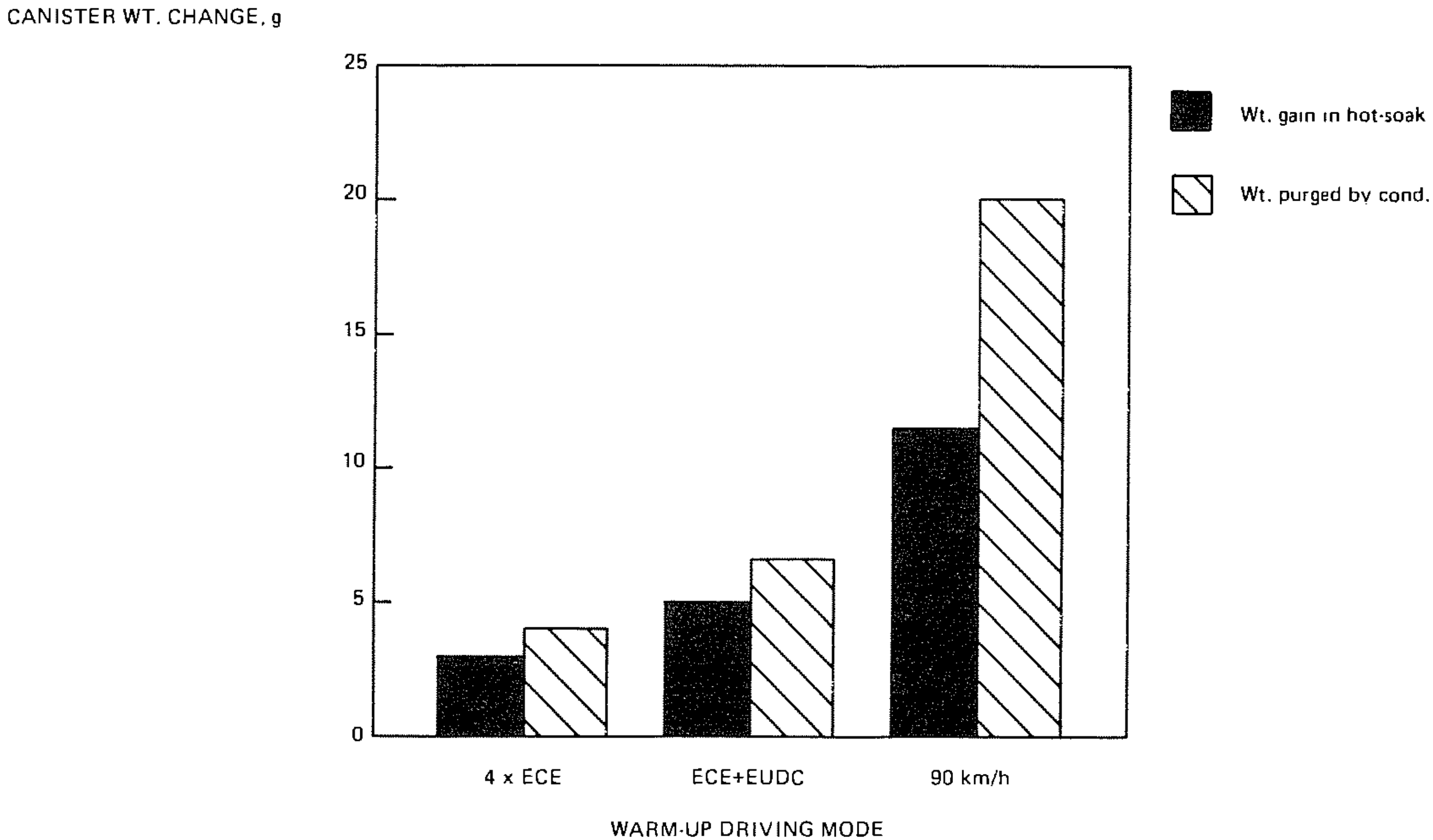


FIG. 20 – Comparison of the Ford Fiesta carbon canister performance under different driving conditions.

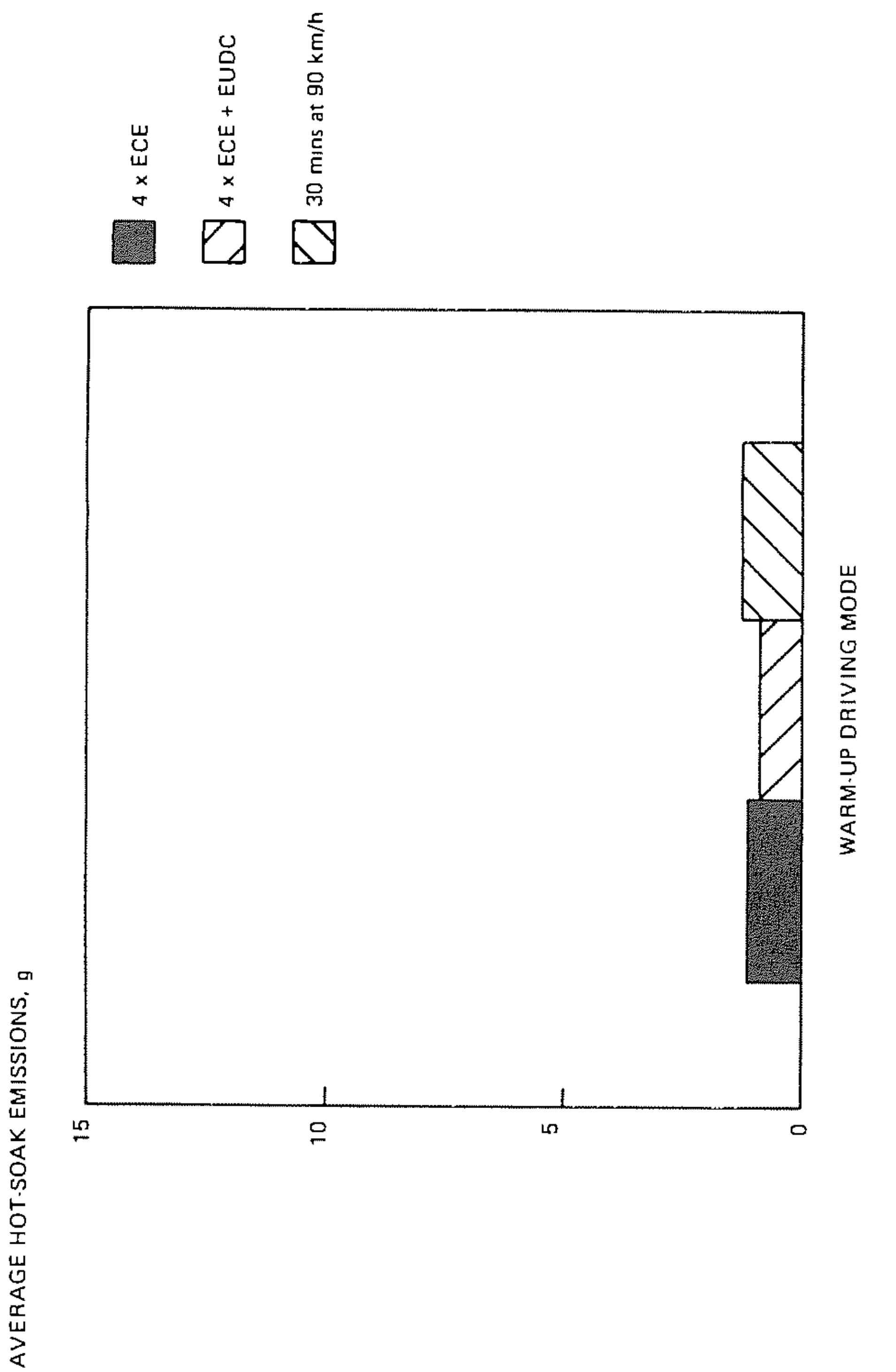


FIG. 21 — Effect of the conditioning cycle on the hot-soak losses from controlled vehicles.

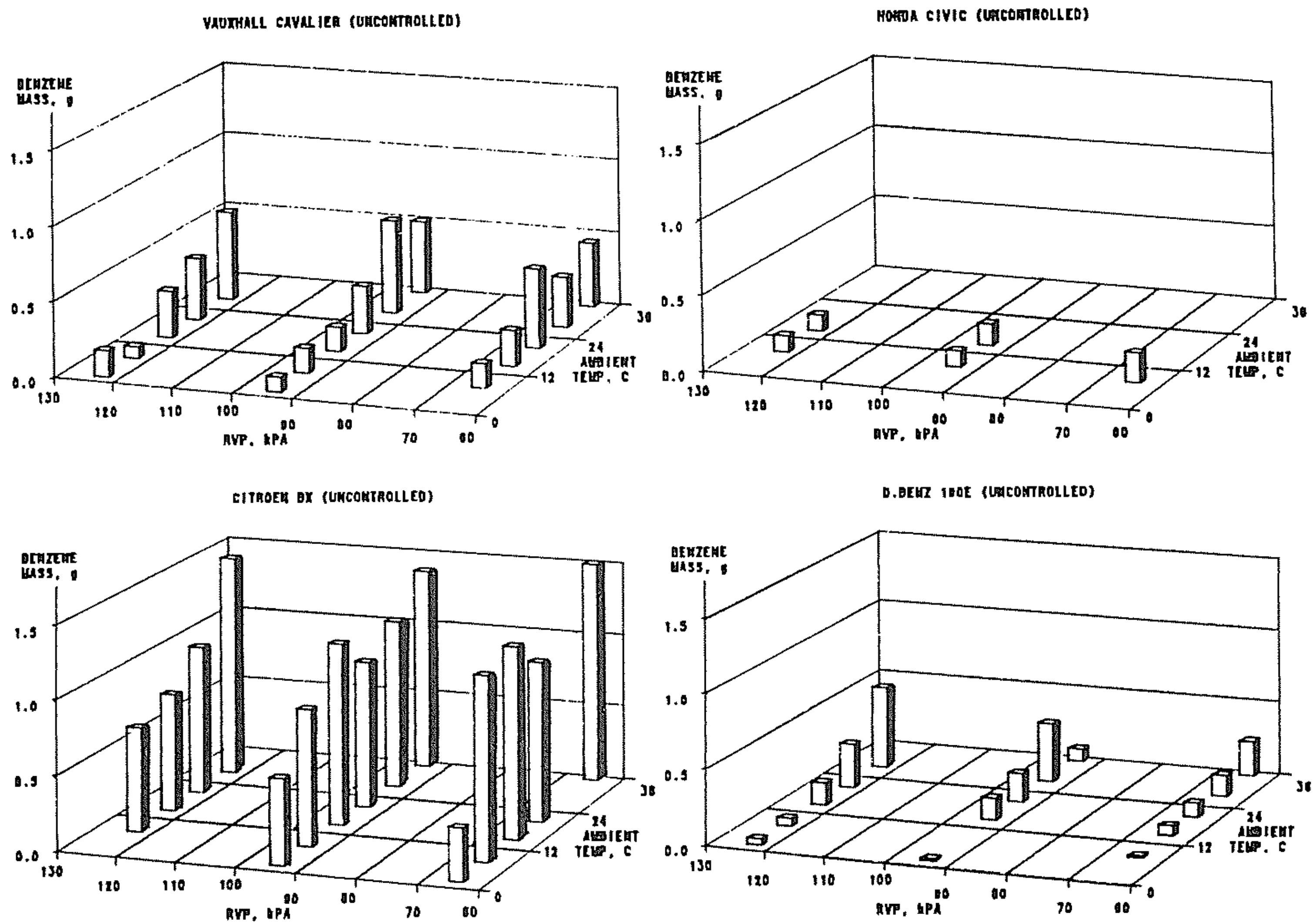


FIG. 22 – Mass emissions of benzene from uncontrolled vehicles during the hot-soak.

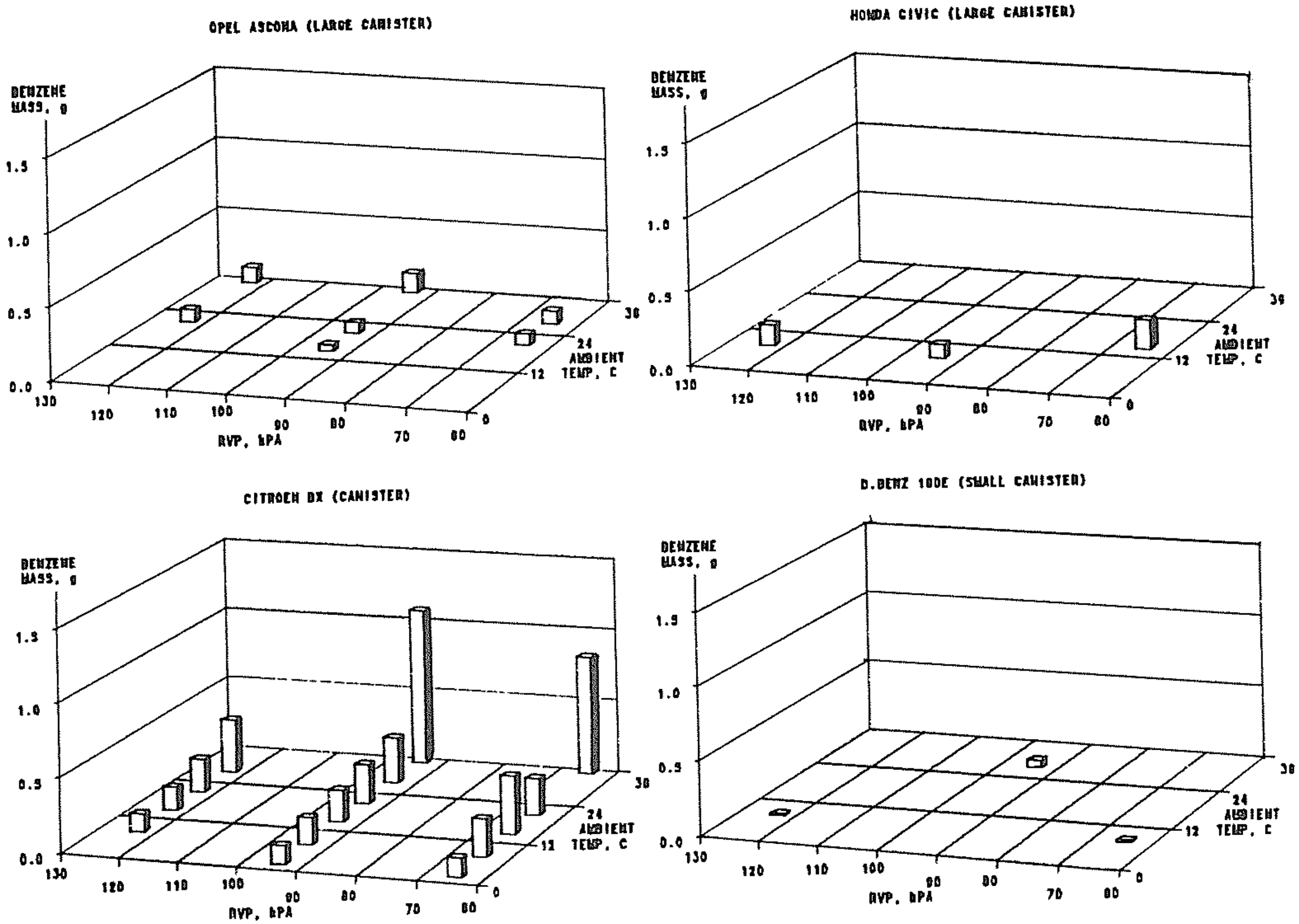


FIG. 23 — Mass emissions of benzene from controlled vehicles during the hot-soak.

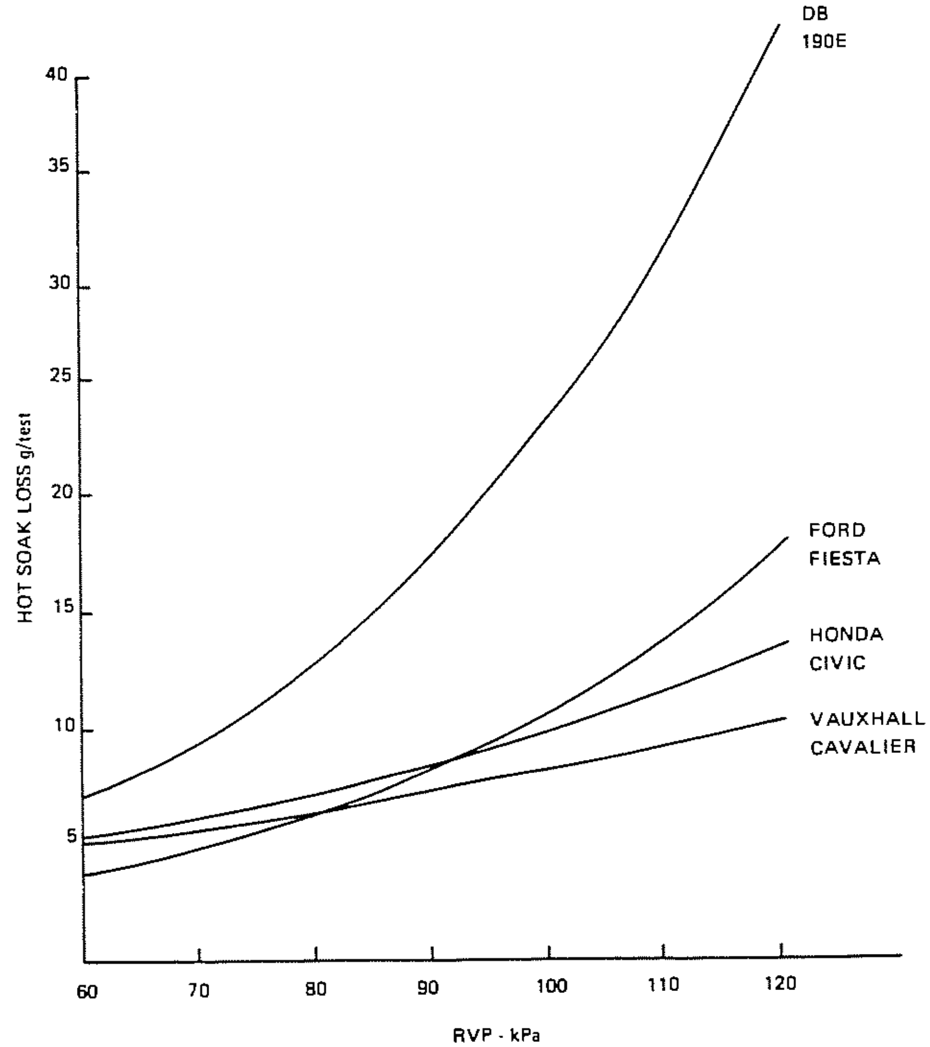


FIG. 24 — Variation in hot-soak loss with RVP at 28^{o}C for different cars (from the statistical models)

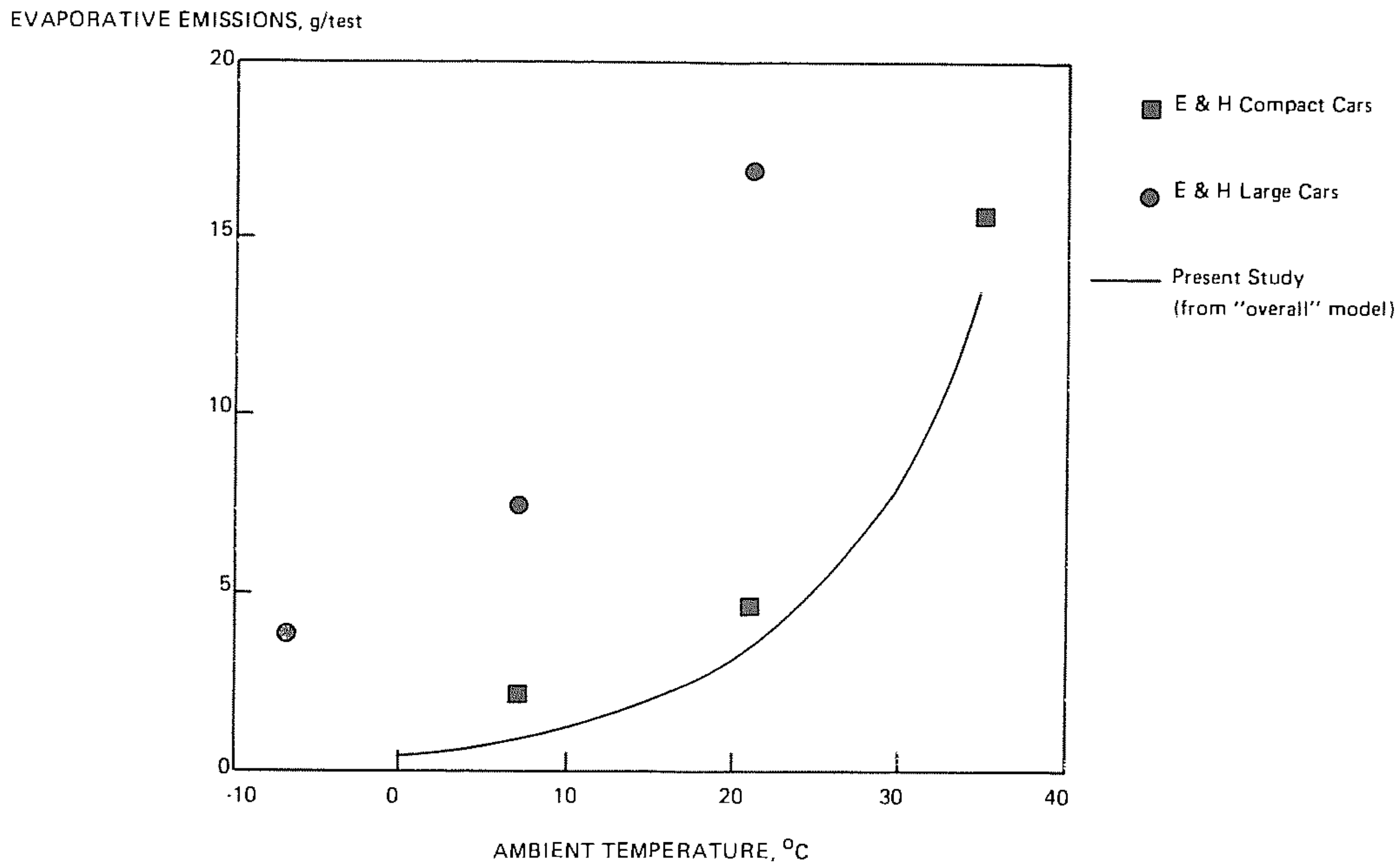


FIG. 25 – Comparison of effect of ambient temperature on evaporative emissions with published data of Eccleston & Hum[3].

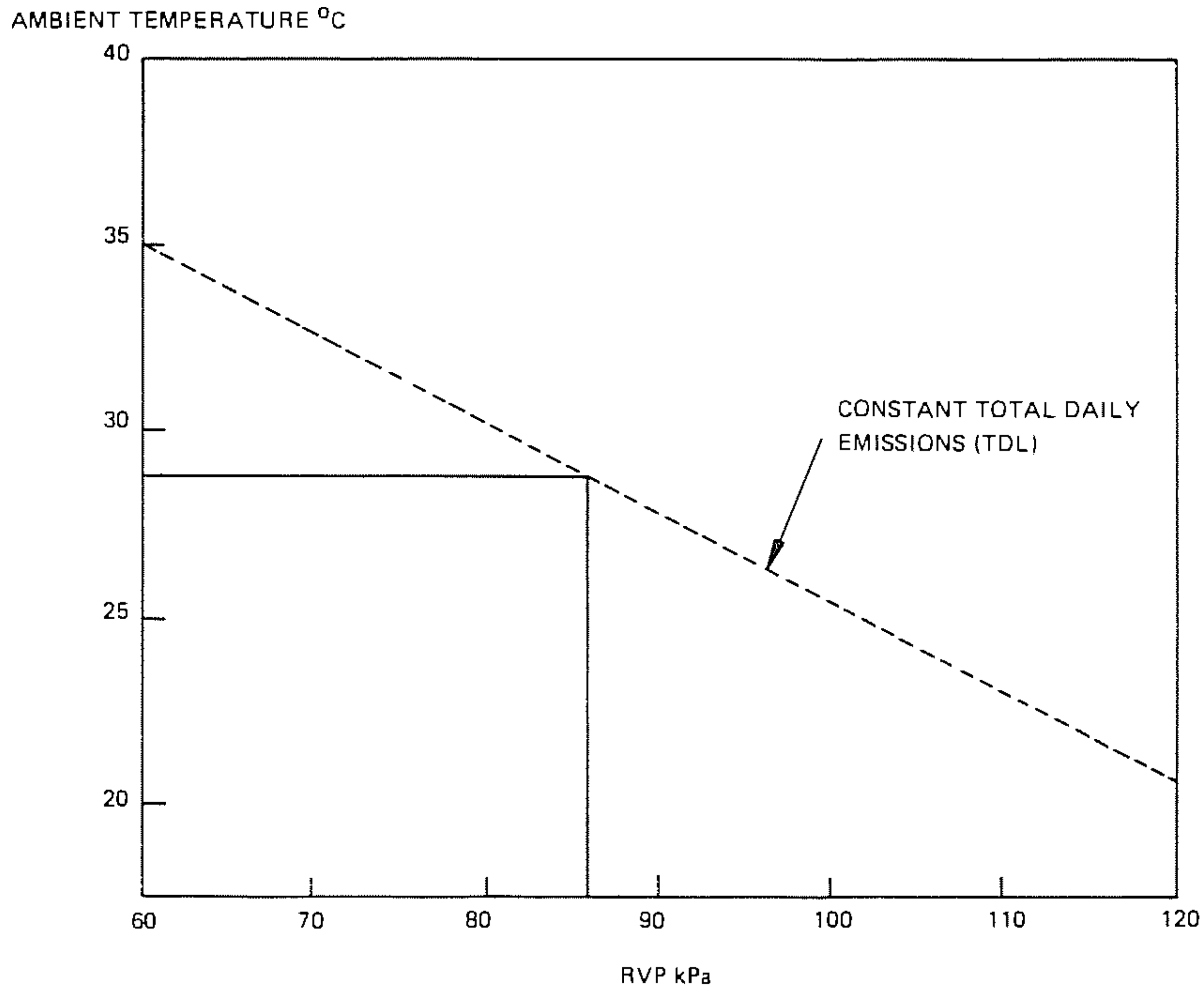


FIG. 26 – Ambient temperature/RVP tradeoff for constant evaporative emission.

APPENDIX A TEST PROCEDURE

This test procedure assumes that the first car to be tested is a controlled vehicle fitted with hot-soak loss (HSL) and/or refuelling canister. If not, then ignore references to HSL canisters.

1. Close SHED door.
2. Remove hot-soak loss (HSL) canister(s) and weigh. Record weight(s).
3. Remove and weigh overnight-soak loss canisters (if used). Record weights.
4. Take 1 litre sample (B) of fuel from tank and label.
5. Refit HSL canister(s).
6. Weigh running loss (RL) canisters and fit to vehicle (tank & canister vents). Record canister weights.
7. Condition car (90 km/hr for 30 mins or other conditions as required).
8. Set zero and span on FID.
9. Calibrate benzene sample tube flow rate.
10. Take background benzene sample from SHED.
11. After 29 mins record temperatures (5 in total).
12. Stop vehicle.
13. Remove RL and HSL canister(s) and reweigh. Record weight(s).
14. Take 1 litre fuel sample (C) and label.
15. Refit HSL canister(s).
16. Set FID to measure and set chart running.
17. Write range setting on chart.
18. Remove car from rolls and push into SHED.
19. Open car boot and windows.
20. Connect thermocouples in SHED (5 in total) and close bonnet.
21. Close SHED door and record time.

22. Mark background ppm on chart.

23. Put second car on rolls.

24. Purge RL canisters used on first car.

25. Calibrate benzene sample tube flow rate.

26. After 1 hr 50 min. soak take first benzene sample.

27. After 2 hrs soak record PPM reading in SHED.

28. Record temperatures.

29. Calibrate second benzene sample tube flow rate.

30. Take second benzene sample at 2 hrs 10 mins.

31. Open SHED door, disconnect thermocouples and purge SHED. Remove car from SHED. (Wear hydrocarbon mask.)

32. Remove HSL canister(s) and reweigh. Record weight(s).

33. Take 1 litre fuel sample (D) and label.

34. Run road fan with SHED and dynamometer door open to purge.

35. Repeat steps 1-21 for second car but excluding HSL canisters if an uncontrolled vehicle. RL canister will be required on carb vent if not internally vented.

During 2 hr soak period:

36. Recharge soak canister(s) of first car to breakthrough weight and seal.

37. Drain fuel tank of first car.

38. Recharge tank with 10 litres of next test fuel.

39. Place car on rolls.

40. Reweigh and refit HSL canister(s). Record weights.

41. Precondition: 2ECE cycles, 80 km/hr for 10 mins, 2 ECE cycles.

42. Remove HSL canister(s) and reweigh. Record weight(s).

43. Drain fuel tank.

44. Refill with appropriate quantity of test fuel (40% + 21).

45. Take 1 litre fuel sample (A) and label.

46. Fit HSL and overnight canister(s) if used.

47. Leave vehicle in dynamometer.

THEN:

48. Repeat steps 26-34 for second vehicle.

49. Precondition second car on dynamometer - steps 36-47.

50. Put first car back on dynamometer rolls.

51. Set dynamometer soak temperature for next day's test.

52. Send fuel samples for storage or analysis.

53. Complete all test sheets/summary sheets/summary graphs.

ALWAYS:

- Have all canisters disconnected when draining or filling tank.

- Weigh canisters when disconnected or reconnected.

D.BENZ 190E (SMALL CANISTER)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
C1	29/04/88	2	3	1229	51.2	0.0	3.9	2.4	.	.	.
C2	05/05/88	28	3	1229	47.2	0.0	43.3	2.2	.	.	.
C3	09/05/88	21	3	1229	42.1	D.0	36.4	11.4	.	.	.
C4	10/05/88	2	2	939	36.7	0.0	0.0	2.7	.	.	.
C5	01/06/88	15	3	1229	10.6	0.5	13.8	3.9	.	.	.
C6	02/06/88	28	1	645	12.3	0.0	6.9	3.5	.	.	35.3
C7	03/06/88	28	2	939	15.1	0.0	27.4	3.8	2.7	1.6	34.0
C8	04/06/88	15	2	939	33.7	0.0	5.2	3.3	1.2	1.5	22.8
C9	05/06/88	2	1	645	23.0	0.0	0.0	1.5	1.0	2.0	9.9
C10	06/06/88	15	1	645	30.0	0.0	1.0	2.7	2.3	2.6	.
C11	07/06/88	21	1	645	33.2	0.0	1.2	3.5	3.4	3.8	27.1
C12	08/06/88	21	2	939	24.3	0.0	5.3	4.0	3.1	2.2	27.9
C13	09/06/88	21	3	1229	20.6	0.0	24.1	4.5	2.5	.	27.8
C14	10/06/88	35	2	939	18.3	0.0	32.4	5.7	4.4	.	40.3
C15	11/06/88	35	1	645	30.4	0.0	8.7	4.2	4.2	.	40.1
C16	13/06/88	28	3	1229	25.5	0.0	43.4	9.7	.	.	33.5
C17	17/06/88	8	3	1229	30.2	0.3	3.7	4.0	0.9	0.9	15.0
C18	18/06/88	2	3	1229	8.2	0.7	4.5	4.3	.	.	12.0
C19	22/06/88	28	2	939	-0.6	0.0	1.0	3.5	.	.	.
C20	23/07/88	28	2	939	2.6	.	13.8	1.4	2.2	1.7	31.6
C21	26/07/88	8	2	939	9.5	.	3.4	3.6	.	.	16.8
C22	27/07/88	8	1	645	6.5	.	0.0	2.6	1.6	2.4	16.4
C24	08/08/88	28	3	1229	27.3	.	47.6	10.8	2.1	0.5	33.7
C26	27/09/88	28	2	939	10.0	.	10.2	3.5	.	.	32.6
C27	02/11/88	15	3	1229	20.1	.	9.1	1.9	.	.	20.6
C28	14/12/88	35	2	939	31.8	.	45.5	4.0	.	.	39.2
C29	15/12/88	35	1	645	36.6	.	15.6	0.5	.	.	39.2
C30	16/12/88	28	2	939	36.2	.	15.7	0.3	1.4	6.4	33.8
C31	19/12/88	28	2	939	25.8	.	15.6	0.3	1.5	7.1	30.2
C32	20/12/88	28	2	939	16.6	.	8.2	0.3	1.1	8.8	29.1
C33	06/01/89	21	3	1229	28.0	.	20.0	0.2	.	.	25.0
C34	09/01/89	28	3	1229	31.8	.	44.4	2.2	.	.	34.0
C37	12/01/89	8	3	1229	23.7	.	8.4	0.2	0.4	3.7	14.0
C38	13/01/89	8	1	645	28.4	.	2.8	0.1	0.4	5.2	14.0

HONDA CIVIC (UNCONTROLLED)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
A1	27/04/88	28	3	1229	.	88.7	.	17.1	.	.	.
A2	28/04/88	15	3	1229	.	4.5	.	14.5	.	.	.
A3	29/04/88	2	3	1229	.	0.0	.	1.2	.	.	.
A4	05/04/88	28	1	645	.	10.6	.	4.3	.	.	.
A5	09/06/88	21	3	1229	.	27.5	.	4.3	.	.	.
A6	11/05/88	15	2	939	.	16.5	.	4.4	.	.	.
A7	12/05/88	15	1	645	.	0.0	.	2.0	.	.	.
A8	16/05/88	28	2	939	.	25.1	.	7.3	.	.	.
A9	17/05/88	21	2	939	.	0.3	.	4.3	.	.	.
A10	18/05/88	2	2	939	.	0.3	.	1.3	.	.	.
A11	19/06/88	21	1	645	.	0.0	.	2.8	.	.	.
A12	20/06/88	35	2	939	.	104.3	.	15.9	.	.	.
A13	21/06/88	35	1	645	.	2.0	.	17.4	.	.	.
A14	23/06/88	8	3	1229	.	0.0	.	11.8	.	.	18.2
A15	24/06/88	28	2	939	.	0.2	.	5.8	.	.	26.0
A16	27/06/88	21	3	1229	.	31.5	.	6.6	.	.	28.7
A17	28/06/88	28	2	939	.	0.0	.	4.1	.	.	29.2
A18	21/07/88	28	2	939	.	7.1	.	4.0	.	.	30.5
A19	22/07/88	21	2	939	.	1.4	.	5.2	.	.	29.0
A20	25/07/88	15	3	1229	.	0.0	.	2.3	3.1	3.7	22.1
A21	28/07/88	8	2	939	.	0.0	.	2.5	3.2	4.0	17.4
A22	19/09/88	8	3	1229	.	0.0	.	2.7	3.2	3.4	6.2
A23	20/09/88	8	1	645	.	0.0	.	1.2	5.9	6.9	16.2
A24	21/09/88	15	2	939	.	0.0	.	2.9	4.3	4.6	21.4
A25	22/09/88	2	1	645	.	0.0	.	0.9	.	.	14.6

HONDA CIVIC (LARGE CANISTER)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
B1	11/05/88	15	2	939	18.1	0.2	1.7	1.2	.	.	.
B2	12/05/88	15	3	1229	-3.4	0.0	2.8	1.2	.	.	.
B3	13/05/88	28	3	1229	-33.0	0.0	34.1	2.2	.	.	.
B4	16/05/88	28	2	939	69.7	0.0	3.5	1.8	.	.	.
B5	17/05/88	21	2	939	58.7	0.0	.	1.5	.	.	.
B6	18/05/88	2	1	645	47.7	0.0	0.0	0.6	.	.	.
B7	19/05/88	28	1	645	50.9	0.0	1.1	2.4	.	.	.
B8	20/05/88	35	3	1229	-49.2	0.0	2.5	20.6	.	.	.
B9	27/06/88	21	3	1229	.	0.0	.	2.9	.	.	27.2
B10	28/06/88	28	2	939	3.3	0.0	2.7	2.3	.	.	28.9
B11	29/06/88	35	1	645	64.5	0.0	3.8	3.3	.	.	40.9
B12	30/06/88	2	3	1229	38.8	0.0	0.7	1.1	.	.	12.8
B13	14/07/88	35	2	939	-14.2	0.0	13.7	2.8	.	.	41.7
B14	15/07/88	21	3	1229	3.3	.	5.6	2.1	.	.	28.4
B15	21/07/88	28	2	939	6.6	.	7.2	1.7	.	.	30.8
B16	19/09/88	8	3	1229	47.7	.	0.1	1.9	4.2	6.7	15.6
B17	20/09/88	8	2	939	50.3	.	1.1	1.4	2.7	5.9	15.0
B18	21/09/88	15	1	645	57.1	.	0.0	2.4	5.9	6.9	23.0
B18	21/09/88	15	1	645	57.1	.	0.0	2.4	.	.	23.0

D.BENZ 190E (UNCONTROLLED)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
D1	12/06/88	28	2	939	.	.	.	16.8	.	.	35.7
D2	13/06/88	28	3	1229	.	.	.	27.5	.	.	34.2
D3	14/06/88	15	2	939	.	.	.	9.6	4.3	.	23.8
D4	15/06/88	15	3	1229	.	.	.	14.0	4.4	.	23.4
D5	16/06/88	28	1	645	.	6.5	.	13.4	4.2	.	35.4
D6	17/06/88	8	3	1229	.	1.7	.	6.9	1.5	0.5	16.9
D7	18/06/88	2	3	1229	.	2.0	.	6.5	1.2	0.5	10.0
D8	19/06/88	21	3	1229	.	26.5	.	33.6	8.7	0.7	28.1
D9	20/06/88	35	2	939	.	146.1	.	17.5	2.5	0.4	41.6
D10	21/06/88	35	1	645	.	10.8	.	16.7	7.0	1.5	42.7
D11	22/06/88	28	2	939	.	4.9	.	5.5	.	.	31.4
D12	23/06/88	8	2	939	.	0.6	.	5.5	.	.	18.0
D13	05/07/88	2	1	645	.	0.0	.	0.6	.	.	8.3
D14	06/07/88	21	2	939	.	8.7	.	10.3	5.7	1.1	28.3
D15	07/07/88	21	1	645	.	1.0	.	4.9	2.8	1.3	27.9
D16	08/07/88	15	1	645	.	0.0	.	1.6	1.9	2.9	22.4
D17	11/07/88	28	2	939	.	9.5	.	15.7	.	.	31.8
D18	12/07/88	28	2	939	.	20.1	.	28.4	11.7	1.2	34.0
D19	20/07/88	28	3	1229	.	78.1	.	50.3	16.3	0.9	33.6
D20	29/07/88	2	2	939	.	0.1	.	1.1	0.4	0.7	9.8
D24	05/08/88	8	1	645	.	0.0	.	0.2	0.4	3.0	16.7

VAUXHALL CAVALIER (UNCONTROLLED)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
F1	29/06/88	35	1	645	.	61.8	.	9.3	13.0	8.5	39.1
F2	30/06/88	2	3	1229	.	5.4	.	3.4	5.2	8.4	.
F3	05/07/88	2	1	645	.	0.0	.	2.1	.	.	11.1
F4	06/07/88	21	3	1229	.	12.9	.	6.0	12.5	5.8	26.5
F5	07/07/88	21	2	939	.	5.3	.	4.4	11.8	6.9	27.2
F6	08/07/88	15	3	1229	.	13.8	.	3.2	9.3	6.7	21.5
F7	11/07/88	28	3	1229	.	75.2	.	21.1	15.6	1.8	33.4
F8	12/07/88	28	1	645	.	31.6	.	4.9	9.7	6.5	35.9
F9	13/07/88	28	2	939	.	77.9	.	9.1	18.9	5.6	39.2
F10	14/07/88	35	2	939	.	120.2	.	9.9	14.8	3.9	41.6
F11	15/07/88	21	1	645	.	9.8	.	4.3	15.7	9.5	27.9
F12	16/07/88	15	1	645	.	5.3	.	3.6	7.2	9.1	25.2
F13	18/07/88	28	2	939	.	5.2	.	3.4	8.7	6.6	31.2
F14	19/07/88	28	2	939	.	21.5	.	6.2	8.4	3.3	33.1
F15	20/07/88	28	1	645	.	21.1	.	4.0	10.3	7.0	37.7
F16	22/07/88	21	2	939	.	35.8	.	2.2	7.2	9.6	31.3
F17	25/07/88	15	2	939	.	20.2	.	3.1	4.9	3.4	26.0
F18	26/07/88	8	3	1229	.	22.1	.	2.6	3.6	4.2	19.3
F19	27/07/88	8	1	645	.	7.4	.	1.5	4.8	7.8	20.9
F20	28/07/88	8	2	939	.	9.9	.	1.7	4.9	6.4	19.9
F21	29/07/88	2	2	939	.	2.5	.	1.3	2.9	6.0	11.7
F25	05/08/88	8	3	1229	.	27.1	.	4.0	1.1	0.8	19.8
F26	08/08/88	28	3	1229	.	111.5	.	15.2	20.7	1.2	36.0

FORD FIESTA (UNCONTROLLED)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
J1	04/11/88	28	3	1229	-7.9	45.0	.	2.6	3.5	4.8	34.8
J2	07/11/88	28	3	1229	.	68.8	.	33.3	25.2	6.0	35.4
J3	09/11/88	21	3	1229	.	44.0	.	18.7	0.8	0.2	31.0
J4	10/11/88	15	3	1229	.	21.2	.	3.9	.	.	25.3
J5	14/11/88	28	2	939	.	45.1	.	9.0	.	.	36.4
J6	15/11/88	21	2	939	.	9.5	.	3.2	7.8	4.6	29.5
J7	16/11/88	15	2	939	.	8.7	.	2.6	.	.	23.2
J8	17/11/88	8	2	939	.	2.4	.	2.1	3.3	4.6	18.7
J9	18/11/88	35	2	939	.	95.0	.	24.0	13.8	1.7	44.4
J10	28/11/88	35	1	645	.	30.1	.	3.7	.	.	42.3
J11	29/11/88	28	1	645	.	13.5	.	3.7	7.1	5.6	36.9
J12	05/12/88	21	1	645	.	5.7	.	2.2	148.0	11.7	31.5
J13	06/12/88	15	1	645	.	1.2	.	2.3	11.0	1.3	25.9
J14	.	15	2	939	.	9.1	.	2.6	.	.	25.6
J15	20/12/88	28	2	939	.	2.6	.	3.7	7.4	5.9	31.8
J16	21/12/88	28	2	939	.	7.6	.	6.1	7.9	3.7	31.0
J19	12/01/89	8	3	1229	.	7.5	.	1.5	1.8	2.5	19.0
J20	13/01/89	8	1	645	.	0.9	.	1.1	1.4	3.3	20.0

FORD FIESTA (SMALL CANISTER)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
I1	04/11/88	28	3	1229	31.0	.	0.0	2.0	2.9	7.2	37.1
I2	07/11/88	28	3	1229	32.2	.	0.0	3.2	5.1	7.3	37.3
I3	08/11/88	28	3	1229	16.6	.	48.5	15.3	.	.	34.7
I4	09/11/88	21	3	1229	19.1	.	13.1	0.9	2.0	14.0	29.9
I5	10/11/88	15	3	1229	20.7	.	5.6	0.5	.	.	23.6
I6	14/11/88	28	2	939	20.0	.	11.5	0.9	.	.	29.9
I7	15/11/88	21	2	939	22.0	.	3.4	0.9	4.8	7.3	23.7
I8	18/11/88	35	2	939	9.0	.	36.1	2.3	4.6	5.7	39.0
I9	28/11/88	35	1	645	7.6	.	6.9	1.4	.	.	39.4
I10	29/11/88	28	1	645	17.7	.	1.5	1.3	4.1	9.1	32.1
I11	05/12/88	21	1	645	17.4	.	0.9	0.9	4.9	0.5	29.4
I12	06/12/88	15	1	645	17.6	.	0.4	0.9	12.6	2.2	23.4
I13	07/12/88	15	2	939	17.9	.	1.2	1.0	.	.	25.0
I14	08/12/88	28	2	939	18.0	.	2.8	1.2	.	.	35.4
I15	12/12/88	28	3	1229	6.8	.	16.1	1.0	4.6	8.3	35.4
I16	13/12/88	28	3	1229	13.7	.	33.2	1.1	.	.	34.7
I17	14/12/88	35	2	939	3.4	.	46.6	6.5	.	.	43.9
I18	15/12/88	35	2	939	-0.3	.	37.5	1.0	.	.	43.8
I19	16/12/88	28	2	939	4.1	.	3.0	0.8	3.0	7.1	28.4
I20	19/12/88	28	2	939	6.7	.	5.1	0.7	3.0	8.3	31.2

OPEL ASCONA (LARGE CANISTER)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
E1	03/06/88	28	3	1229	-31.2	.	105.2	19.7	24.2	3.3	39.8
E2	04/06/88	15	3	1229	47.7	.	4.7	27.2	4.5	0.5	26.8
E4	06/06/88	15	2	939	88.9	0.0	1.8	0.5	1.3	10.0	26.8
E5	07/06/88	21	2	939	91.9	0.0	2.6	0.8	2.1	9.6	38.1
E6	08/06/88	21	1	645	74.3	0.0	0.5	0.9	2.2	9.1	35.6
E7	09/06/88	21	3	1229	66.1	0.0	1.1	1.0	2.6	.	33.2
E8	10/06/88	35	2	939	55.8	0.0	7.6	2.3	4.1	.	47.1
E9	11/06/88	35	3	1229	-45.4	0.3	81.0	6.5	3.3	.	47.1
E10	12/06/88	28	2	939	33.9	0.0	2.8	1.8	.	.	42.5
E11	14/06/88	15	1	645	43.6	0.0	0.0	1.0	.	.	.
E12	15/06/88	15	3	1229	35.8	0.0	1.4	1.2	.	.	29.7
E13	16/06/88	28	3	1229	25.2	0.0	54.0	3.5	.	.	40.7
E14	13/07/88	28	1	645	50.2	0.0	3.4	0.9	2.7	8.1	40.0
E15	18/07/88	28	2	939	-1.8	.	1.4	1.3	2.5	7.4	33.3
E16	19/07/88	28	2	939	10.5	.	10.4	0.9	2.6	7.2	.

CITROEN BX (UNCONTROLLED)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
H1	31/08/88	28	2	939	.	16.5	.	17.5	30.3	5.4	34.3
H2	01/09/88	28	3	1229	.	74.5	.	58.8	65.0	2.6	32.8
H3	02/09/88	8	3	1229	.	4.3	.	11.4	20.7	5.0	16.1
H4	05/09/88	15	3	1229	.	13.2	.	13.6	23.4	4.8	21.3
H5	06/09/88	28	1	645	.	5.0	.	16.5	.	.	34.3
H6	07/09/88	21	3	1229	.	15.8	.	15.2	29.9	5.5	25.0
H7	08/09/88	2	3	1229	.	1.7	.	11.2	.	.	10.0
H8	09/09/88	35	3	1229	.	99.4	.	92.5	.	.	37.5
H9	12/09/88	21	2	939	.	16.7	.	14.1	29.4	5.3	28.3
H10	13/09/88	28	2	939	.	24.9	.	16.1	39.5	5.8	34.3
H11	16/09/88	15	2	939	.	3.9	.	13.9	36.4	5.3	21.5
H12	23/09/88	8	2	939	.	2.9	.	11.3	27.0	4.9	15.7
H13	26/09/88	28	2	939	.	32.5	.	15.8	40.0	6.0	34.4
H14	28/09/88	28	3	1229	.	42.6	.	31.7	62.0	3.5	31.7
H15	29/09/88	21	1	645	.	3.0	.	15.6	32.0	5.3	27.4
H16	30/09/88	2	1	645	.	0.1	.	9.2	10.4	5.4	9.6
H17	04/10/88	8	1	645	.	1.1	.	13.1	36.5	5.4	17.8
H18	05/10/88	15	1	645	.	2.9	.	18.1	38.4	5.5	23.3
H19	01/10/88	35	1	645	.	9.8	.	23.0	57.0	6.0	39.9
H20	07/10/88	28	2	939	.	1.9	.	14.7	26.4	5.3	28.0
H21	10/10/88	28	2	939	.	6.5	.	15.9	32.0	5.4	30.0
H22	11/10/88	35	2	939	.	44.6	.	15.7	41.0	6.1	39.0
H23	12/10/88	2	2	939	.	3.7	.	7.9	17.0	4.3	14.1
H24	14/10/88	-5	3	1229	.	0.9	.	6.5	13.2	4.0	3.7

CITROEN BX (CANISTER)

TEST	DATE	TEMP	FUEL	RVP	CANCAP	RL	GAIN	HSL	BENZ	PCTBENZ	TANKTEMP
G1	31/08/88	28	2	939	20.1	.	0.1	4.2	4.9	3.4	35.7
G2	01/09/88	28	3	1229	-22.6	.	0.0	76.6	6.0	0.2	34.6
G3	02/09/88	8	3	1229	19.9	.	0.0	2.3	3.6	5.5	17.9
G4	05/09/88	15	3	1229	20.4	.	0.0	2.3	4.7	6.7	21.3
G5	06/09/88	28	1	645	23.2	.	0.0	4.1	.	.	35.7
G6	07/09/88	21	3	1229	17.4	.	0.0	3.1	6.8	7.6	29.0
G7	08/09/88	2	3	1229	19.4	.	0.0	1.1	.	.	14.3
G8	09/09/88	35	3	1229	-31.2	.	0.0	176.3	.	.	40.6
G9	12/09/88	21	2	939	9.8	.	0.0	2.8	7.9	8.0	29.8
G10	.	28	2	939	4.8	.	0.0	3.7	9.7	8.2	35.4
G11	16/09/88	15	2	939	10.6	.	0.0	2.3	6.4	8.6	24.5
G12	22/09/88	2	2	939	9.4	.	0.2	1.2	.	.	19.4
G13	23/09/88	8	2	939	10.0	.	0.6	1.6	5.2	8.1	26.3
G14	26/09/88	28	2	939	5.6	.	2.7	4.3	13.2	7.3	34.3
G15	28/09/88	28	3	1229	-18.1	.	0.8	99.6	15.6	0.4	35.6
G16	29/09/88	21	1	645	8.6	.	0.0	2.9	7.4	8.2	29.8
G17	30/09/88	2	1	645	8.1	.	0.3	1.4	3.7	8.5	12.9
G18	04/10/88	8	1	645	8.0	.	0.1	2.5	7.4	7.0	16.7
G19	05/10/88	15	1	645	9.4	.	0.1	3.6	11.6	8.2	25.7
G20	06/10/88	35	1	645	10.4	.	0.3	8.0	24.4	7.9	44.5
G21	07/10/88	28	2	939	5.7	.	0.0	3.9	11.4	7.6	30.7
G22	10/10/88	28	2	939	5.9	.	0.4	3.9	131.0	1213	33.3
G23	11/10/88	35	2	939	0.6	.	6.2	57.0	32.3	1.4	40.8
G24	12/10/88	2	2	939	12.6	.	0.7	0.9	3.6	6.5	15.4
G25	14/10/88	-5	3	1229	12.5	.	0.0	0.4	1.6	7.6	3.6
G26	16/10/88	21	3	1229	9.3	.	2.7	2.3	.	.	26.4
G30	02/11/88	15	3	1229	.	.	.	1.7	.	.	24.6
G31	08/12/88	28	1	645	17.1	.	0.0	2.0	.	.	29.0
G32	12/12/88	28	3	1229	12.9	.	1.3	2.9	.	.	30.2

APPENDIX C STATISTICAL MODEL FITTING

This appendix provides details of the various statistical models that have been fitted to the data.

Hot soak losses

Uncontrolled cars

The Citroen was excluded from the analysis because of the abnormally high background losses. The small number of loss measurements made using low-benzene fuels were also excluded as the results seemed abnormally high relative to the rest of the data.

The simple exponential model

$$\ln(HSL + 0.01) = a + b.RVP + c.T$$

and the "Esso model"

$$\ln(HSL + 0.01) = a + \ln(RVP/(T + b)) - (c - d.RVP)/(T + 273)$$

were fitted to each of the four remaining uncontrolled cars in turn. An offset of 0.01 was added to all observations before taking logs because of the problem of zero observations. The coefficients found were as follows:

(DB) $\ln(HSL\ (g) + 0.01) = -2.283 + 0.02973.RVP\ (kPa) + 0.08734.T\ (°C)$ (RMS = 0.1687)

(Ford) $\ln(HSL\ (g) + 0.01) = -2.620 + 0.02550.RVP\ (kPa) + 0.08646.T\ (°C)$ (RMS = 0.2380)

(Civic) $\ln(HSL\ (g) + 0.01) = -1.292 + 0.01530.RVP\ (kPa) + 0.07286.T\ (°C)$ (RMS = 0.2612)

(Cavalier) $\ln(HSL\ (g) + 0.01) = -0.699 + 0.01171.RVP\ (kPa) + 0.05781.T\ (°C)$ (RMS = 0.1441)

(DB) $\ln(HSL\ (g) + 0.01) = 29.62 + \ln(RVP\ (kPa) / (T°C + 355.3)) - (8102 - 5.457.RVP\ (kPa)) / (T°C + 273)$ (RMS = 0.1688)

(Ford) $\ln(HSL\ (g) + 0.01) = 30.12 + \ln(RVP / (T°C + 444.0)) - (7986 - 4.023.RVP\ (kPa)) / (T°C + 273)$ (RMS = 0.2659)

(Civic) $\ln(HSL\ (g) + 0.01) = 25.99 + \ln(RVP / (T°C + 902.1)) - (6280 - 1.201.RVP\ (kPa)) / (T°C + 273)$ (RMS = 0.2815)

(Cavalier) $\ln(HSL\ (g) + 0.01) = 20.25 + \ln(RVP / (T°C + 371.3)) - (5054 - 0.120.RVP\ (kPa)) / (T°C + 273)$ (RMS = 0.1686)

In the above, RMS denotes the residual mean square, residuals being differences between measured and predicted values on the logarithmic ln(HSL) scale; the lower the RMS the better the fit. The RMSs under the simple exponential model are typically less than or equal to those under the Esso model, despite the Esso model having one more adjustable parameter. Thus one may conclude that the former provides the better data summary. The Esso model is overparameterized with the correlation coefficient between the estimates of the first three parameters a, b and c all exceeding 0.999. The fitted coefficients a, b and c in the above models have absurdly large standard errors and no physical significance may be ascribed to their numerical values.

It may be noted that the coefficients of T in the simple exponential model are similar for different cars; a formal statistical test indicates no significant differences at the 5%-level. The RVP coefficients are less homogeneous, differing at the 1%-level. Nevertheless, the common-slopes model

(DB)	$\ln(HSL\ (g) + 0.01) = -1.068 + 0.01953.RVP\ (kPa) + 0.07452.T\ (°C)$
(Ford)	$\ln(HSL\ (g) + 0.01) = -1.832 + 0.01953.RVP\ (kPa) + 0.07452.T\ (°C)$
(Civic)	$\ln(HSL\ (g) + 0.01) = -1.727 + 0.01953.RVP\ (kPa) + 0.07452.T\ (°C)$
(Cavalier)	$\ln(HSL\ (g) + 0.01) = -1.732 + 0.01953.RVP\ (kPa) + 0.07452.T\ (°C)$

does still provide a reasonably decent data summary with the overall RMS only increasing from 0.2023 to 0.2268.

Various alternative models were also tried, including

$$HSL = a + b.RVP + c.T$$
$$HSL = a + b.\exp(k.RVP) + c.T$$
$$HSL = a + b.RVP + c.\exp(m.T)$$

These models did not in general fit the HSL values for particular cars as well as the simple exponential model, although there were occasional exceptions.

Controlled cars

It was not sensible to model measured hot-soak losses for controlled cars directly because of the discontinuity caused by the "breakthrough" effect. The canisters keep the measured emissions in most tests down to low background levels except at high temperatures where high-RVP fuels can cause the canisters to breakthrough. The measured emissions then suddenly start to rise rapidly with RVP and T.

Hot-soak losses for controlled cars were, therefore, characterized by the variable HSLGAIN, this being the sum of the hot-soak emissions and the gain in weight of the canister. Fitting the simple exponential model to each of the 5 controlled cars in turn, the coefficients were as follows:

(Citroen) ln(HSLGAIN (g) + 0.01) = -1.684 + 0.01557.RVP (kPa) + 0.09714.T (°C) (RMS = 0.8483)

(DB) ln(HSLGAIN (g) + 0.01) = -1.055 + 0.02154.RVP (kPa) + 0.07458.T (°C) (RMS = 0.0706)

(Ford) ln(HSLGAIN (g) + 0.01) = -4.714 + 0.03947.RVP (kPa) + 0.12708.T (°C) (RMS = 0.1034)

(Civic) ln(HSLGAIN (g) + 0.01) = -1.800 + 0.01872.RVP (kPa) + 0.07772.T (°C) (RMS = 0.1472)

(Ascona) ln(HSLGAIN (g) + 0.01) = -4.102 + 0.02671.RVP (kPa) + 0.13240.T (°C) (RMS = 0.5689)

The high RMSs for the Citroen and Ascona reflect the very sharp increases in losses at high temperatures using high-RVP fuels in these particular two cars. Such sharp features cannot be accurately reproduced by fitting the simple exponential model as this curves too gently.

A formal statistical test showed no significant differences at the 5%-level between the coefficients of RVP in different cars, nor between those of T, and so the common-slopes model:

(Citroen) ln(HSLGAIN (g) + 0.01) = -2.332 + 0.02272.RVP (kPa) + 0.09444.T (°C)
(DB) ln(HSLGAIN (g) + 0.01) = -1.633 + 0.02272.RVP (kPa) + 0.09444.T (°C)
(Ford) ln(HSLGAIN (g) + 0.01) = -2.410 + 0.02272.RVP (kPa) + 0.09444.T (°C)
(Civic) ln(HSLGAIN (g) + 0.01) = -2.506 + 0.02272.RVP (kPa) + 0.09444.T (°C)
(Ascona) ln(HSLGAIN (g) + 0.01) = -2.813 + 0.02272.RVP (kPa) + 0.09444.T (°C)

may be used as a data summary. The overall RMS is 0.4881, only marginally higher than the 0.4763 found for the separate slopes model.

Comparison of controlled and uncontrolled cars

The 10 test cars form five matched pairs, one car in each pair being controlled and the other uncontrolled. The coefficients in the simple exponential models for HSL (uncontrolled) and for HSLGAIN (controlled) are remarkably similar, in fact no significant differences could be found at the 5%-level between the two fitted models for three pairs, namely the DB, Ford and Civic. Thus the following joint models may be used for either HSL (uncontrolled) or HSLGAIN (controlled):

(DB) ln(HSL (g) or HSLGAIN + 0.01) = -2.578 + 0.03148.RVP (kPa) + 0.09237.T (°C) (RMS = 0.2603)

(Ford) ln(HSL (g) or HSLGAIN + 0.01) = -3.409 + 0.03139.RVP (kPa) + 0.10085.T (°C) (RMS = 0.2091)

(Civic) ln(HSL (g) or HSLGAIN + 0.01) = -1.516 + 0.01689.RVP (kPa) + 0.07489.T (°C) (RMS = 0.2024)

Signficicant differences, on the other hand, were found between the uncontrolled Cavalier and the controlled Ascona ($P < 1\%$). This is not particularly surprising as the simple exponential model was previously found to provide a poor fit for the Ascona HSLGAIN data. For completion, the best joint model was:

(Ascona/Cavalier) $\ln(\text{HSL (g) or HSLGAIN} + 0.01) = -1.628 + 0.01808.\text{RVP (kPa)} + 0.07104.\text{T (°C)}$
(RMS = 0.3910)

No sensible comparison is available for the Citroen pair because of the high-background-loss problem discussed earlier.

The similarity across pairs allows us to fit a global common-slopes model as follows

(Citroen) $\ln(\text{HSL (g)} + 0.01) = -2.103 + 0.02203.\text{RVP (kPa)} + 0.08535.\text{T (°C)}$

(DB) $\ln(\text{HSL (g) or HSLGAIN} + 0.01) = -1.544 + 0.02203.\text{RVP (kPa)} + 0.08535.\text{T (°C)}$

(Ford) $\ln(\text{HSL (g) or HSLGAIN} + 0.01) = -2.217 + 0.02203.\text{RVP (kPa)} + 0.08535.\text{T (°C)}$

(Civic) $\ln(\text{HSL (g) or HSLGAIN} + 0.01) = -2.198 + 0.02203.\text{RVP (kPa)} + 0.08535.\text{T (°C)}$

(Asc./Cav.) $\ln(\text{HSL (g) or HSLGAIN} + 0.01) = -2.288 + 0.02203.\text{RVP (kPa)} + 0.08535.\text{T (°C)}$

with an overall RMS of 0.3800; the uncontrolled Citroen data were excluded when fitting the above model.

Running losses

The simple exponential model

$\ln(\text{RL}) = a + b.\text{RVP} + c.\text{T}$

was fitted to the running-loss data for each of the five uncontrolled cars in turn.

The coefficients found were as follows

(Citroen) $\ln(\text{RL(g/test)} + 0.01) = -3.351 + 0.03388.\text{RVP (kPa)} + 0.1069.\text{T (°C)}$
(RMS = 0.5378)

(DB) $\ln(\text{RL(g/test)} + 0.01) = -10.49 + 0.07952.\text{RVP (kPa)} + 0.2172.\text{T (°C)}$
(RMS = 1.0995)

(Ford) $\ln(\text{RL(g/test)} + 0.01) = -3.574 + 0.03700.\text{RVP (kPa)} + 0.1311.\text{T (°C)}$
(RMS = 0.0844)

(Civic) $\ln(\text{RL(g/test)} + 0.01) = -10.10 + 0.04602.\text{RVP (kPa)} + 0.2769.\text{T (°C)}$
(RMS = 6.1440)

(Cavalier) $\ln(\text{RL(g/test)} + 0.01) = -3.034 + 0.03425.\text{RVP (kPa)} + 0.1357.\text{T (°C)}$
(RMS = 1.6131)

The high RMSs for certain cars indicate that the fit is not particularly good. However, these RMSs are inflated by artificially high residuals which arise when one tries to model zero or near-zero losses on a log scale; further work is needed to determine the optimal offsets for HSL, HSLGAIN, RL, etc. instead of 0.01.

The coefficients of RVP for different cars are not significantly different from one another at the 5%-level and so a better data summary is provided by fitting a common value, leading to the equations:

(Citroen)	$\ln(RL\ (g/test) + 0.01) = -4.411 + 0.04460.RVP\ (kPa) + 0.1083.T\ (°C)$
(DB)	$\ln(RL\ (g/test) + 0.01) = -7.216 + 0.04460.RVP\ (kPa) + 0.2095.T\ (°C)$
(Ford)	$\ln(RL\ (g/test) + 0.01) = -4.329 + 0.04460.RVP\ (kPa) + 0.1339.T\ (°C)$
(Civic)	$\ln(RL\ (g/test) + 0.01) = -9.954 + 0.04460.RVP\ (kPa) + 0.2764.T\ (°C)$
(Cavalier)	$\ln(RL\ (g/test) + 0.01) = -4.068 + 0.04460.RVP\ (kPa) + 0.1393.T\ (°C)$

with the RMS only increasing slightly from 2.1078 to 2.1624. A common temperature coefficient can also be fitted, giving the models:

(Citroen)	$\ln(RL\ (g/test) + 0.01) = -5.500 + 0.04400.RVP\ (kPa) + 0.1691.T\ (°C)$
(DB)	$\ln(RL\ (g/test) + 0.01) = -6.457 + 0.04400.RVP\ (kPa) + 0.1691.T\ (°C)$
(Ford)	$\ln(RL\ (g/test) + 0.01) = -4.980 + 0.04400.RVP\ (kPa) + 0.1691.T\ (°C)$
(Civic)	$\ln(RL\ (g/test) + 0.01) = -8.082 + 0.04400.RVP\ (kPa) + 0.1691.T\ (°C)$
(Cavalier)	$\ln(RL\ (g/test) + 0.01) = -4.548 + 0.04400.RVP\ (kPa) + 0.1691.T\ (°C)$

However, there is a significant worsening of fit ($P < 1\%$) with the overall RMS rising to 2.5463.

<u>Total losses</u>

Total daily losses for uncontrolled cars are defined as:

$$TOT = 3.4 \times HSL + 35 \times RL / 45\ (g/day)$$

This is based on average European journeys. Fitting the simple exponential model to the data from the 4 uncontrolled cars (excluding the Citroen), the coefficients were found to be

(DB)	$\ln(TOT\ (g/day) + 0.01) = -1.760 + 0.03550.RVP\ (kPa) + 0.1067.T\ (°C)$ (RMS = 0.1027)
(Ford)	$\ln(TOT\ (g/day) + 0.01) = -1.420 + 0.02830.RVP\ (kPa) + 0.1015.T\ (°C)$ (RMS = 0.0871)
(Civic)	$\ln(TOT\ (g/day) + 0.01) = -0.704 + 0.02049.RVP\ (kPa) + 0.0947.T\ (°C)$ (RMS = 0.2782)
(Cavalier)	$\ln(TOT\ (g/day) + 0.01) = 0.620 + 0.01509.RVP\ (kPa) + 0.0756.T\ (°C)$ (RMS = 0.1167)

The simple exponential model fitted better than the "Esso model" for all four cars.

The coefficients of temperature in different cars in the simple exponential model are not significantly different from one another at the 5% level. Thus a more succinct data summary may be obtained by fitting a common value, leading to the equations:

(DB) $\ln(TOT\ (g/day) + 0.01) = -1.392 + 0.03423.RVP\ (kPa) + 0.0929.T\ (°C)$
(Ford) $\ln(TOT\ (g/day) + 0.01) = -1.201 + 0.02781.RVP\ (kPa) + 0.0929.T\ (°C)$
(Civic) $\ln(TOT\ (g/day) + 0.01) = -0.662 + 0.02037.RVP\ (kPa) + 0.0929.T\ (°C)$
(Cavalier) $\ln(TOT\ (g/day) + 0.01) = 0.203 + 0.01623.RVP\ (kPa) + 0.0929.T\ (°C)$

The overall RMS only increases slightly from 0.1594 to 0.1695. A common RVP coefficient can also be fitted, giving the models:

(DB) $\ln(TOT\ (g/day) + 0.01) = -0.380 + 0.02325.RVP\ (kPa) + 0.0926.T\ (°C)$
(Ford) $\ln(TOT\ (g/day) + 0.01) = -0.778 + 0.02325.RVP\ (kPa) + 0.0926.T\ (°C)$
(Civic) $\ln(TOT\ (g/day) + 0.01) = -0.935 + 0.02325.RVP\ (kPa) + 0.0926.T\ (°C)$
(Cavalier) $\ln(TOT\ (g/day) + 0.01) = -0.451 + 0.02325.RVP\ (kPa) + 0.0926.T\ (°C)$

However, there is now a smallish but statistically significant worsening of fit ($P < 5\%$) with the overall RMS rising to 0.1885.

Combined models

Overall models which include results for all controlled or uncontrolled cars have also been developed. These are intended for use in models to predict evaporative emission inventories for Europe.

The errors are significantly greater (RMS values) for these models than the individual car models described above, and care must be exercised in their use. Also it should be noted that the models are only based on results from four or five cars.

Both the simple exponential and the 'Esso' model have been fitted for hot-soak losses (uncontrolled cars excluding Citroen), HSLGAIN (controlled cars), running loss (all uncontrolled cars) and total loss (uncontrolled cars except Citroen), as below:

Hot-soak losses (uncontrolled cars excluding the Citroen)

$$\ln(HSL\ (g) + 0.01) = -1.644 + 0.01993.RVP\ (kPa) + 0.07521.T\ (°C)$$
(RMS = 0.3082)

$$\ln(HSL\ (g) + 0.01) = 34.48 + \ln(RVP\ (kPa) / (T\ (°C) + 8.13)) - (10201 - 2.647.RVP\ (kPa) / (T\ (°C) + 273)$$
(RMS = 0.3128)

HSLGAIN (all controlled cars):

$$\ln(HSLGAIN\ (g) + 0.01) = -2.410 + 0.02302.RVP\ (kPa) + 0.09408.T\ (°C)$$
(RMS = 0.5543)

$$\ln(HSLGAIN\ (g) + 0.01) = 37.39 + \ln(RVP\ (kPa) / (T\ (°C) + 14.10)) - (11079 - 3.318.RVP\ (kPa) / (T\ (°C) + 273)$$
(RMS = 0.5783)

Running losses (all uncontrolled cars):

$$\ln(RL\ (g/test) + 0.01) = -5.967 + 0.04259.RVP\ (kPa) + 0.1773.T\ (°C)$$
(RMS = 4.1900)

$$\ln(RL\ (g/test) + 0.01) = 66.08 + \ln(RVP\ (kPa) / (T\ (°C) + 6.00)) - (20119 - 8.976.RVP\ (kPa) / (T\ (°C) + 273)$$
(RMS = 4.1886)

Total daily loss: (3.4 x HSL + 35 x RL / 45)

$$\ln(TOT\ (g/day) + 0.01) = -0.609 + 0.0227\ RVP\ (kPa) + 0.0928\ T(°C)$$
(RMS 0.2363)

$$\ln(TOT\ (g/day) + 0.01) = 40.16 + \ln(RVP\ (kPa) / (T\ (°C) + 6.17) - (12154 - 3.47\ RVP\ (kPa) / (T\ (°C) + 273))$$
(RMS = 0.2362)