

Report for
Thermostore



Thermostore

**Reduction of Exhaust Emissions
with a Heat Storage
Tests on a Mercedes E 200**

Ecotraffic R&D AB
May 1998

Peter Ahlvik

Ecotraffic

TABLE OF CONTENTS

Page

ABSTRACT

| | | |
|-------|-------------------------------------|----|
| 1 | INTRODUCTION..... | 1 |
| 2 | BACKGROUND..... | 2 |
| 3 | METHODOLOGY..... | 3 |
| 3.1 | Test Equipment..... | 3 |
| 3.1.1 | Chassis Dynamometer..... | 3 |
| 3.1.2 | Measurement of Emissions..... | 3 |
| 3.2 | Test Objects..... | 4 |
| 3.2.1 | Test Car..... | 4 |
| 3.2.2 | Heat Storage..... | 5 |
| 3.2.3 | Electric Engine Block Heater..... | 7 |
| 3.3 | Driving Cycle..... | 7 |
| 3.4 | Test Program..... | 8 |
| 4 | EARLIER TESTS WITH THERMOSTORE..... | 10 |
| 5 | RESULTS..... | 13 |
| 5.1 | Emissions..... | 13 |
| 5.2 | Fuel consumption..... | 16 |
| 5.3 | Air-fuel ratio..... | 17 |
| 5.4 | Temperatures..... | 18 |
| 6 | DISCUSSION..... | 20 |
| 7 | CONCLUSIONS..... | 20 |
| 8 | REFERENCES..... | 21 |

LIST OF TABLES

Page

| | | |
|-----------------|--|----------|
| <i>Table 1:</i> | <i>Emission components and analysis methods.....</i> | <i>3</i> |
| <i>Table 2:</i> | <i>Data for the Ford Taurus FFV.....</i> | <i>5</i> |

LIST OF FIGURES

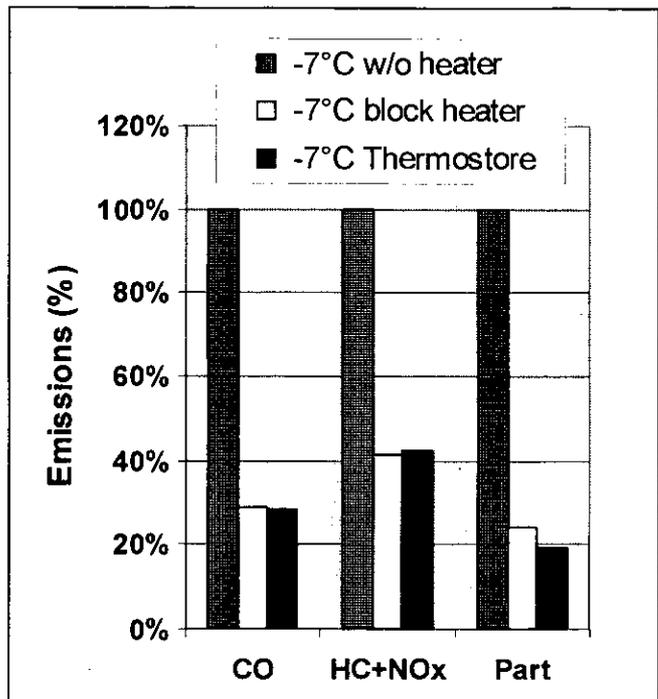
Page

| | | |
|-------------------|---|-----------|
| <i>Figure 1:</i> | <i>Mercedes E 200.....</i> | <i>4</i> |
| <i>Figure 2:</i> | <i>Installation of Thermostore in the test car, side view.....</i> | <i>6</i> |
| <i>Figure 3:</i> | <i>The new European driving cycle (NEDC).....</i> | <i>7</i> |
| <i>Figure 4:</i> | <i>The FTP-75 driving cycle.....</i> | <i>8</i> |
| <i>Figure 5:</i> | <i>Start procedure with Thermostore, 2 min preheat.....</i> | <i>10</i> |
| <i>Figure 6:</i> | <i>Summary of the emission potential in the NEDC cycle at -7°C on a Ford Taurus with Thermostore and an electric engine block heater.....</i> | <i>11</i> |
| <i>Figure 7:</i> | <i>Emissions in the NEDC cycle, Ford Taurus FFV.....</i> | <i>12</i> |
| <i>Figure 8:</i> | <i>Emissions in the NEDC cycle.....</i> | <i>14</i> |
| <i>Figure 9:</i> | <i>Summary of the emission potential in the NEDC cycle at -7°C with Thermostore and an electric engine block heater.....</i> | <i>15</i> |
| <i>Figure 10:</i> | <i>Particulate emissions.....</i> | <i>16</i> |
| <i>Figure 11:</i> | <i>Fuel consumption in the first phase of the NEDC cycle.....</i> | <i>17</i> |
| <i>Figure 12:</i> | <i>Air-fuel ratio in the first km driven.....</i> | <i>18</i> |
| <i>Figure 13:</i> | <i>Logging of temperatures at -7°C with Thermostore, 2 min preheat.....</i> | <i>19</i> |

ABSTRACT

The exhaust emissions from on-road vehicles have been reduced considerably during recent years, mainly due to the introduction of the three-way catalyst (TWC) on passenger cars. Further reductions are, however, necessary in order to achieve a level tolerable for nature and humans. One problem with the TWC technology is that 80 % or more of the emissions in a driving cycle are generated during the cold start phase. Due to the cold climate in Sweden this problem is accentuated in the cold start phase. A heat storage has a great potential to considerably reduce these emissions.

A Thermostore heat storage has been tested to investigate its emission reduction capabilities on two passenger cars. In an earlier report from Thermostore the tests on a Ford Taurus FFV have been reported. In this investigation a Mercedes E 200 has been tested. As a reference, an electric engine block heater has been tested as well. Some of the results are shown in the Figure to the right.



Thermostore considerably reduces the CO, HC and particulate emissions at cold start. At an ambient temperature of -7°C the reduction can be as great as 60 – 80 %. The reduction of the compounds that pose health hazards will most likely be *greater* than the reduction of the HC and particulate emissions. The NO_x emissions increase with Thermostore, but since these emissions were so low for this car the increase is not of concern.

By using the best control strategy for Thermostore, the emissions from the Mercedes E 200 can be reduced about the same as when using a conventional electric engine block heater. The emissions could be reduced even more than when using a block heater on the Ford Taurus FFV tested earlier. There is also a potential for further reductions by using a more advanced control strategy. It must also be stressed that that a block heater cannot be used at every start occasion and thus the emission reduction advantage by using Thermostore will be much greater in practice. Another advantage is that a heat storage has no need for an external supply of energy and therefore has a considerably lower total energy consumption than a block heater.

By logging of temperatures, emissions and other parameters it has been shown that there is further potential of reducing the emissions.

1 INTRODUCTION

The exhaust emissions from passenger cars in Sweden increased considerably from World War 2 to 1990 due to the increase in traffic intensity [1 – 6]¹. The emission regulations introduced in the 1970s reduced the rate of increase but these measures were not sufficient to reverse this trend. It was only after the introduction of the emission regulations that more or less demanded the three-way catalyst (TWC) emission control² that the emissions started to decrease. This regulation was first introduced in Sweden in 1987 as a voluntary measure, promoted by tax incentives, and was made mandatory for all cars after the model year 1989.

The catalytic emission control is very efficient – it can reduce the emissions by much more than 90 % on a warm engine at constant speed. However, during cold start the TWC technology does not operate at all, leading to very high emissions under these driving conditions. Due to the design constraints of the gasoline engine, fuel enrichment is needed at start in order to ensure that a sufficient amount of fuel can be evaporated and premixed (air-fuel preparation) to an ignitable mixture. The surplus gasoline supplied to the engine considerably increases the CO and HC emissions. It should also be noted that the cold start emissions from TWC cars are of the same order of magnitude as from cars without catalyst. The increase in cold start emissions is further enhanced at low ambient conditions. The emission regulations used so far in the European Union (EU) are valid in the temperature interval between +20 and +30°C. Since the yearly average temperature in Sweden is about +7°C it is clear that the conditions in the regulation do not reflect the actual driving conditions in Sweden. In the cold climate of Sweden it is very important to decrease the cold start emissions. The cars certified according to the Swedish Environmental Class 1 (EC1) regulation, which is equal to the Californian TLEV limit, have a limit for the CO emissions at –7°C. Cold start emission limits will also be introduced in the EU for the year 2000.

A well-established method of reducing the emissions at cold start is to preheat the engine with an electric engine block heater. Results from tests at Motortestcenter (MTC) of the Swedish Motor Vehicle Inspection Co. have been published by Laveskog et al. [7 – 9]. CO and HC emission reductions of up to 80 % have been measured at cold ambient conditions in these studies. However, the block heater has to be connected to the grid power and must rely on an external supply of energy. The infrastructure for this energy supply only exists to a very limited extent today and is also very expensive to introduce on a large scale. Since the block heater does not work without an external energy supply the emission reductions can only be considered as an upper potential. It is therefore of interest to develop a technology that is autonomous, i.e. that works without being connected to the grid power. This is one of the main features of a heat storage.

Some years ago a couple of reports were published covering results from emission test with a heat storage developed by the German inventor Oscar Schatz [10 – 16].

¹ Number in brackets designates references in the reference list at the end of the report.

² The regulations do not demand TWC technology but with few exceptions this technology has to be used due to the strict emission levels.

The authors of these reports showed that the system had a potential to significantly reduce the exhaust emissions. The early prototypes of the Schatz heat storage as well as a commercial heat storage from Modine, which is used by BMW, are based on the principle of storing the heat in a molten salt. Later patents from Schatz, which have been commercialized by the Canadian manufacturer Centaur, use only stored hot cooling water instead of using molten salt. Thermostore is based on similar technology. The main advantage of this technology is the simplified design compared to heat storage with salt.

Even if the main objective of this report has been to report on the exhaust emission results it must be stressed that the main reason for the customers to buy a heat storage, either as an option or as an after-market installation, is not primary the emission reductions. Enhanced driver's comfort is most likely the main reason. A reduction of fuel consumption and emissions are of less importance. However, it may be of interest for some car manufacturers to be able to offer an option that reduces the emissions and the fuel consumption instead of increasing them as do most of the other options (such as climate control etc.). The experience from the marketing by BMW, which for the moment is the only carmaker that can offer a heat storage on the Swedish market, shows that the environmental issues play a very small role in the marketing of their product. The cost for the heat storage from BMW is about SEK 10 000. This can be compared with the cost for a fuel heater, which is between 10 000 and 25 000 for most cars.

This report, as well as the previously published report on the tests on a Ford Taurus FFV, has also been published in a Swedish version.

2 BACKGROUND

Thermostore has developed a heat storage based on the technology of storing the coolant fluid in a superinsulated vessel. The basic functions have been proven for a couple of prototype generations that have been tested by installation and vehicle testing.

During June 1997 a couple of emission tests at MTC with the Thermostore heat storage were conducted in order to assess the potential for emission reductions. The tested car was a Ford Taurus, which was a so-called fuel flexible vehicle (FFV³). The car was run on gasoline during the tests. Thermostore recently has published these results in a technical report [17].

The positive results obtained on the Ford Taurus have resulted in the initialization of a new test series with a second car, which is more characteristic for the European and the Swedish market. The car chosen was a Mercedes E 200. The results from this test series are reported in this report. The main objective with these tests was to assess the emission potential using the European driving cycle and by carrying out simultaneous logging of emissions and temperature to obtain valuable insights about how the system should be controlled to fully use the emission potential and to ensure good comfort.

³ FFV is an abbreviation for Fuel Flexible Vehicle, i.e. a car that can be run on any mixture of gasoline and E85 (85 % ethanol and 15 % gasoline).

3 METHODOLOGY

In this chapter the test equipment, the test objects and the test procedure are described. More information can be found in the emission regulations and in the literature cited which is listed in the reference list at the end of this report.

3.1 Test Equipment

All testing was carried out in Jordbro 20 km south of Stockholm at the facilities of **Motortestcenter** (MTC), a subsidiary of the Swedish Motor Vehicle inspection Co. The tests were conducted in the test cell number 4 that has the capability to cool the vehicle to a temperature of -15°C (to -20°C in the winter). In this test series temperatures of $+22^{\circ}\text{C}$ and -7°C were used. The air conditioning system has the capability to keep the temperature constant during the entire test, i.e. the cooling capacity is sufficient to handle the heat dissipation (cooling losses) from the vehicle. In the following sections a more thorough description of some of the details of the test equipment is given.

3.1.1 Chassis Dynamometer

The testing was carried out at a chassis dynamometer at MTC. The chassis dynamometer is fully dynamic, i.e. it can simulate an inertia corresponding to the weight of the car. The basic inertia is a flywheel and the rest of the inertia is simulated with the electric dynamometer. Thus the transient conditions such as accelerations and retardations in a driving cycle can be simulated. The inertia for the Mercedes E 200 was 1590 kg. The chassis dynamometer can also simulate the road load. This load is the sum of the rolling resistance and the air resistance. The settings of the parameters above were made according to the EC regulation.

3.1.2 Measurement of Emissions

In this chapter an overview is given about the measurement methodology for the emission measurements. The emission components, which were analyzed, and the corresponding measurement principles are shown in Table 1.

Table 1: Emission components and analysis methods

| Emission component | Analysis method |
|-------------------------------------|---|
| Total hydrocarbons, HC | Heated Flame Ionization Detector (FID) |
| Carbon monoxide, CO | Non Dispersive Infrared Spectroscopy (NDIR) |
| Oxides of nitrogen, NO _x | Chemiluminescence (CLA) |
| Carbon dioxide, CO ₂ | Non Dispersive Infrared Spectroscopy (NDIR) |
| Fuel consumption, FC | Carbon balance ⁴ |
| Particulate emissions | Gravimetric method |

⁴ Exhaust gas analysis of CO₂, HC and CO is used to calculate the fuel consumption (knowing the H/C ratio of the fuel)

All the measured emission components except the particulate emissions are regulated for passenger cars in the EU, i.e. there is an emission limit for these components in the regulation. Particulate emissions are regulated for all diesel vehicles in the EU. All vehicles certified according to the Swedish Environmental Class 1 (EC1) regulation (i.e. all fuels) also have to comply with a particulate emission limit. The EC1 uses the same limits as the Californian TLEV regulation⁵.

The emissions were measured in a dilution tunnel. One reason for using a dilution tunnel is to cool the exhaust gases and the second reason is to obtain a constant flow. The procedure is described in the US Federal Register and in the Swedish emission regulations [18]. A partial flow of the diluted exhaust gases was collected in Tedlar bags for subsequent emission analysis.

The emission instrument used for measurement of gaseous emissions was an instrument from Horiba 9000 series. The particulate emissions were collected after dilution on a Teflon coated filter (Pallflex) and were weighed on a balance with an accuracy of 1 microgram.

3.2 Test Objects

In this section a short description of the test objects is given.

3.2.1 Test Car

The test car chosen was a 1997 model year Mercedes E 200. A picture of a similar car is shown in Figure 1 to the right.

Even if the car is quite large it represents the size of cars corresponding to the average size of current cars in Sweden. The engine capacity of 2 liters is however somewhat smaller than the average size of the corresponding cars from the Swedish manufacturers. Some data for the car and its engine is shown in Table 2.

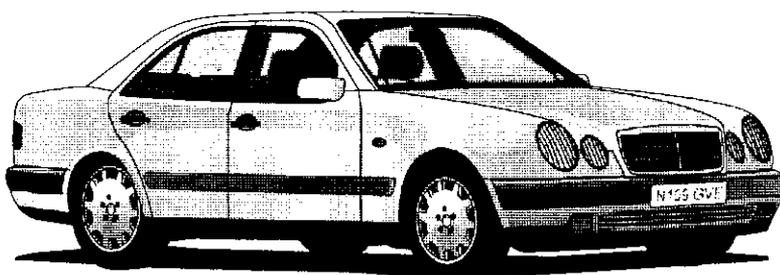


Figure 1: Mercedes E 200

⁵ The vehicles certified according to the EC1 regulation also have to comply with the current European regulation 94/12/EC.

Table 2: Data for the Ford Taurus FFV

| Parameter | Data | Unit |
|----------------------------------|---------------|-----------------|
| Car maker | Mercedes | --- |
| Model | E 200 | --- |
| Model year | 1997 | |
| Odometer | 9 300 | km |
| Inertia ⁶ | 1 590 | kg |
| Engine family | 3G1-CE230-96 | --- |
| Cylinder capacity (V) | 1 988 | cm ³ |
| Cylinder diameter (D) | 89,9 | mm |
| Stroke (S) | 78,7 | mm |
| Compression ratio (ϵ) | 10,4 | Dim. less |
| Rated power (P) | 100 | kW |
| Rated speed (n) | 5500 | r/min |
| Certification | 94/12/EC | --- |
| Emission control ⁷ | TWC, EGR, CAN | --- |

3.2.2 Heat Storage

The Thermostore heat storage is of the type where the energy is stored in the hot cooling water only. This technology is also called "sensible" heat storage. Other methods are the molten salt type, so-called "latent" heat storage, and the "thermochemical" storage, which stores the energy chemically.

The Thermostore heat storage comprises a superinsulated cylinder where the cooling fluid is stored. Inside the cylinder a piston separates hot and cold fluid. When the storage is discharged or charged the piston travels between the two ends of the cylinder. Using a pump, valves, connectors and an electronic control unit performs this task. One special feature of the storage is the excellent separation between the hot and cold fluid, which not only minimizes the losses, but also makes an intermittent use of part of the stored heat possible. All the different possibilities with the heat storage have not yet been investigated thoroughly enough to choose the best control strategy. An appropriate size of the heat storage is about the same volume as the cooling water volume in the engine block or a somewhat larger volume. Since the tested prototype is not yet fully developed there is some potential for further improvements.

The heat storage can be installed basically in two different positions – under the hood or in the luggage compartment. In Figure 2 the installation of the heat storage under the hood is shown on the Mercedes E 200.

⁶ Inertia corresponds to the vehicle weight that is simulated on the chassis dynamometer

⁷ TWC: Three Way Catalyst, EGR: Exhaust Gas Recirculation and CAN: Carbon Canister (used to adsorb the fuel vapors from the fuel tank).

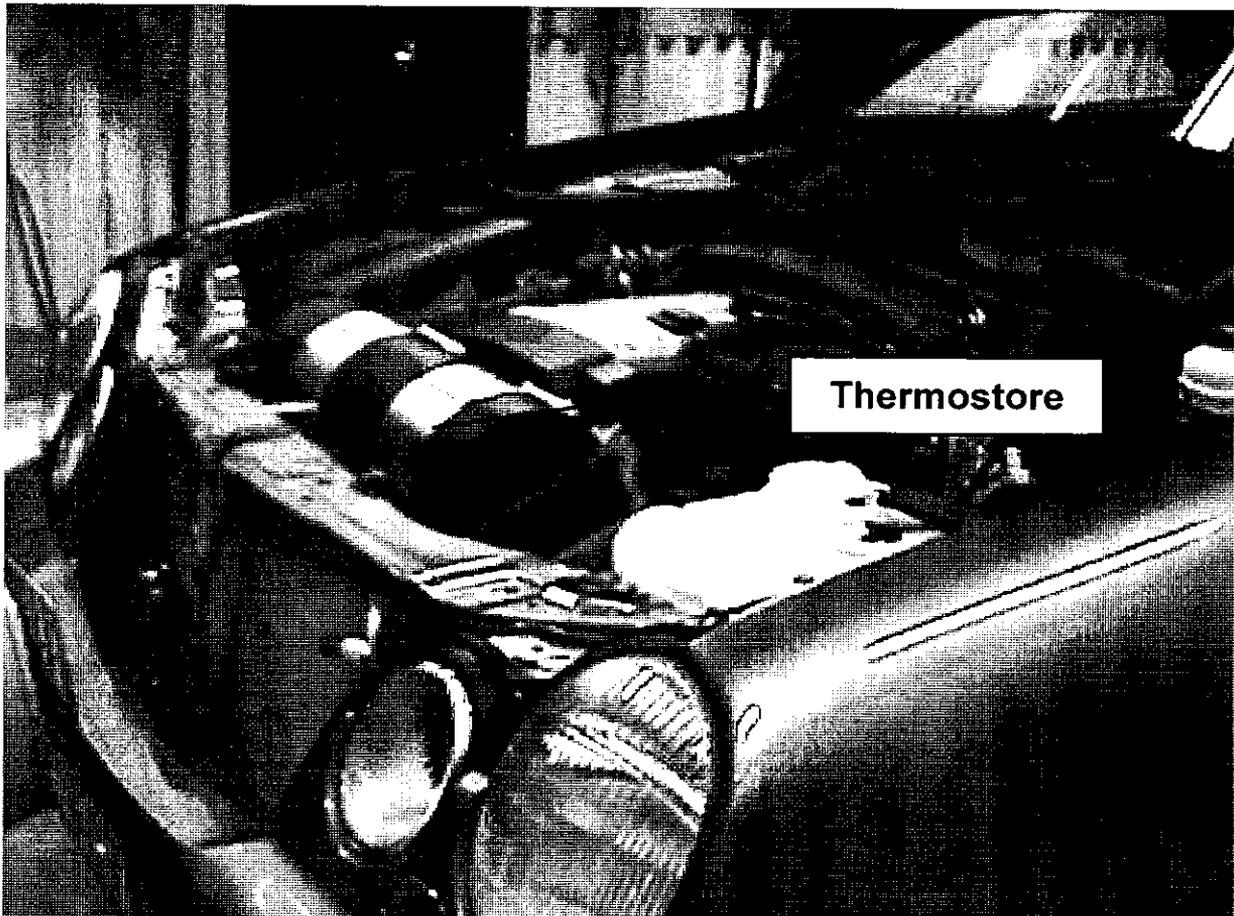


Figure 2: Installation of Thermostore in the test car, side view

The total weight for the heat storage in the Mercedes is 11 kg. As a comparison the weight of a normal battery of 60 Ah is about 20 kg. In the Mercedes it is possible to install the heat storage either between the radiator and the engine or under the front bumper. The first position was used for the car in the picture since a good access to the storage was of great importance on the prototype to be tested. The second position would most likely be better for practical reasons since the heat storage does not normally need any maintenance.

In the Ford Taurus the heat storage was installed in the luggage compartment, mainly since the space under the hood was limited. The volume of this storage was 9 liters. For the Mercedes a size of 8 liters was used and it was possible to install it under the hood. An installation as close to the engine as possible is advantageous since the heat losses are lower and the heating will be faster. Thermostore has investigated possible installations on 15 common car models on the market and found that the heat storage could be installed under the hood in 8 of them. It has also been found that there are alternative positions (under the hood) on many cars. A normal coolant volume on a medium size 4-cylinder car is about 4 liters. Since the heat storage can be manufactured in different sizes the volume can be adapted to the space and needs in the particular case. It is also possible to install the heat storage in a vertical position under the hood on some cars. Furthermore, the possibility of manufacturing an oval shape has been investigated and it has been found that this is a feasible solution. It is also important to note for future work that the best installation

can be made if the heat storage can be integrated already in the design phase of the car.

3.2.3 Electric Engine Block Heater

The electric engine block heater tested had a power of 550 W. The block heater was mounted in the water jacket through a hole in the engine block. The preheat time was 1,5 hours according to the recommendations in a recent report published by the Swedish Consumer Agency [19].

It has been shown in earlier work at MTC that block heaters can significantly reduce the exhaust emissions and it was therefore decided to compare the heat storage with a block heater in this respect.

3.3 Driving Cycle

The driving cycle chosen for the test series was the new European driving cycle (NEDC) to be used after the year 2000 in the European Union. The driving cycle is shown in Figure 3.

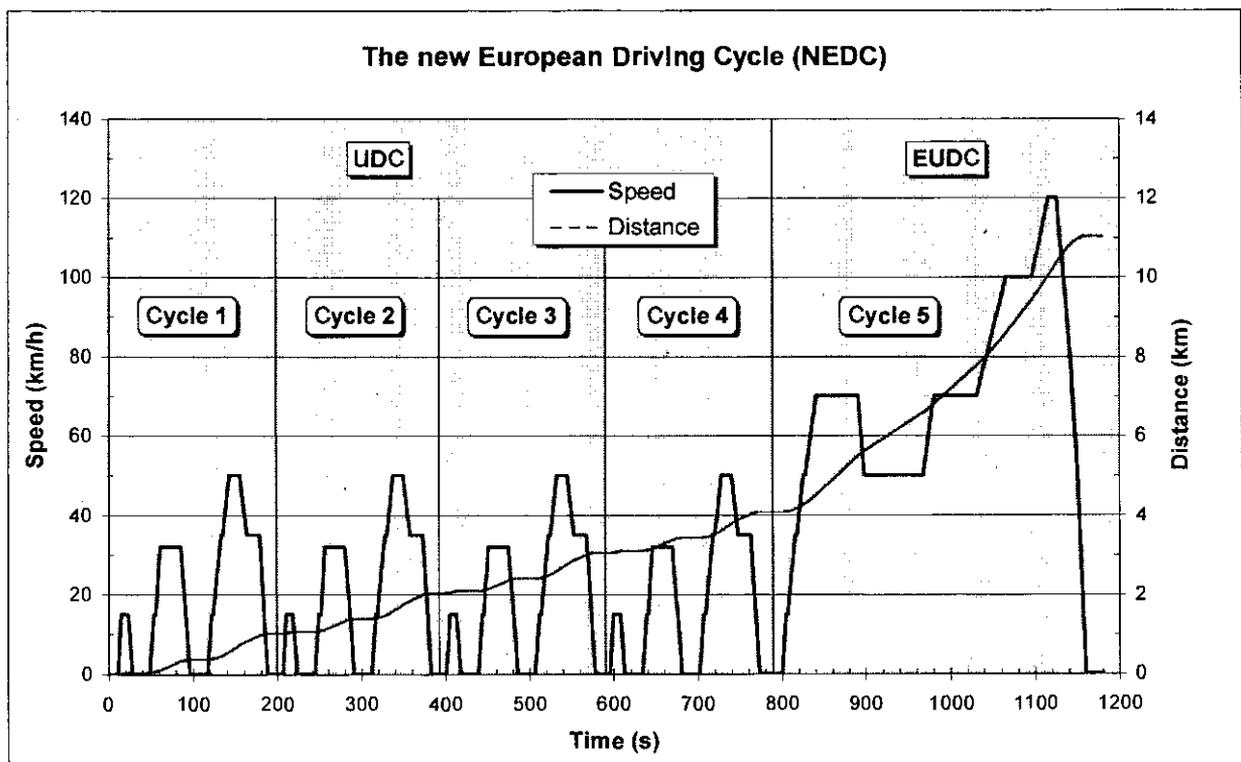


Figure 3: The new European driving cycle (NEDC)

In the driving cycle used so far in the EU the engine is first started and then run on idle for 40 seconds before the sampling of exhaust emissions is started. Thus the emissions from the first 40 seconds will not be measured and taken into account in the calculation of the total cycle emissions. The driving cycle will be changed in the Euro 3 regulation for the year 2000. The modification is that the idle phase is omitted and therefore the start of the engine and the start of sampling are simultaneous. The car chosen for the test series had been certified according to the present emission

regulation. The reason for selecting the new driving cycle (NEDC) after all was that it was of interest to measure the emissions during the whole start-up phase since this is more realistic regarding the impact on the environment.

As a comparison the American FTP-75 driving cycle used in the US and Californian emission regulations is shown in Figure 4. Some of the emission data cited in this report have been generated in this driving cycle. It is obvious that there is a considerable difference between the driving cycles. Furthermore, the FTP-75 driving cycle uses weighting factors for each phase of the cycle whereas the European cycle has no weighting factors. Summarizing it is not possible to directly compare results generated in the two driving cycles.

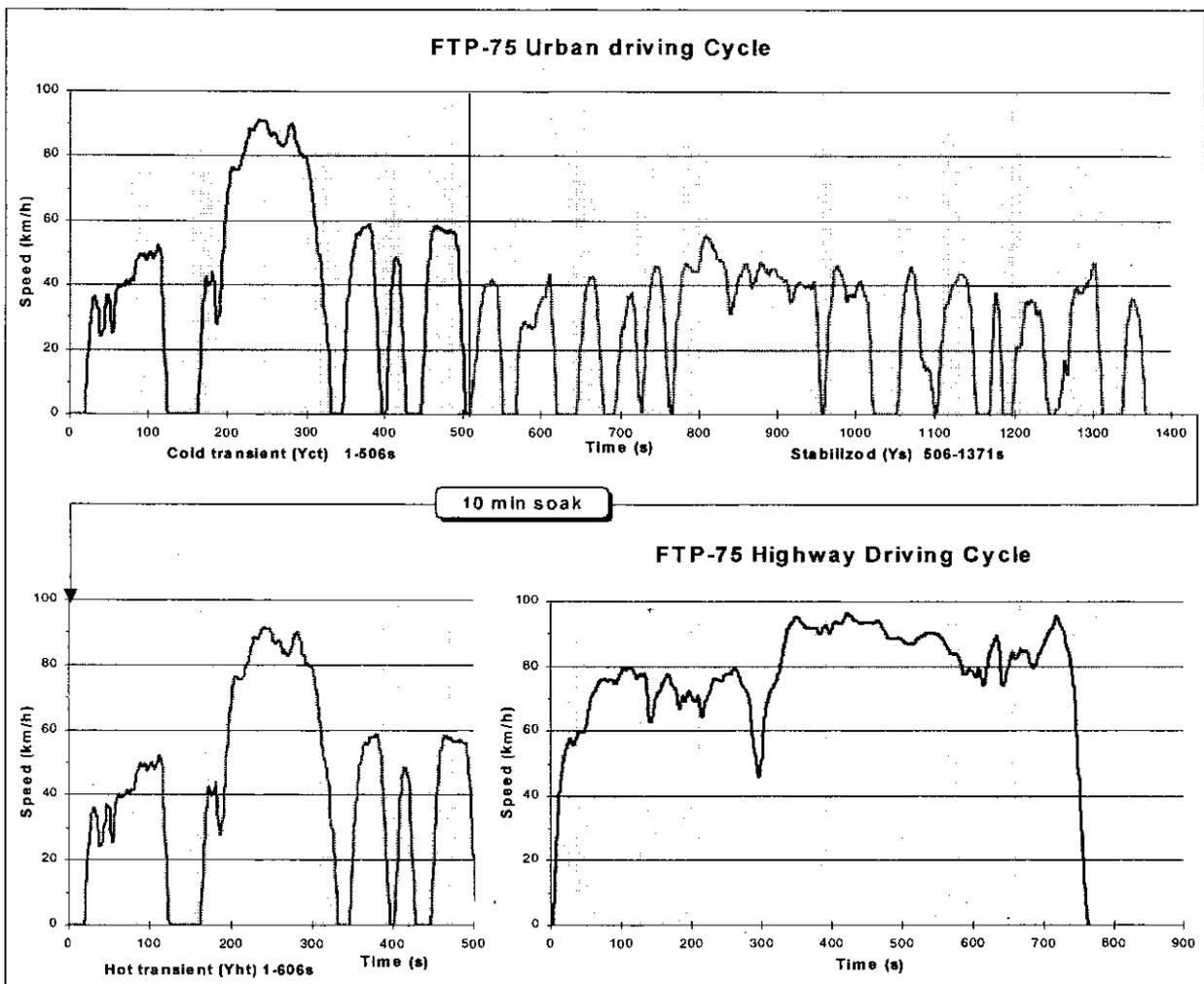


Figure 4: The FTP-75 driving cycle

3.4 Test Program

The test program can be seen in the list below.

1. Conditioning in the NEDC-cycle, the heat store is not connected.
2. NEDC without block heater and Thermostore, +22°C

3. NEDC with block heater 1,5 hours preheat, -7°C
4. NEDC without block heater and Thermostore, -7°C
5. NEDC with Thermostore, 4 minutes preheat, -7°C
6. NEDC with Thermostore, 2 minutes preheat, -7°C
7. NEDC with Thermostore, no preheat, -7°C
8. NEDC with Thermostore, no preheat, +22°C

It is worth noting that the first point in the list is not a test run but is used only for conditioning of the vehicle. Between the tests the car was allowed to cool down to the test temperature (soaking) for a period equivalent to 12 hours. Since the prototype used in the test series did not have as good insulation as the new prototypes and the production model, the soak period was somewhat shortened to represent a temperature decrease of 12 hours on a storage with a proper insulation. In the testing the previous test was used as the conditioning cycle and the possibility for a shortened soak period allowed in the EU regulation, was used as well. One criterion was that the temperature in the oil sump should be within +/- 1°C of the intended test temperature.

The start procedure used in preheating the engine was that the cooling fluid was pumped into the engine in the opposite direction to the flow direction of the engine coolant pump. Thus, rapid heating of the engine temperature sensor was avoided. This sensor is mounted on the coolant inlet at the engine block. Earlier tests had shown that preheating by using the same flow direction as the coolant pump heated the sensor so much that this car was difficult to start due to too much leaning of the air-fuel mixture. Unfortunately the reverse flow direction gave too rich air-fuel ratio (see ch. 5). An optimization of the engine electronic control unit taking the use of Thermostore into account could avoid these problems. When no preheating was used, a so-called direct start, the same flow direction as the coolant pump must be used.

In Figure 5 the start procedure with 2 minutes of preheat is shown as an example of the preheating procedure. The volume of the heat storage is roughly equal to twice the coolant volume in the engine block. Since the heat storage can be emptied in a period less than 2 minutes, a break of 20 seconds was inserted to allow certain temperature leveling. The intention was to use as much of the heat from the first recharge as possible before the rest of the hot coolant was pumped into the engine.

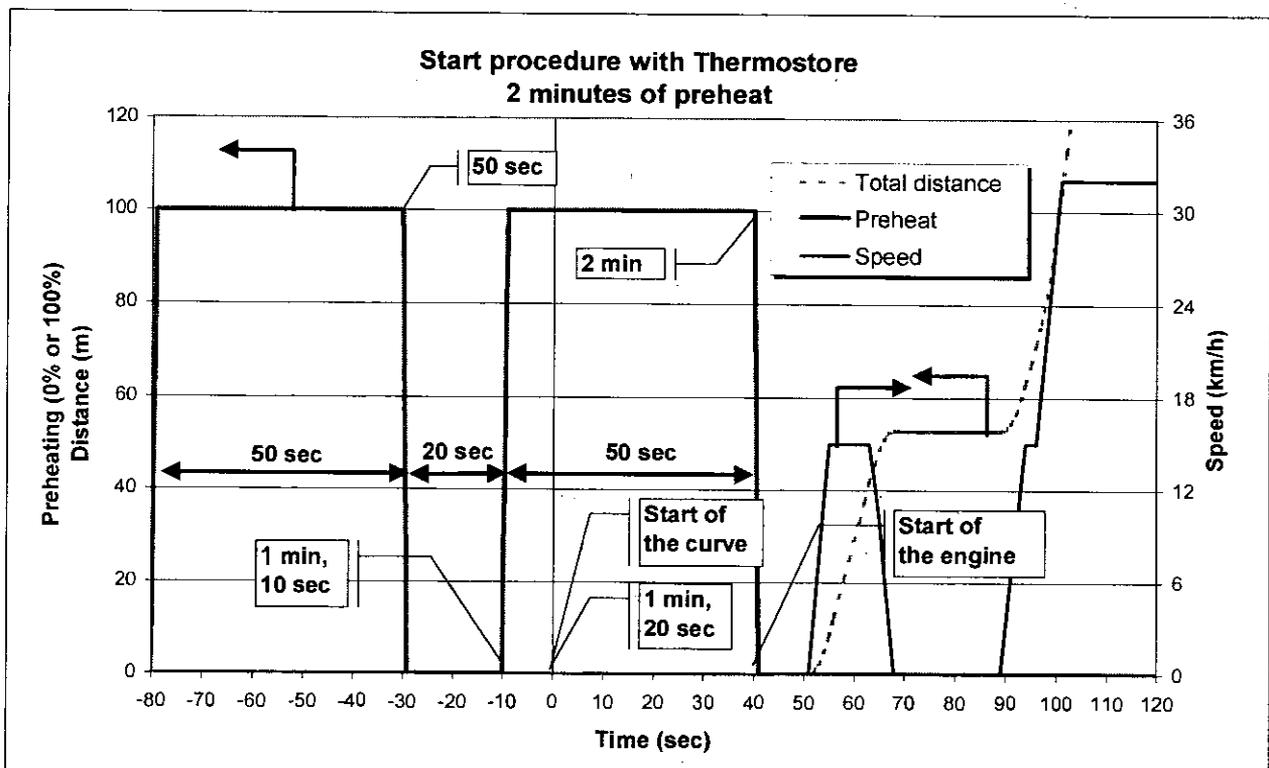


Figure 5: Start procedure with Thermostore, 2 min preheat

4 EARLIER TESTS WITH THERMOSTORE

As mentioned earlier, a test series on a Ford Taurus FFV with Thermostore heat storage installed has been carried out at MTC. The results have been reported in a report that has been published by Thermostore [17]. A short summary of these results is given in this chapter.

The test program for this car was very similar to the program for the Mercedes car. The results in the new European driving cycle (NEDC) are shown in Figures 6 and 7. In Figure 6 a summary of the emission reductions at -7°C by using an engine block heater and the Thermostore with the best control strategy is shown. In Figure 7 a more detailed diagram with the results from all the tests is shown.

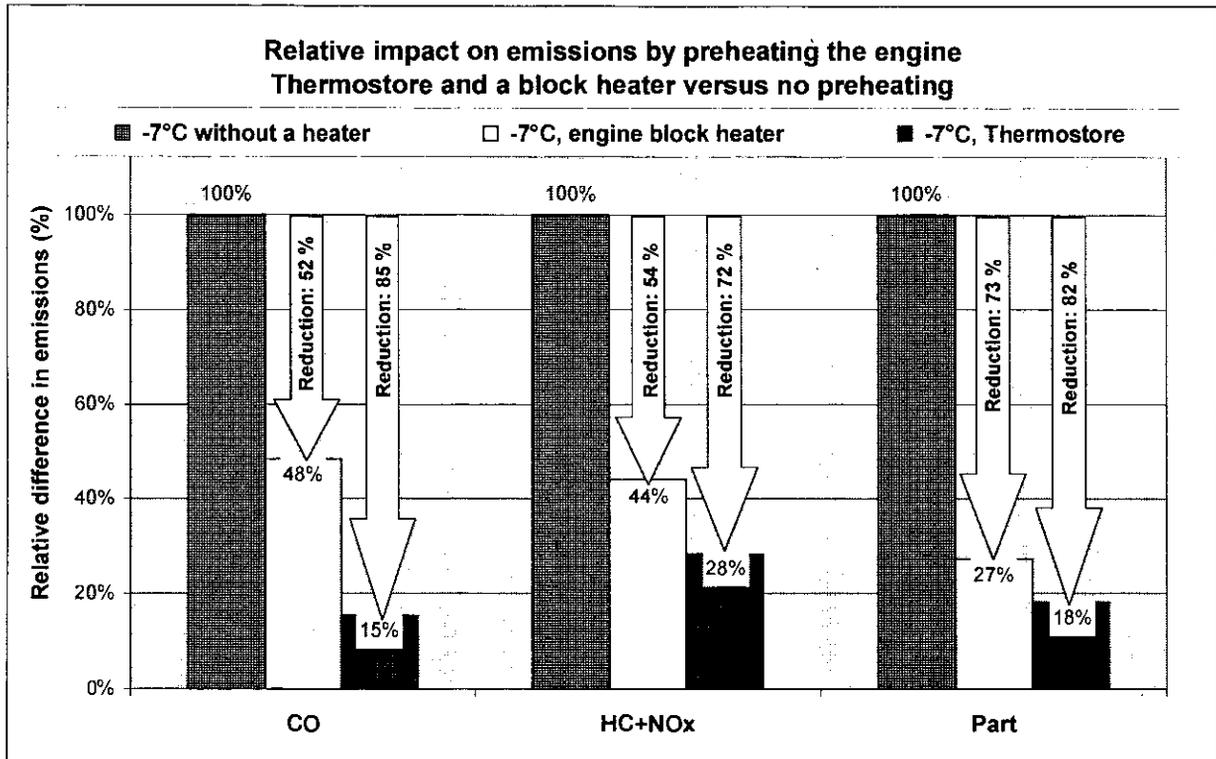


Figure 6: Summary of the emission potential in the NEDC cycle at -7°C on a Ford Taurus with Thermostore and an electric engine block heater

A general feature of this car is the very low NO_x emissions. The increase in NO_x emissions due to preheating is therefore of minor importance. The NO_x emissions are not affected negatively by a low ambient temperature, as are the other emissions. For example the CO emissions increase by a factor of 10 and the HC emissions by a factor of 5 when the temperature is decreased from $+22^{\circ}\text{C}$ to -7°C .

As can be seen in Figure 6, the CO and HC emissions can be reduced considerably by means of a block heater. Thermostore without preheat has higher CO emissions and somewhat higher HC emissions in comparison to a block heater. A preheat time of 2 minutes with Thermostore reduces the emissions further, to a level below the level of a block heater. Thus a level of the same magnitude as with an ambient temperature of $+22^{\circ}\text{C}$ can be achieved. From these tests the conclusion can be drawn that an optimum control strategy for preheating can give very low emissions but that even without preheating the Thermostore can give significant reductions of the emissions.

Emissions in the new European driving cycle (NEDC) Thermostore heat storage and an electric engine block heater

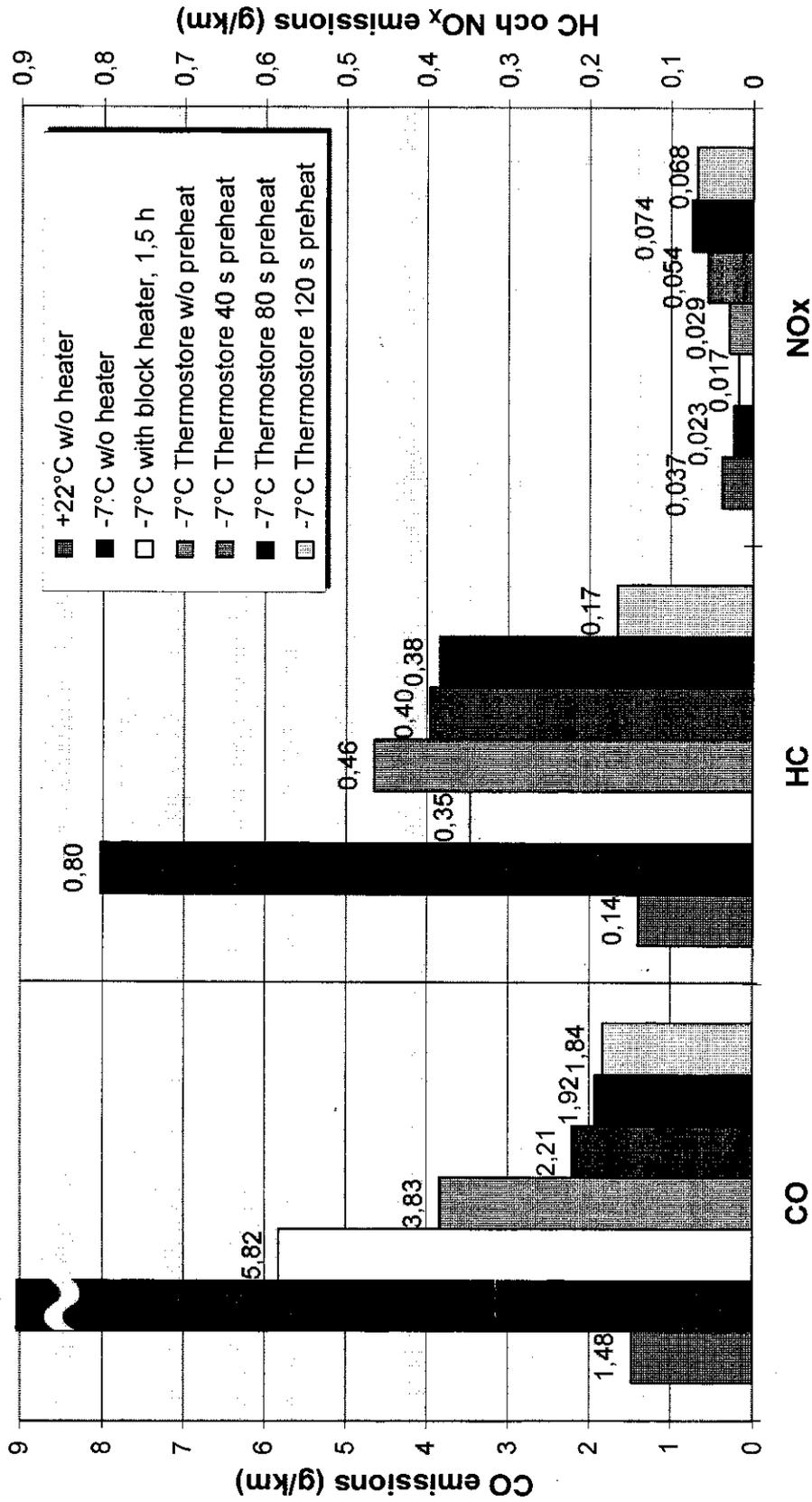


Figure 7: Emissions in the NEDC cycle, Ford Taurus FFV

5 RESULTS

5.1 Emissions

The emission results for CO, HC and NO_x for the Mercedes E 200 that was tested in this study are shown in Figure 8.

As the Ford Taurus tested earlier, this car is also characterized by very low NO_x emissions and the change of this emission component is of minor importance. The NO_x emissions are not very much affected by the test temperature, as are the other emissions. For example, the CO emissions were increased by almost a factor of 4 and the HC emissions by a factor of 5 on this car when the ambient temperature was decreased from +22°C to -7°C. However, the increase in CO emissions was less for this car in comparison to the Ford Taurus tested earlier. This indicates that the engine electronic control unit was better optimized on the Mercedes.

As can be seen in Figure 8, the CO and HC emissions can be reduced considerably by means of a block heater. Thermostore without preheat has higher CO and HC emissions in comparison to a block heater. A preheat time of 2 minutes with Thermostore reduces the emissions to the same level as the block heater. Thus a level of the same magnitude as with an ambient temperature of +22°C can be achieved. It is interesting to note that using the Thermostore at +22°C also gives significant emission reductions. The test at this temperature was carried out without preheat since the driver hardly would initiate the preheating procedure at this temperature. Since the yearly Swedish average temperature is about +7°C and the temperature in the morning usually is low even in the summer time, it can be concluded that Thermostore will give significant emission reductions even under these conditions.

From these test the conclusion can be drawn that an optimized control strategy for preheating will give very low emissions but moreover that a direct start with Thermostore will also give significant emission reductions.

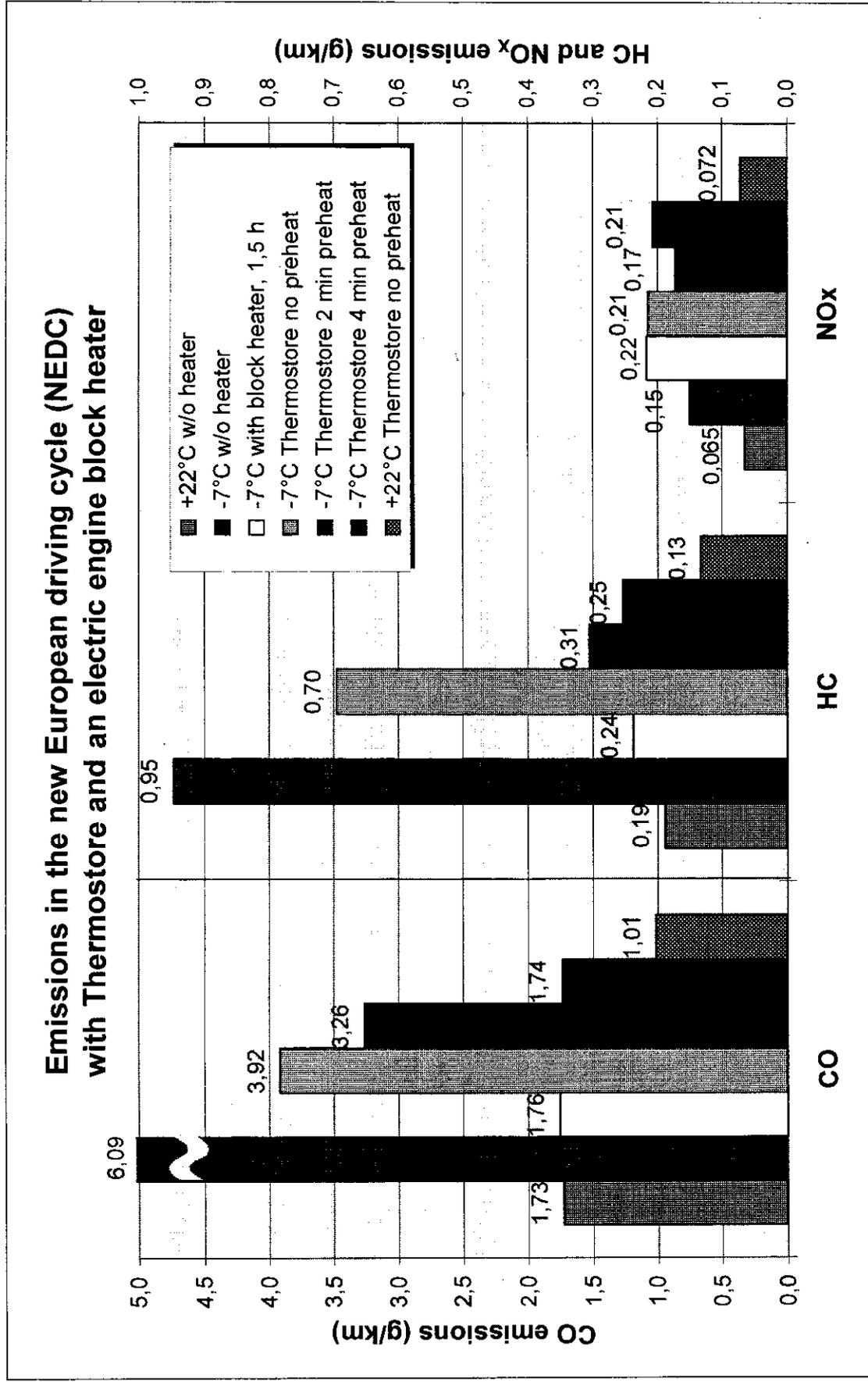


Figure 8: Emissions in the NEDC cycle

In Figure 9 the reduction of emissions is shown for the regulated emissions and the particulate emissions when using a block heater and Thermostore (with the best control strategy). In the Figure the sum of HC and NO_x emissions has been shown, this being used in the current EU regulations.

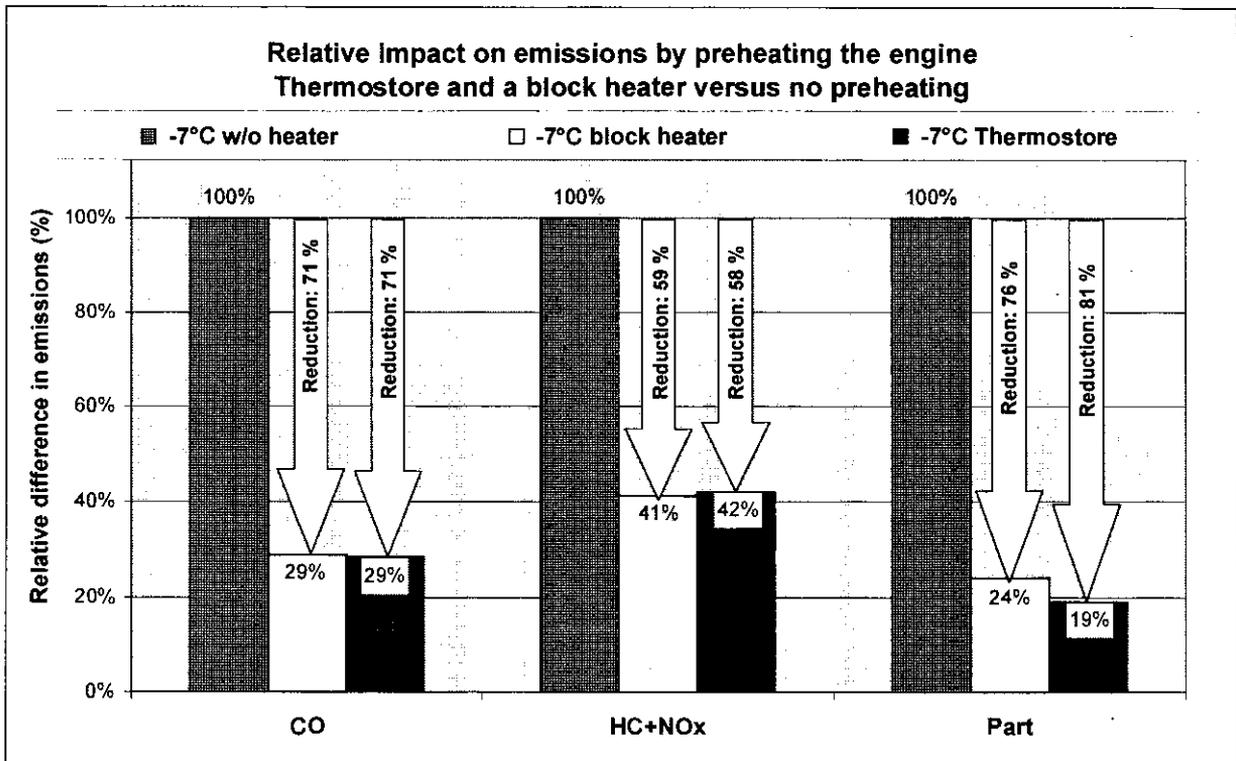


Figure 9: Summary of the emission potential in the NEDC cycle at -7°C with Thermostore and an electric engine block heater

In Figure 10, the particulate emissions for the Mercedes E 200 are shown. In both Figures the particulate emissions for the *whole* driving cycle have been shown. Since the particulate emissions for a gasoline fueled car are greatest during the cold start phase and that after this phase they are very low, the common practice is to show these emissions in the first phase only in the FTP-75 driving cycle [20, 21].

As can be seen in Figure 10, the particulate emissions increase significantly when the ambient temperature is decreased and if no heating is used. Without preheating the particulate emissions with Thermostore are higher than with a block heater but with preheating Thermostore can reach as low level or lower as the block heater. This is the same level as the start without preheating at +22°C. Thermostore has even a small advantage regarding the particulate emissions at +22°C. It is also worth noting that the particulate emissions are highest during the first two km driven, and that the contribution to the total emissions from this phase totally dominates the cycle emissions.

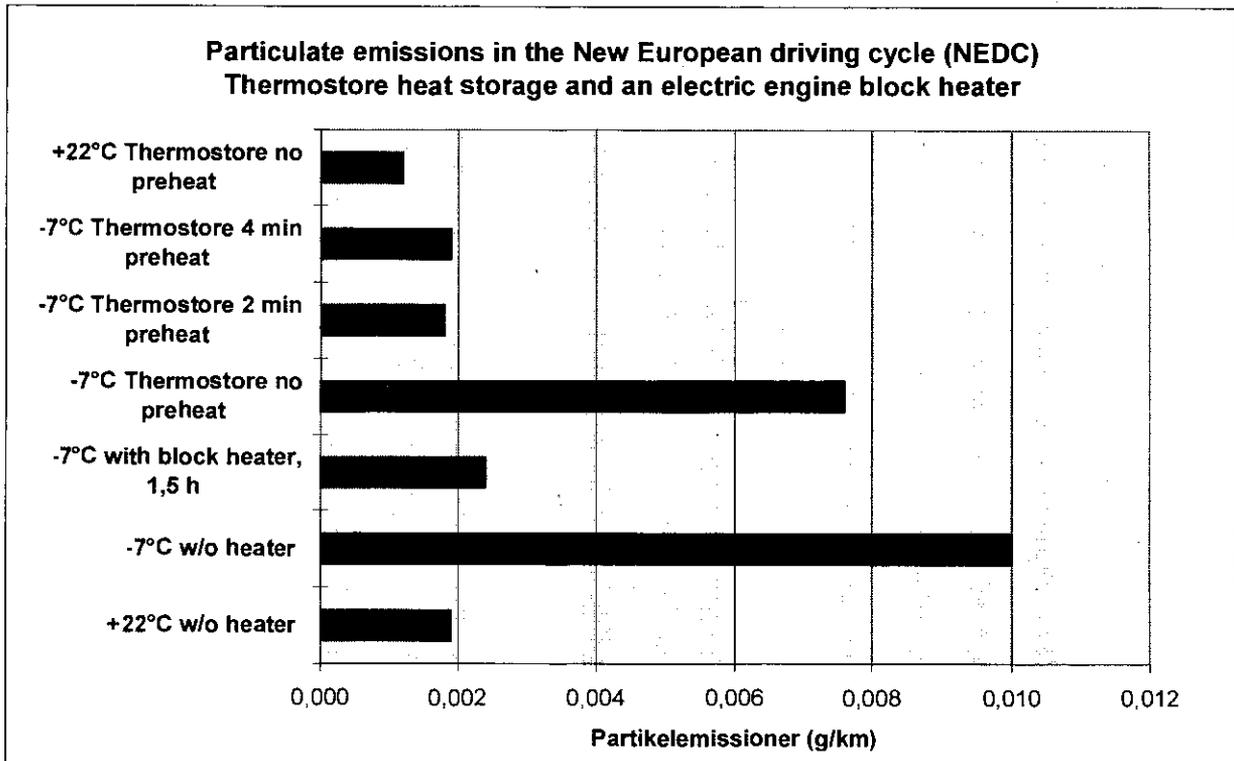


Figure 10: Particulate emissions

5.2 Fuel consumption

When the fuel consumption measurements were evaluated an unusually high scatter was found in the last phase of the test cycle. Normally the fuel consumption should be almost equal for all tested versions in this part of the cycle since the engine is warm (except the oil temperature, which still has not reached the full operating temperature). Another reason for these differences (besides scatter) could be that the charging of the heat storage in this phase (when the engine temperature has reached 80°C) was too fast. Thus, the cooling of the engine could have increased the engine friction. A lower temperature can also be seen at the temperature recordings. The charging procedure, which at present has been manually controlled, will be optimized in the future to avoid this problem. Thermostore has excellent possibilities to achieve an optimum control strategy in this respect due to its good separation of the cold and the hot coolant in the heat storage. In the earlier test series on the Ford Taurus, the charging of the heat storage was carried out in a separate test run. Therefore this problem did not exist in these tests.

To show a somewhat more representative figure for the fuel consumption, only the first phase in the NEDC cycle (cycle 1+2, approximately 2 km) is reported here. These results are shown in Figure 11.

A cold start has, as previously has been pointed out, a significant influence on the fuel consumption. Since the complete car is cooled down to the ambient temperature used in the test there are no possibilities of obtaining the same fuel consumption at -7°C as at +22°C solely by heating the engine. Nevertheless, heating the engine significantly reduces the fuel consumption. Without preheating Thermostore reduces the

fuel consumption somewhat less than a block heater but with preheating the reduction is almost as great. Since the control strategy is not fully optimized yet and there is some concern about measurement scatter, the results for the Thermostore could be significantly improved in this respect.

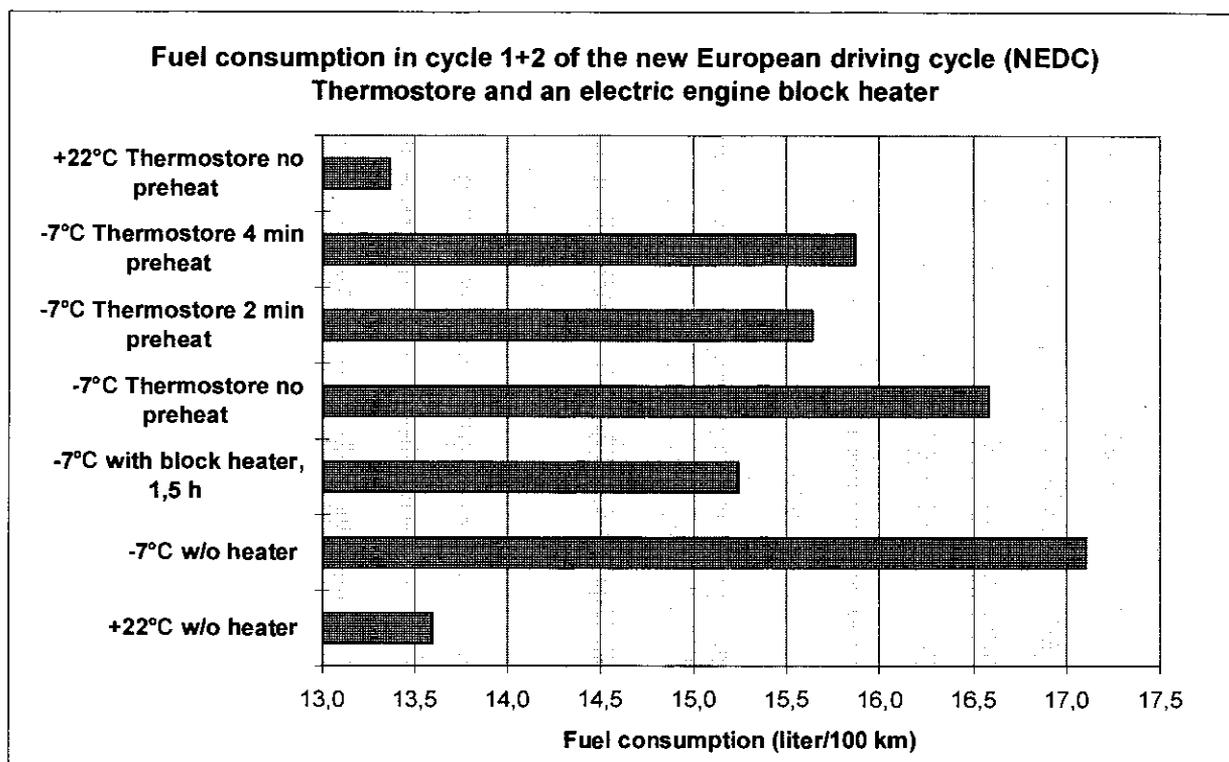


Figure 11: Fuel consumption in the first phase of the NEDC cycle

5.3 Air-fuel ratio

By using the recording of the emissions the air-fuel ratio was calculated (using the formula by Brettschneider). This was carried out in each segment of the test cycle (modal analysis) and likewise a separation of acceleration, retardation and idle phases was performed. Since the calculated air-fuel ratio for a certain segment of the cycle is the average of different driving conditions this value is often higher than the stoichiometric value. This is due to fuel cut-off in the retardation phases. If the comparison is made in the same driving cycle it is still possible to compare the differences in the air-fuel ratio. In Figure 12 some of the results are shown.

The results in Figure 12 clearly show that the mixture ratio is richer at -7°C than at $+22^{\circ}\text{C}$, which is the main reason for the increase in the emissions at cold start. Using a block heater increases the air-fuel ratio to the same level as at $+22^{\circ}\text{C}$. Thermostore gives a significantly richer mixture, which gives unnecessary high emissions of CO and HC. It is possible that an optimized control strategy and/or a longer preheat can improve the situation but the best solution would be to optimize the engine control units instead. There is still a potential for further improvements in this area.

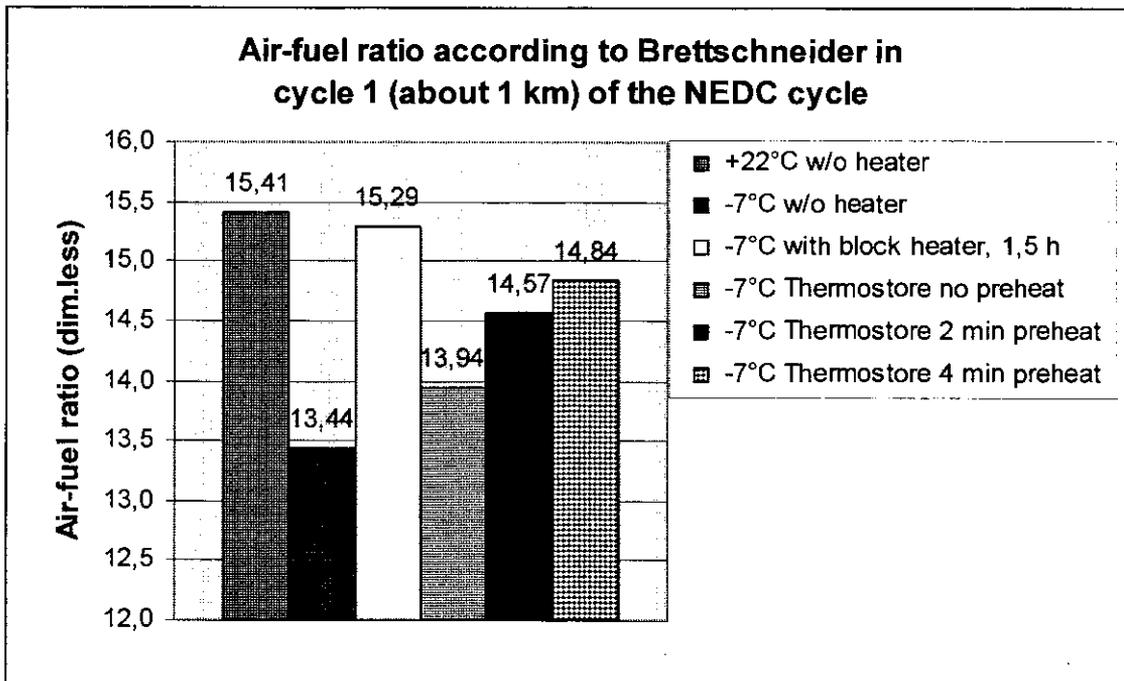


Figure 12: Air-fuel ratio in the first km driven

5.4 Temperatures

In order to investigate the heating of the engine by using Thermostore a logging of some temperatures in the engine and in the heat storage was carried out. As an example some results are shown in Figure 13 from a test when 2 minutes of preheat was used.

As seen in Figure 13, the temperature out of the heat storage was increased to about 75°C and at the engine coolant inlet to over 70°C after a few seconds. The temperature in the cylinder head increased to 40°C but it decreased momentarily again when the hot water mixed with water from sections of the engine block, where the water was colder. In Figure 13, the temperature decrease mentioned earlier (when the heat storage was charged) is also clearly seen.

When the tests were carried out a minor manufacturing error was discovered in the separating piston. The result was a certain unwanted mixing of the hot and the cold engine coolant. As a consequence, the temperature in the last phase of the preheating is reduced as can be noted in the Figure. The new prototypes will not have this problem. Therefore the impact on emissions and comfort can be further improved.

**Logging of temperatures at -7°C, with Thermostore, 2 min of preheat
The new European driving cycle (NEDC)**

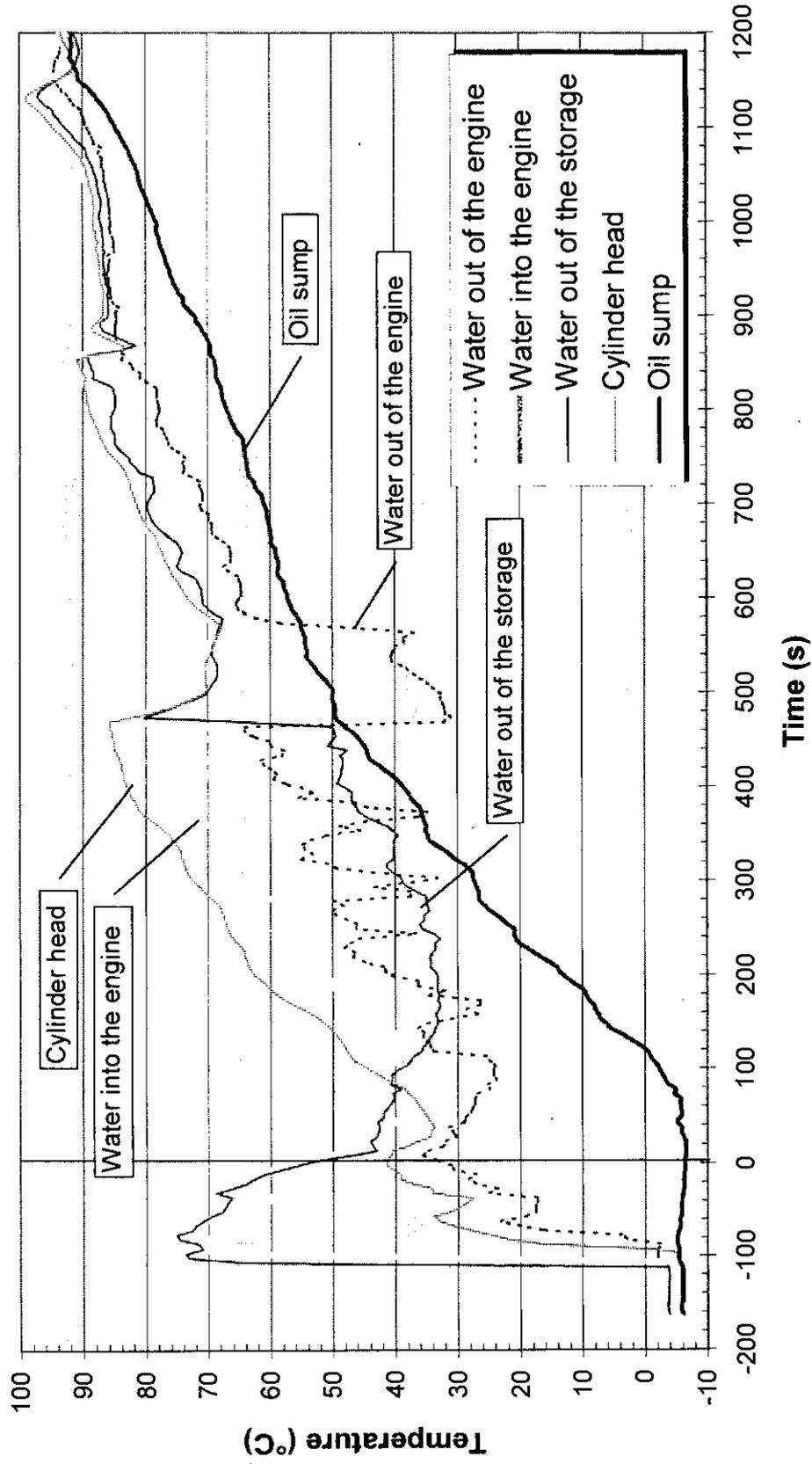


Figure 13: Logging of temperatures at -7°C with Thermostore, 2 min preheat

6 DISCUSSION

It is clear from the data generated on the Ford Taurus tested earlier and the Mercedes tested in this project, that Thermostore has a remarkable potential of reducing the exhaust emissions. By using an optimized strategy for the control system there are possibilities of reducing the emissions more than with an electric engine block heater. It must also be noted that a block heater is totally dependent on external energy supply. Studies at the Swedish Road and Transport Research Institute (VTI), cited in reference [18]⁸, have shown that a block heater is used only in a small fraction of the cold starts. A heat storage, on the contrary, can be used in almost every start, except when the car has been parked for more than a week. Due to the frequent use of the heat storage the emission reductions will be greater than for a block heater. Studies have also shown that block heaters are connected much longer than necessary, thus much energy is wasted. A heat storage has a considerable advantage in this respect.

The literature survey reported in the previous report [17], has shown that there are other heat storages than Thermostore that also have a great potential of reducing the emissions. The investigations in this and the previous report, has shown that the potential with Thermostore is at least as great as that of other types of heat storages and other types of preheat devices. Due to the distinct separation of the hot and cold water in Thermostore, new possibilities emerge for controlling the heating of the engine. A heat storage actually does not compete very much with a block heater, since the heat storage has other capabilities. The main competitor is instead the fuel heater. Since the cost of a heat storage presumably is much lower than for a fuel heater the former has a good opportunity to compete. The possibilities for Thermostore to compete with other heat storages will most likely be determined by the cost as well. A simple assessment of the design shows no reason why Thermostore should be more expensive than the main competitor from Centaur. Thermostore should likewise be considerably less expensive than a heat storage based on molten salt.

The influence on some unregulated emissions has been investigated in a project at MTC on a Volvo 850 car [22]. It was shown that the impact by using a block heater was greater for the unregulated emissions than for HC and particulate emissions. The same trend can be expected with other types of preheating devices, as for example the Thermostore.

7 CONCLUSIONS

A heat storage from Thermostore has been tested on a Mercedes E 200 concerning the impact on the exhaust emissions. This test program is complementary to the previously reported test on a Ford Taurus. The following conclusions can be made:

- Thermostore can significantly reduce the CO, HC and particulate emissions at cold start. At an ambient temperature of -7°C the reduction can be as significant as 80 %.

⁸ The complete report from VTI was not available when this report was written.

- Based on previously reported tests with a block heater at MTC, one can assume that the reduction of the emission compounds posing health hazards will be ever greater than the reductions of HC and particulate emissions.
- NO_x emissions are not much affected on the test car even if there was a small increase.
- With the best control strategy, Thermostore can reduce the emissions at least as much as a conventional electric engine block heater. Furthermore, the reduction by using Thermostore is greater than for other types of heat storages.
- With an well-optimized control strategy it should be possible to reduce the emissions even more. However, a certain compromise between comfort and emissions has to be made. The commercially available heat storages are not controlled to obtain the best emission reduction but are optimized solely for the best comfort.
- By logging the temperatures the preheating has been investigated in detail. Several possible improvements have been identified.
- Calculations of the air-fuel ratio have shown that the air-fuel mixture could be too rich when Thermostore is used. There is some scope for further improvements in this area.

8 REFERENCES

- 1 Banverket, Luftfartsverket, Sjöfartsverket, Vägverket: "Trafikverkens Miljörapport 1993", Publikation 1994:92, 1994, In Swedish.
- 2 Banverket, Luftfartsverket, Sjöfartsverket, Vägverket: "Trafikverkens Miljörapport 1994, 1995", In Swedish.
- 3 Vägverket: "Miljörapport 1994", Publikation 1995:14, 1995, In Swedish.
- 4 Vägverket: "Miljörapport 1994", underlagsrapport, Publikation 1995:15, 1995, In Swedish.
- 5 Bilindustriföreningen: "Kväveoxider - Klarar vägtrafiken målet?", 1996, In Swedish.
- 6 Bilindustriföreningen: "Framtida vägtrafik - Miljöperspektiv till 2020", 1996, In Swedish.
- 7 Laveskog A.: "Emissions from Catalyst Cars Outside Regulated Test Cycles", MTC Report MTC 9001, 1990.
- 8 Laveskog A, Hedbom A. and Kutscher E.: "Emissions at Regulated and Non Regulated Test Conditions", MTC Report MTC 9227, 1992 (Also presented at ISATA 1992).
- 9 Laveskog, A., "Emissions and fuel consumption at FTP test cycles at +22°C and - 2°C from vehicles equipped with block heaters." SAE Paper 920014, Subzero Engineering Conditions Conference; Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, 1992.

- 10 Schatz, O.: "Cold start improvements with a heat store", SAE Paper 910305, SAE International Congress and Exposition; Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, 1991.
- 11 "Latent heat storage", Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, Automotive Engineering, ISSN 0098-2571, Vol. 100, No. 2, p. 58 (4 pp), February 1992.
- 12 Schatz, O.: "Cold start improvement by use of latent heat stores", SAE Paper 921605, Future Transportation Technology Conference and Exposition; Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, SAE Trans., Vol. 101, Section 6, 1992.
- 13 Hellman, K. H.; Piotrowski, Gregory K.; Schaefer, R. M.: "Evaluation of heat storage technology for quick engine warm-up", SAE Paper 922244, International Fuels and Lubricants Meeting and Exposition; Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, SAE Trans., Vol. 101, Section 4, 1992.
- 14 Azpiazu, M. N.; Morquillas, J. M.; Vazquez, A. "Evaluation of a thermal storage system on warm-up exhaust emissions", SAE Paper 921459, Mobility Technology Conferences and Exhibit; Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, October 1992.
- 15 "Heat storage technology update", Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, USA, Automotive Engineering, Vol. 101, No. 2, p. 46 (3 pp), February 1993.
- 16 Zobel, W.; Strahle, R., "Heat storage battery for car applications", SAE Paper 954047 ImechE Paper C496/017, Vehicle Thermal Management Systems; Institution of Mechanical Engineers, London, England, May 1995.
- 17 Ahlvik P.: "Thermostore – Reduced Exhaust Emissions with a Heat Storage – Tests on a Ford Taurus FFV", Thermostore, 1998.
- 18 Naturvårdsverket: "Regulation on the Control of Air Pollution from Light Motor Vehicles; Environment Categories – A14-Regulation", SNFS 1992:4 MS:45, 1992.
- 19 Konsumentverket, Vägverket, Naturvårdsverket, NUTEK, KFB, Svenska Kommunförbundet och Motortestcenter: "Användning av motorvärmare vid kallstart av bensindrivna personbilar", Konsumentverket, 1997.
- 20 Ahlvik P., Erlandsson L. and Laveskog A.: "The Influence of Block Heaters on the Emissions from Gasoline Fueled Cars with Varying Emission Control Technology at Low Ambient Temperatures", SAE Paper 970747, 1997.
- 21 Ahlvik P.: "The influence of block heaters on the emissions from 6 cars at low ambient temperatures", MTC Report MTC 9620A, 1997.
- 22 Ahlvik P., Almén J., Westerholm R. and Ludykar D.: "Impact of a Block Heater on Regulated and Some Unregulated Emissions from a Gasoline Fueled Car at Low Ambient Temperatures", SAE Paper 972908, 1997.

