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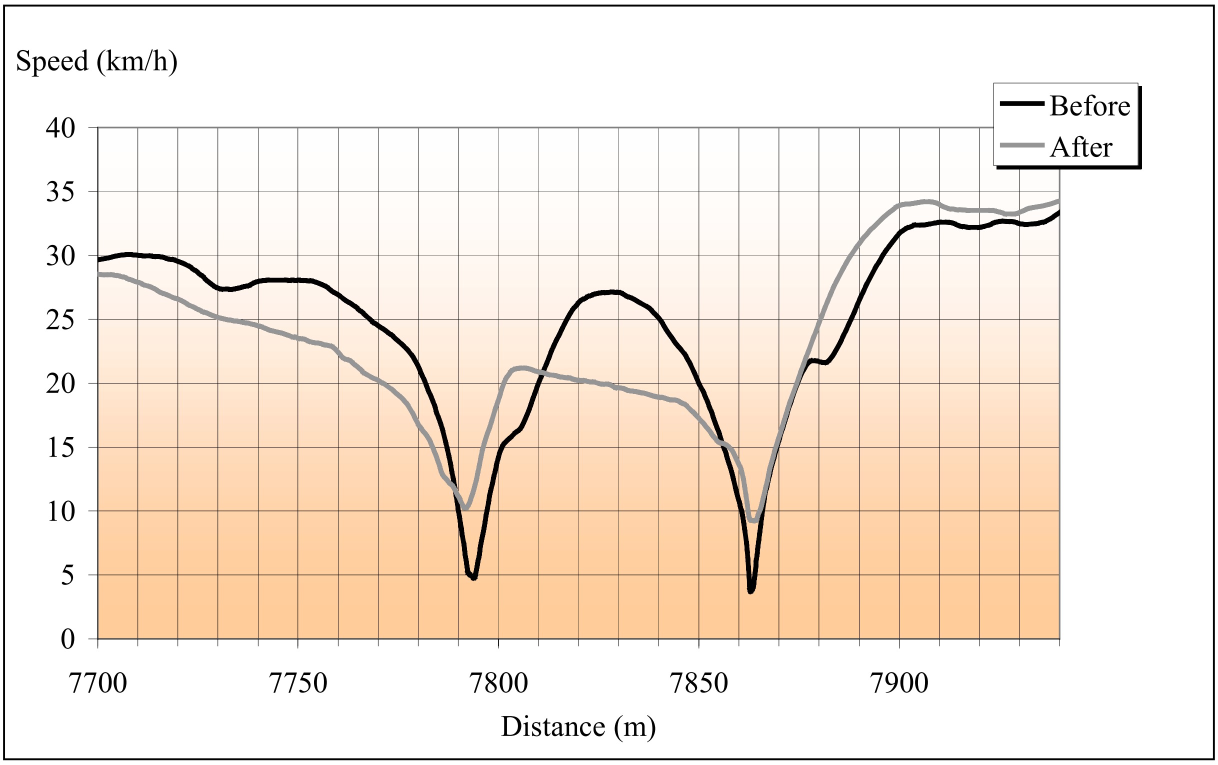
Impact of EcoDriving on emissions and fuel consumption

A pre-study



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Main content

This pre-study is designed to determine whether EcoDriving has any negative impact on emissions and to identify what needs to be changed in the concept to minimise emissions and fuel consumption.

In this pre-study, a car with measurement equipment for driving style, position (GPS) and a large number of engine parameters was used to give 16 students training in EcoDriving. A model that was specially developed for this vehicle made it possible to calculate fuel consumption and emissions.

This report presents the impact of EcoDriving on fuel consumption and emissions, together with a validation of the Econen trip computer.

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Key words

Economical driving style, EcoDriving, Econen, driving style, fuel consumption, emissions

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Preface

In the work involved in the gradual creation of a sustainable transport system, interest should not focus on individual issues and effects. An holistic approach should instead be adopted and attempts should be made to identify measures that produce the greatest possible benefit. This can be achieved using measures that solve a number of problems simultaneously or by the benefit that is produced by measures designed to solve a current problem being so great that it overshadows any negative impact on other problems.

EcoDriving is a measure that is primarily designed to reduce fuel consumption and the emission of carbon dioxide, but it has also demonstrated that it is capable of reducing travelling times and the cost of accidents. In order to determine whether EcoDriving really is a good measure in the move towards a sustainable transport system, it is important to ascertain whether it has any negative impact on other emissions. To date, our knowledge in this area has been extremely limited. This pre-study represents the first step towards an improvement in our knowledge of the impact EcoDriving has on emissions.

The pre-study was conducted as a joint venture between the Swedish National Road Administration (SNRA), Environment and Natural Resources Division, and Rototest AB.

Special thanks are extended to Jan Alexandersson at the National Association of Swedish Driving Schools (STR) who, at short notice, put us in touch with the different driving schools and thereby helped to make it possible to conduct the study. We would naturally also like to thank the various driving schools that agreed to participate in the trial, filled in the questionnaire and drew maps of the routes.

Pär Gustafsson at the Environment and Natural Resources Division also contributed some very valuable views and comments on the report and during the analysis of the data.

Borlänge, December 1999

Gerd Åström

Contents

Summary

In recent years, the concept of economical driving styles has gained in significance, following the realisation that it can now also be regarded as a means of reducing the emission of carbon dioxide. The most common training concept for economical driving styles in Sweden is EcoDriving. This concept, which originated in Finland, was translated and adapted by the National Association of Swedish Driving Schools (STR) at the end of 1998, with the support of the SNRA and the Swedish National Energy Administration. The STR is also responsible for the training of instructors.

The impact of fuel consumption on both EcoDriving and other concepts for economical driving styles has been studied on a relatively large scale. At the present time, however, there are virtually no direct comparisons of the emissions produced by economic driving styles and ”normal” ones.

This pre-study was therefore designed to determine whether EcoDriving has any negative impact on emissions and to to identify what needs to be changed in the concept to minimise emissions and fuel consumption.

In this pre-study, training in EcoDriving has been used to make measurements of driving styles, fuel consumption and emissions both before and after instruction on ways of driving in a fuel-efficient manner.

The trial was conducted in three different places with three different instructors and a total of 16 students. The same petrol-driven car, a 1998 model, was used throughout the trial. It was equipped with measurement equipment for driving style, position and a large number of engine parameters. The last of these made it possible to calculate fuel consumption and emissions using a model specially developed for this car.

The average speed for all 16 drivers was basically the same before and after instruction (36.9 km/h before and 36.7 km/h after instruction). The same thing applied to the average acceleration (0.67 m/s^2 before and 0.69 m/s^2 after). The average retardation did, however, change from –0.49 m/s^2 before instruction to –0.41 m/s^2 after. This reduction in retardation level is due to the fact that more powerful retardation using the foot brake was replaced by slower retardation using the engine brake.

The students spent far more time driving in top gear after receiving instruction than they did before. Gears were missed out during acceleration, reducing the number of gear changes after instruction by 25% compared with the number before.

EcoDriving includes recommendations for a maximum engine speed of 3,000 rpm and a maximum of half-throttle (pedal position) when accelerating. The main purpose of these recommendations is to minimise emissions. The maximum engine speed was exceeded both before and after instruction, but the percentage of time during which it was exceeded declined after instruction. However, the amount of time at more than half-throttle doubled after instruction compared with before; this was probably due to the fact that the students were not informed of these recommendations with sufficient clarity.

Fuel consumption and the emission of carbon dioxide were reduced by an average of 10.9% as a result of the instructions. When it came to emissions, it was not possible statistically to demonstrate any increase or decrease, as there were very large variations in the emissions produced by different students.

An analysis of the material revealed that there was a clear connection between the percentage of time spent at more than half-throttle and the emission of hydrocarbons and carbon monoxide. It was not possible to demonstrate any connection between the percentage of time spent with the accelerator at more than half-throttle and fuel consumption and the emission of nitrogen oxides. This means that the use of the accelerator can be reduced, thereby reducing the emission of hydrocarbons and carbon monoxide, without increasing fuel consumption and the emission of nitrogen oxides.

Some connection was also found between higher engine speeds and an increase in the emission of nitrogen oxides.

In this analysis, the students were divided into a group that had followed the recommendations relating to maximum engine speed and throttle to a large degree and a group that had followed these instructions to a lesser degree. By doing this, it was possible to establish that, if the students follow the recommendations relating to maximum engine speed and throttle, emissions can be reduced using EcoDriving for the vehicle in question. The level of uncertainty is, however, high and its is not possible statistically to establish these reductions, with the possible exception of the emission of hydrocarbons.

It is not, in fact, possible to say anything about the way emissions would be changed in another car with different emission characteristics. The emissions could both increase and decrease. It is, however, highly likely that instructions relating to maximum engine speed and throttle could help to increase the potential for reducing emissions.

The division into two groups also revealed that the students who had had an aggressive driving style prior to receiving instruction generally retained it afterwards. If this problem is to be rectified, more emphasis must be placed on the recommendations relating to maximum throttle and engine speed when it comes to students with tendencies of this kind.

The trip computer, Econen, which is used in EcoDriving training, was also validated in the trial.This validation revealed that Econen provided sufficient accuracy when determining fuel consumption, driving distance and average speed.

Econen has no functions to provide an indication of the size of emissions (apart from carbon dioxide). It would, however, be an advantage if the students were given some feedback on whether their driving did or did not result in a reduction in emissions. To achieve this, the instructors’ cars should be fitted with equipment that provides some indication of emissions. In the case of hydrocarbon and carbon monoxide emissions, the signal from the Lambda sensor could probably be used for this purpose. However, when it comes to nitrogen oxides, it is more difficult to obtain an indication of these emissions.

1 Background

Economical driving styles are nothing new. This is exemplified by the classical report entitled ”The impact of driving style on fuel consumption” by Laurell (1985). However, a great deal has changed since then. Since 1989, almost all petrol-driven cars have electronically-controlled fuel injection and, as a result, the recommendations relating to economical driving styles have changed. Moreover, the concept of economical driving styles has gained in significance, as it is currently also regarded as a means of reducing the emission of carbon dioxide.

The most common concept for economical driving styles in Sweden is EcoDriving. This concept, which originated in Finland, was translated and adapted by the National Association of Swedish Driving Schools (STR) at the end of 1998, with the support of the SNRA and the Swedish National Energy Administration. The STR is also responsible for the training of instructors. During the spring of 1999, some one hundred driving school teachers were trained as instructors in EcoDriving.

A great deal is also being done at international level to train drivers to drive economically. In addition to EcoDriving in Finland, the activities that are being run within the ”Energie 2000” projects in Switzerland and and ”The New Driving Force” in the Netherlands are particularly worthy of mention (Reinhardt, 1999 and Wilbers, 1999).

The impact on fuel consumption of both EcoDriving and other economical driving concepts has been investigated on a relatively large scale. At the present time, however, direct comparisons of the emissions generated by economical driving styles and normal driving styles are lacking.

This pre-study is therefore designed to determine whether EcoDriving has any negative impact on emissions and to identify what needs to be changed in the concept to minimise emissions and fuel consumption.

EcoDriving training is divided into a practical part and a theoretical part.

In the practical part of the EcoDriving training, the student drives twice along a 10-kilometre route, which includes some roads with high speed limits. On the first run, which begins the training, the students drive in their normal way without any comments by the instructor on their driving style. The instructor then gives the students some advice on ways of improving their driving style and also demonstrates what they can do in certain situations. The students then drive the same route again and apply their new knowledge, together with the instructor. Fuel consumption is measured on both occasions using an advanced trip computer (Econen).

Experience from Sweden and Finland indicates that average fuel consumption is more than 10% lower on the second occasion after instruction compared with the first. Perhaps the most comprehensive material available in Sweden relates to the demonstrations of EcoDriving, i.e. only the practical part of the training, which were conducted in Borlänge and Tylösand in 1998 and 1999. These demonstrations involved a total of 101 people. Fuel consumption decreased by an average of 11% in Borlänge and 12.5% in Tylösand. The time it took to cover the route also decreased significantly by 5.3% and 1.8% in the two places.

One possible objection to this way of measuring the effects is that the students are not used to either the car or the route the first time they drive, while they are somewhat more familiar with them on the second occasion. This could have some effect on fuel consumption. One way of avoiding effects of this kind is to conduct long-term follow-ups both before and after the training. Long-term follow-ups of this kind are in progress in a number of places in Sweden. However, owing to the limited period since the introduction of EcoDriving in Sweden, no results are as yet available. Some long-term follow-ups have, however, been conducted in Finland, by the Finnish Post Office and the police force in the Country of Southern Finland. They demonstrate a reduction in fuel consumption of the same magnitude as that found during the actual training. The follow-up conducted by the Finnish Post Office also revealed a reduction in the costs associated with accidents (Donner, 1998).

In neither Borlänge nor Tylösand was there any really dense traffic or congestion. The reduction in fuel consumption that could be achieved using economical driving styles in this kind of traffic is not clear. More stoppages would be likely to have a greater effect on fuel consumption and thereby save fuel, while intensive traffic makes it more difficult to drive economically unless this style of driving is applied generally.

A study booklet is available as support for the theoretical training (Mikkola et al., 1999). In addition to driving style, it also deals with the environmental impact of cars and the importance of the choice of car, cold starting, air pressure, choice of route and maintenance when it comes to fuel consumption.

The basic principles of an economical style of driving according to EcoDriving are as follows.

- When starting, an attempt should be made to change up as quickly as possible to second gear and then to higher gears at one-third to half-throttle.

- Accelerate in each gear until the engine speed reaches the point at which engine torque is at its highest (normally around 3,000 rpm), thereby avoiding driving at excessively high engine speeds.

- If your car does not have a tachometer, accelerate in first gear to a speed of 10-15 km/h, in second to 40 km/h, in third to 60 km/h and then in fourth or fifth gear to higher speeds.

- Plan before you reach intersections and traffic lights or if you see that the car in front of you is going to turn. Put the car in neutral and freewheel (cars with carburettors) or brake via the engine (injection engines) and approach in such a way as to give the traffic lights time to change to green or to enable you to continue driving without stopping unnecessarily.

- Drive to match the rhythm of the remainder of the traffic. On roads with busy traffic, overtaking does not save that much time, but it does increase fuel consumption.

- Learn to drive, keeping the throttle at a uniform level (a suitable engine speed is around 2,000 rpm) and, depending on the topography of the road, use fourth or fifth gear whenever possible.

- If your car has a powerful engine and high torque, it is better to accelerate a little more rather than changing down to a lower gear.

Adaptations to cars with more powerful engines were made in Sweden compared with Finland by recommending driving in fifth gear from speeds as low as 50 km/h, which often correspond to around 1,500 rpm.

This report is based to some extent on two previous reports (Söderberg and Engström, 1999a and Söderberg and Engström, 1999b). Additional analyses have, however, been made in this report. Some background material has also been added to enable the report to be aimed at a wider target group.

2 Trial design

As has already been mentioned in the previous section, virtually no studies of the impact of economical driving styles on emissions have been conducted. This also applies to EcoDriving. So the idea behind this pre-study is to use training in EcoDriving to make measurements of driving style, fuel consumption and emissions, both before and after instruction. Measurements of driving during the training of 16 students in Solna, Jönköping and Köping were used in this pre-study.

2.1 Instructors and students

The trial was conducted using three different instructors in Solna, Jönköping and Köping at different times between 17 February and 26 March 1999. At the beginning of the same year, these instructors had taken part in the first training session in Sweden of chief instructors in EcoDriving. They had therefore practised EcoDriving themselves for a relatively limited period prior to the trial.

The 16 students who took part in the trial were all driving school teachers, who were going to be trained as instructors in EcoDriving. There were therefore experienced drivers and probably more involved than students who were not going to be trained as instructors. Both male and female driving school teachers took part. Eight of the students were trained in Köping, while the remaining eight were evenly split between Jönköping and Solna.

2.2 Vehicle

During the trial, the same petrol-driven 1998 VW Golf 1.6 was used in all three places. To eliminate the effect of cold starts, the vehicle was driven until it was warm before the next training session took place. The technical specification of the car is shown in Table 2.1.

Table 2.1 Technical specification – 1998 VW Golf 1.6 (factory data)

Engine	Four-cylinder, in-line
Displacement	1,595 cm^3
Max. output	74 kW at 5,600 rpm
Max. torque	145 Nm at 3,800 rpm
Kerb weight	1,170 kg
Fuel consumption according to EU standard	7.6 l/100 km (mixed driving)
Emissions HC+NOx (EDC)	0.18 g/km

2.3 Routes

The three routes are shown in Figure 2.1 to Figure 2.3. In all cases, the GPS signal from the vehicles was used to map out the route. The length of the routes was more or less the same. The shortest route, 11.4 km, was in Jönköping, while the longest was in Köping, 12.1 km. The routes differed in some ways. The one in Solna differed from the other two as almost half of it comprised major roads and roads with only a few intersections, which meant that there were relatively few stops (E4, E18 and Sjövägen). Köping was the only route containing some motorway with a speed limit of 110 km/h. On the other two routes, the maximum permissible speed was 70 km/h. Jönköping had the largest percentage of driving in a pure urban setting.

Figure 2.1 Route in Solna

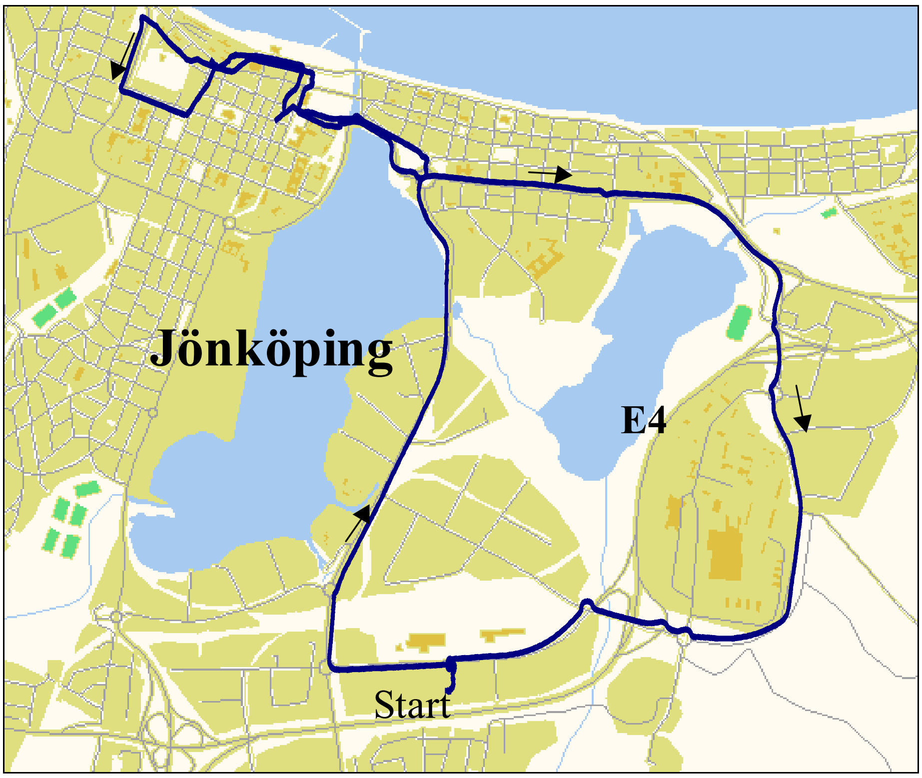

Figure 2.2 Route in Jönköping

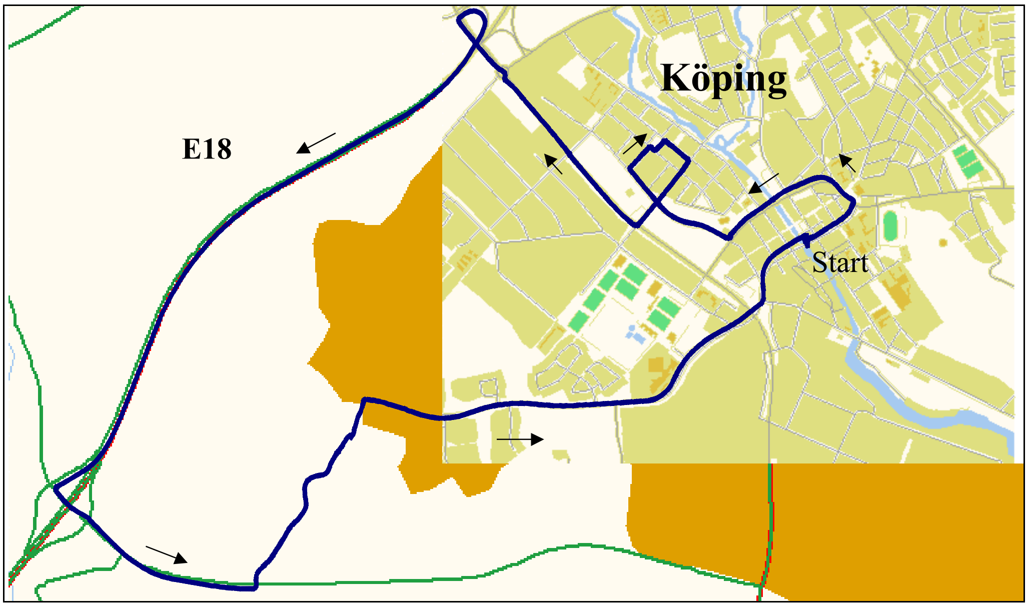

Figure 2.3 Route in Köping

2.4 Measurement equipment in the vehicle

The vehicle was equipped with measurement equipment for driving styles, position and a large number of engine parameters. The engine parameter measurements made it possible to calculate fuel consumption and emissions. The measurement system, Rototest IVAS, had previously been developed by Rototest AB for the SNRA and the Lund Institute of Technology for the test subject study Swedish Driving Pattern Study 98 (SDPS 98), which was conducted in Västerås in the autumn of 1998 (Johansson et al., 1999). The measurement equipment is therefore only briefly described in this report. A more detailed description can be found in Johansson et al. (1999). The parameters that were measured in the vehicle are listed in Table 2.2.

Table 2.2 Parameters measured in the vehicle

Parameter	**Type**	**Sensor**	**Measurement frequency**
1) Fuel consumption	[ml/sec]	Jet	10 Hz
2) Engine intake temperature	[° C]	Thermo element	1 Hz
3) Engine coolant temperature	[° C]	Thermo element	1 Hz
4) Exhaust temperature before catalytic con.	[° C]	Thermo element	1 Hz
5) Exhaust temperature after catalytic con.	[° C]	Thermo element	1 Hz
6) Ambient temperature	[° C]	Thermo element	1Hz
7) Oxygen content of emissions	[Volt] (1)	Lambda sensor	10 Hz
8) Throttle angle	[Volt]	Voltage level	10 Hz
9) Mass flow meter	[Volt]	Voltage level	10 Hz
10) Engine speed	[rpm]	Pulse sensor	10 Hz
11) Wheel speed	[rpm] (2)	Inductive sensor	10 Hz
12) Use of brakes	[On/off]	Brake light contact	10 Hz
13) Position	[Pos.co-ordinator]	GPS + DGPS	2 Hz

(1) Both original and extra broadband Lambda sensor
(2) The wheel speed was registered on a non-driving wheel

The wheel speed, together with the measured roll circumference, was used to determine the speed of the vehicle. The driving distance and acceleration were then calculated on the basis of this speed.

The measurement equipment functioned without any problems throughout the trial.

In addition to Rototest IVAS, the vehicle was also equipped with the Econen trip computer, which was used during the training in EcoDriving. Econen is basically a trip computer which specifies fuel consumption, but it also features a learning function which attempts the whole time to get the driver to drive in an even more fuel-efficient manner. Econen measures and calculates driving time, driving distance, speed, average speed, current consumption, average consumption, for example, and it also has an adjustable speeding warning for two speeds.

2.5 Model for calculating emissions and fuel consumption

In order to evaluate the effect of different road types, vehicles and drivers on emissions and fuel consumption, it is necessary to have a model with a high time resolution. Models of this type are normally known as instantaneous emission models and can then be divided into mechanistic and matrix models (SNRA, 1999). The mechanistic models include a description of engine and vehicle using which the emissions are simulated. The matrix models are normally based on a matrix in which the emissions are expressed as a function of instantaneous acceleration and speed. Matrix models are less advanced and are normally not able to describe the significance of changes in trip resistance and gear position, for example.

In an R&D project funded by the SNRA, Rototest AB developed a mechanistic model for the SDPS 98 project for the VW Golf 1.6 used in this trial. This model was also used in this pre-study to calculate emissions and fuel consumption.

The modelling work was based on tests conducted in Finland by VTT and tests conducted at Rototest's laboratory in Rönninge where emissions were measured before and after the catalytic converter. This model applies to a vehicle that has been driven until it is warm (engine oil temperature $\geq$ 80° C and normal coolant temperature). Unlike traditional mechanistic models, this model is able to describe the effect of transients, which is essential in order to obtain a high level of precision for petrol-driven cars with a catalytic converter.

The model is based on continuous measurements of the following parameters.

- The amount of air supplied to the engine
- The amount of fuel supplied to the engine
- Engine speed
- Engine load
- Measured Lambda value (before catalytic converter)
- Exhaust temperature before catalytic converter
- Exhaust temperature after catalytic converter

The Rototest Vehicle Emission Model RVEM VW Golf 1.6 1998 was based on a comparison of the above parameters with the measured emissions of CO_2, CO, THC, O_2 and NO_x before and after the catalytic converter and the model describes the empirical relationship between these parameters. One of the difficulties involved determining the ”memory functions” and performance of the catalytic converter in different operating conditions.

The target was to determine emissions with a maximum deviation of 10% from the measured emissions. This was not realised in full, but the model produced results which almost matched the set targets. In this context, it should perhaps be mentioned that it is relatively easy to develop a model which produces good results for one or two different driving cycles, but it is a completely different thing to get the model to match a wide range of different operating conditions. Rototest is also convinced that is is possible to improve the model still further. However, we regard the present results as satisfactory. The model has been verified using the tests listed in Table 2.7. An example of an evaluation is given in Figure 2.3.

Table 2.3 Verification of a model for a 1998 VW Golf 1.6

Number of tests	Driving cycle	Vehicle weight
2	EC 2000	1,500 kg
2	EC 2000	2,500 kg
1	FTP 75	1,500 kg
1	FTP 75	2,500 kg
2	US06	1,500 kg
1	Heavily laden	1,500 kg
1	Heavily laden	2,500 kg

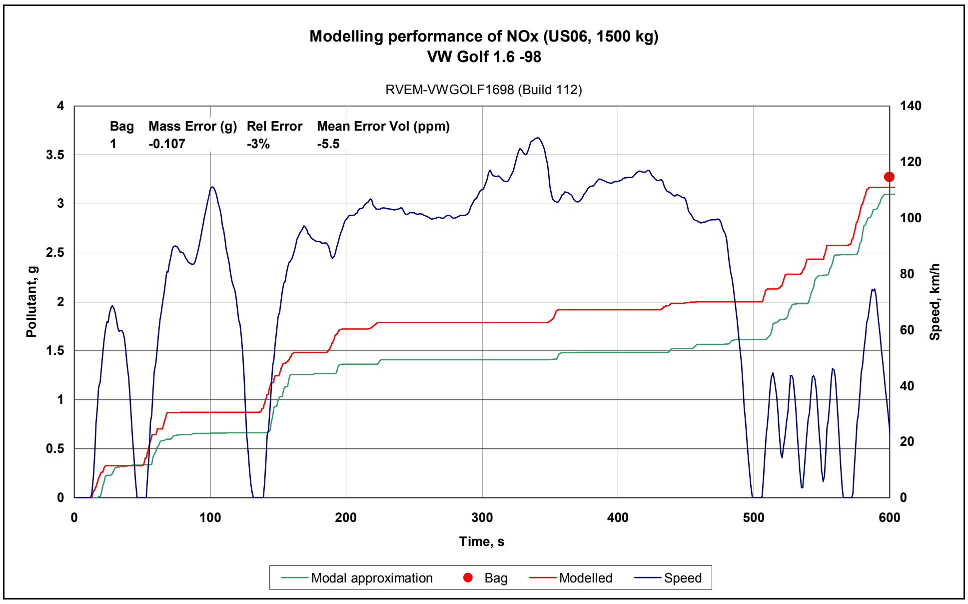

Figure 2.4 Example of an evaluation of a model for a 1998 VW Golf 1.6.

3 Results

Data were registered for all 16 drivers both before and after receiving instruction. Fuel consumption and emissions were then calculated using these data. The total registered driving distance for the 32 journeys was 375 km.

All the data quoted below were based on the Rototest IVAS and calculations made with Rototest RVEM. A comparison between Econen and Rototest IVAS is made in Chapter 3.3.

It is important to point out that this pre-study is only based on measurements made using one car. The results should therefore be regarded as indications and not as absolute truths.

3.1 Driving styles

The average speed for all sixteen drivers was 36.9 km/h before instruction and 36.7 km/h after instruction. This change is not statistically significant. The average acceleration before instruction was 0.67 m/s^2 and it was virtually unchanged (0.69 m/s^2) after instruction. The average retardation did change, however, from –0.49 m/s^2 before instruction to –0.41 m/s^2 after. This reduction in retardation level was also expected in view of the fact that the training stresses the importance of planned driving with fewer, gentler retardations, preferably using the engine brake.

Figure 3.1 shows the distribution of retardation levels before and after instruction. It shows relatively clear-cut differences in this distribution. The percentage of retardations under –0.5 m/s^2 is larger before the training than after, but the situation when it comes retardations over –0.5 m/s^2 is reversed. In all probability, this is due to more powerful retardations with the footbrake being replaced by slower retardations using the engine brake. This is supported by the fact that the percentage of time spent with the brake pedal depressed decreased from 19% before instruction to 15% after. The percentage of the driving distance that was spent with the brake pedal depressed decreased still further from 37% to 23%.

Figure 3.2 shows the corresponding distribution for acceleration. The differences between before and after instruction are not as clear cut as those for retardation. The percentage of accelerations over 1.7 m/s^2 was, however, slightly higher after instruction than before.

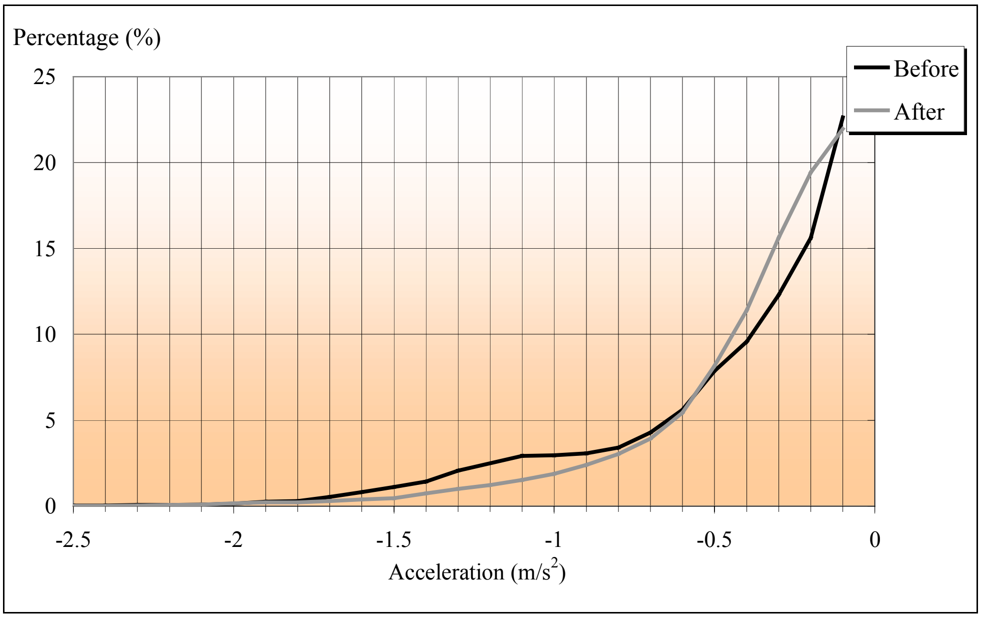

Figure 3.1 Distribution of retardations before and after instruction.

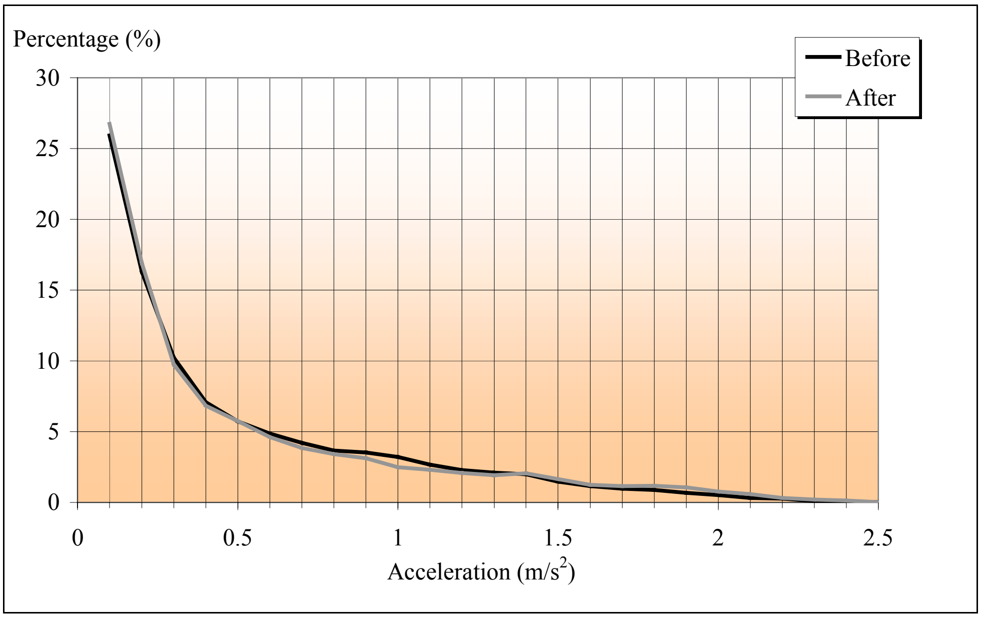

Figure 3.2 Distribution of acceleration before and after instruction.

Figure 3.3 shows a typical example of a driving pattern before and after instruction. The two minimum speeds took place before two intersections at which the car turned 90 degrees. The figure clearly shows that, after instruction, the driver looks much further ahead and plans the retardation much earlier. Moreover, between the intersections, the driver also realises that there is no point in accelerating and then being obliged to brake before the next intersection. It is easy to see in this figure that the retardation levels are lower after instruction than before. It is, however, difficult to see any difference in acceleration level in this figure. This also agrees with the statistics in Figures 3.1 and 3.2.

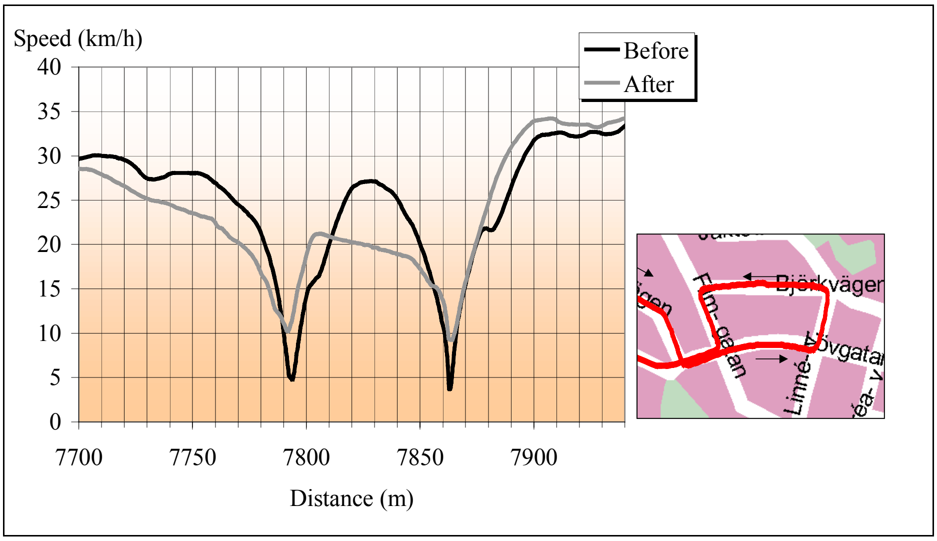

Figure 3.3 Comparison of driving styles before and after training in EcoDriving in Solna. The first minimum speed took place when the driver braked before the intersection between Björkvägen and Filmgatan. The driver then turned 90 degrees and increased speed before braking, after which a new minimum speed took place before the intersection between Filmgatan and Lövgatan.

According to the instructions for EcoDriving, the driver should only accelerate in every gear up to an engine speed of no more than 3,000 rpm (or the engine speed at which the driver knows that maximum torque is reached). Figure 3.4 shows the average distribution of engine speed before and after instruction. As can be seen, instruction resulted in a far lower engine speed.

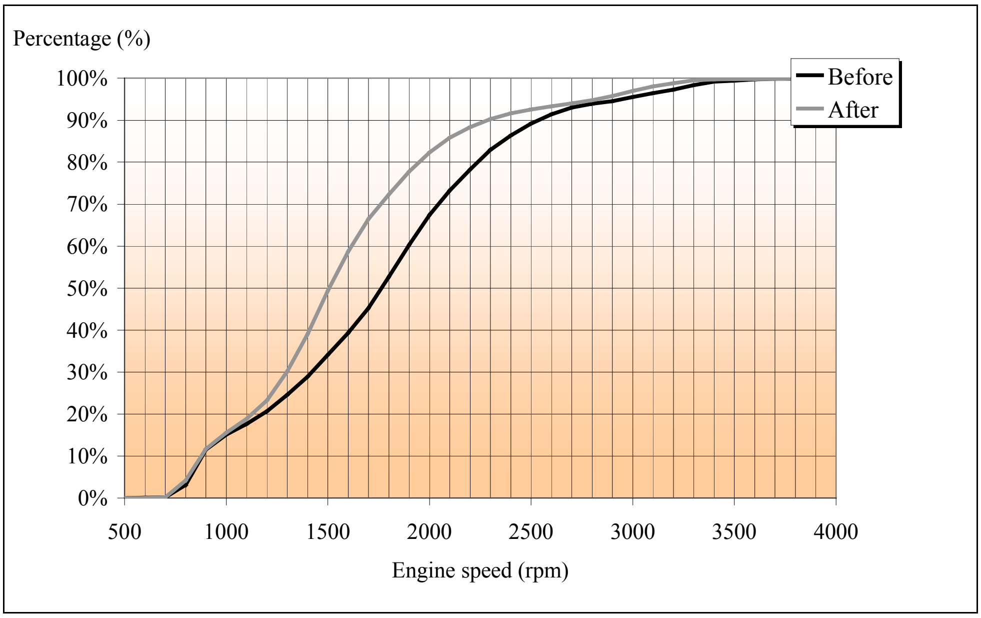

Figure 3.4 Cumulative distribution of time distribution of engine speed for all journeys.

EcoDriving recommends that gears should be missed out to save fuel. This is virtually never done when normal driving styles are employed (Johansson et al., 1999). Figure 3.5 shows the gear-changing sequences during acceleration before and after instruction. Before instruction, the trial subjects almost always changed up from second gear to third, for example. After instruction, on the other hand, it was more common for them to change up from second gear to fourth. This was also expected in view of the training. Missing out gears also reduced the number of gear changes by 25%.

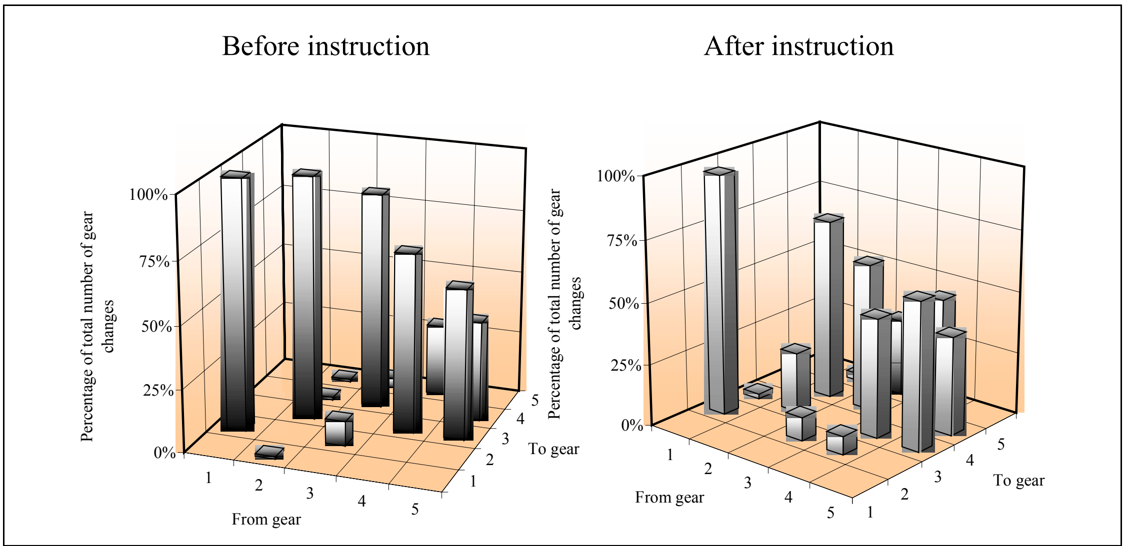

Figure 3.5 Gear-changing sequences during acceleration.

Once the correct speed has been reached, EcoDriving specifies that driving should be done in the highest possible gear. Figure 3.6 shows the percentage of driving at constant speed (±0.1 m/s^2) which was done in fifth gear before and after instruction. As the figure shows, fifth gear was used on a far larger scale at lower speeds after instruction compared with before.

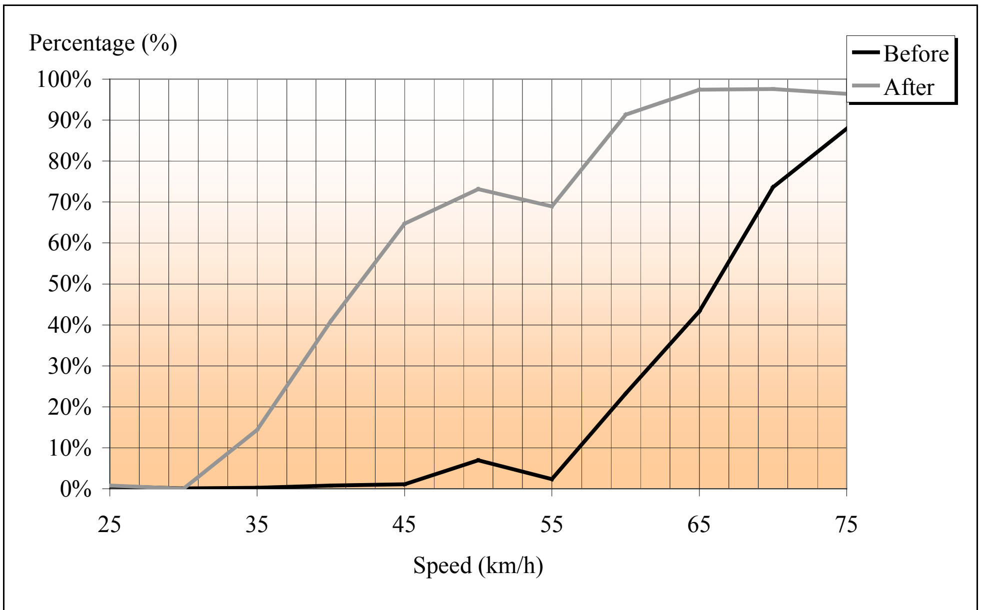

Figure 3.6 Percentage of driving in fifth gear at constant speed.

The principles of EcoDriving which state that the driver should not accelerate at an engine speed of more than 3,000 rpm and at more than half-throttle are based to some extent on the fact that there is otherwise a risk of large-scale emissions. The percentage of time that was spent at more than 3,000 rpm decreased from 4.5% before instruction to 3% after. Most of this percentage is the result of driving in top gear on the motorway in Köping. Figure 3.7

shows that the percentage of time spent at more than both half-throttle and three-quarter throttle more than doubled after instruction compared with before, despite the fact that the result should have been completely the opposite. It is very clear that either the instructors were not sufficiently clear in their instructions on this particular point or that the students failed to comply with their instructions.

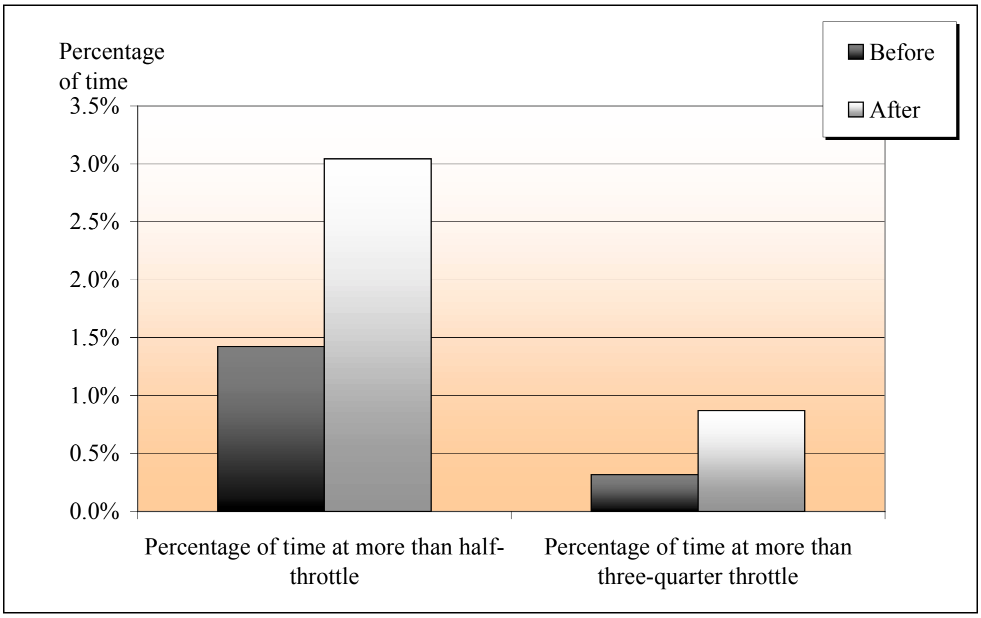

Figure 3.7 Percentage of time spent at more than half-throttle (pedal position) and more than three-quarter throttle before and after instruction.

3.2 Fuel consumption and emissions

As has already been mentioned, previous experience reveals that average fuel consumption decreases by more than 10% before and after instruction. In this study, fuel consumption declined by 10.9%. As the emission of carbon dioxide is directly proportional to fuel consumption, emissions of carbon dioxide also fell by 10.9%. This reduction was clearly significant and all the students reduced their fuel consumption. The 75th percentile was 14.5% (75% had a reduction of less than 14.5%) and the 25th percentile was 6.7% (25% had a reduction of less than 6.7%).

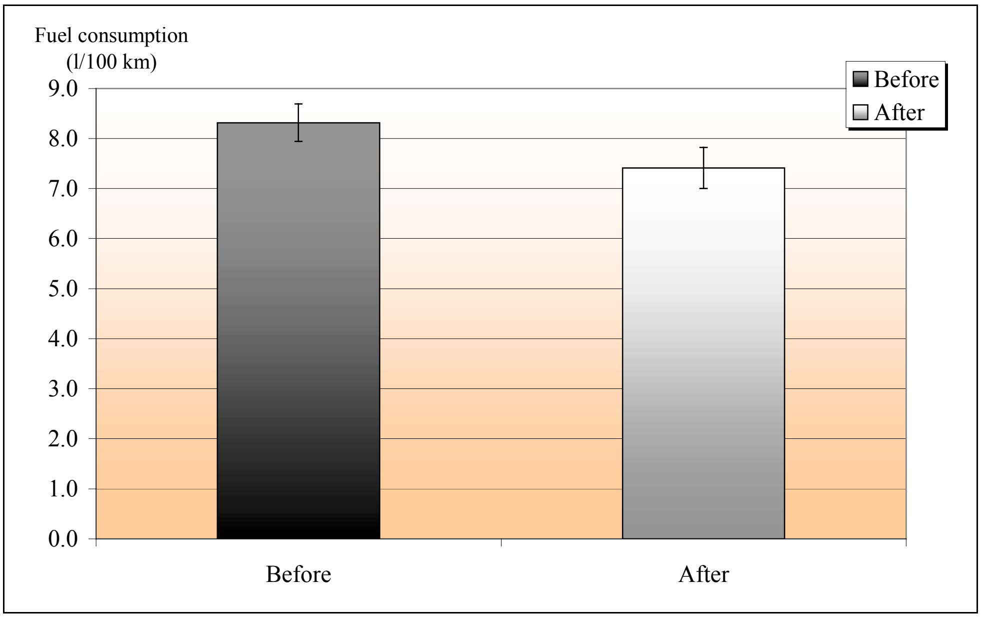

Figure 3.8 Fuel consumption before and after instruction. The line indicates the limits for the average value, including a 95 per cent confidence interval.

Figures 3.9-3.11 present emissions. There is a relatively large distribution in the emissions produced by different students' driving styles. This is also indicated by the standard deviations in the figures. The average emission of hydrocarbons and carbon monoxide increases, while that of nitrogen oxides decreases. At student level, however, the variation is substantial. Some students increase their emissions, while others reduce theirs from before instruction until after. Table 3.1 shows the average change in fuel consumption and emissions including a 95% confidence interval. The table also shows that only the reduction in fuel consumption is statistically secure.

Table 3.1 Change in fuel consumption and emissions including a 95 per cent confidence interval (i.e. the average value is within the interval with 95% security).

Parameter	**Change (%)**
Fuel consumption	-10.9±3.3
Carbon monoxide	+103±180
Hydrocarbons	+12±26
Nitrogen oxides	-16±23

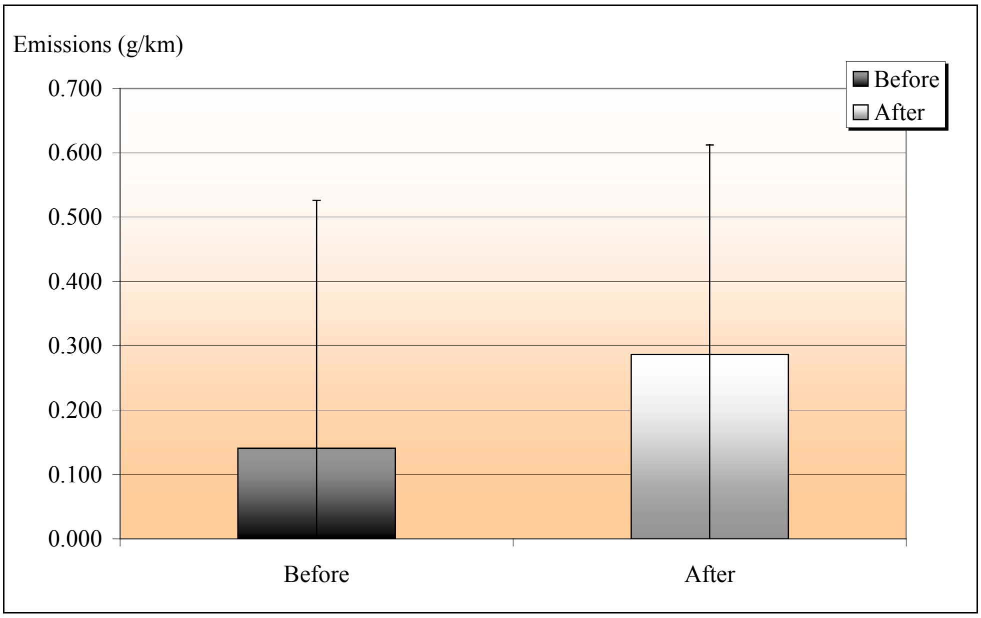

Figure 3.9 Emission of carbon monoxide before and after instruction. The line indicates the limits for the average value, including a 95 per cent confidence interval.

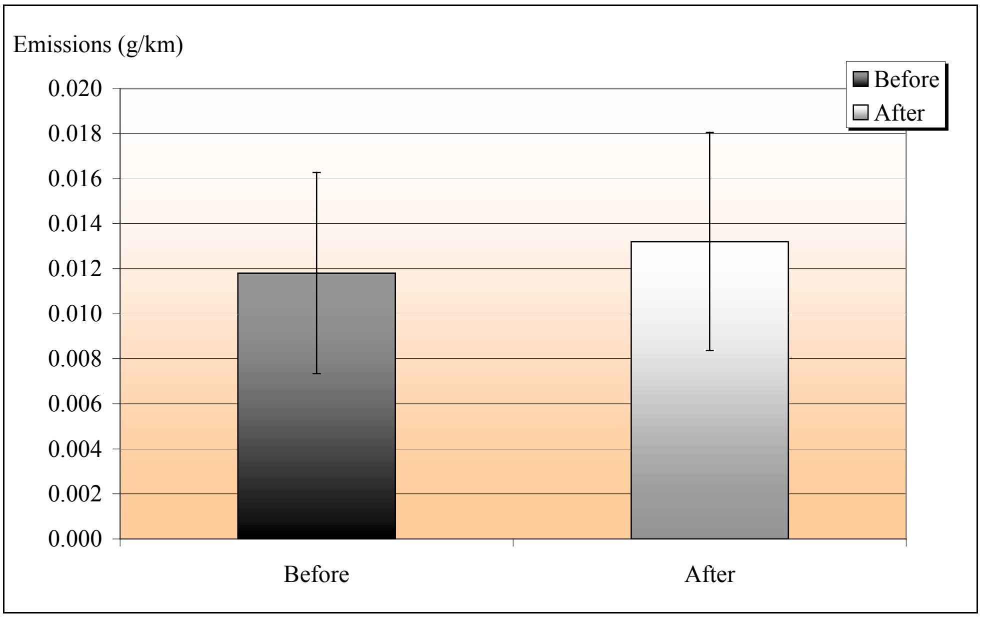

Figure 3.10 Emission of hydrocarbons before and after instruction. The line indicates the limits for the average value, including a 95 per cent confidence interval.

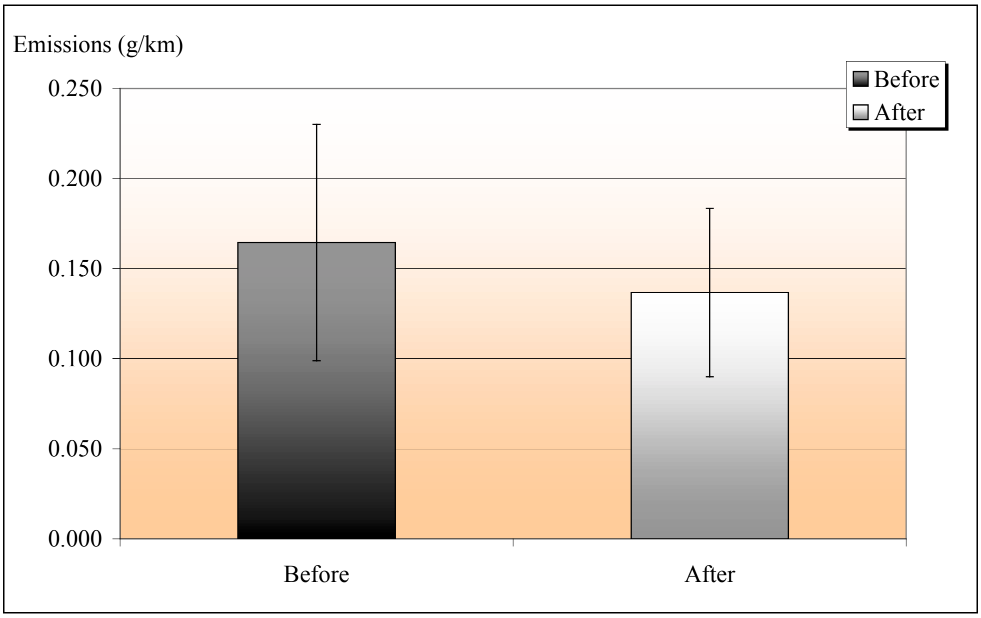

Figure 3.11 Emission of nitrogen oxides before and after instruction. The line indicates the limits for the average value, including a 95 per cent confidence interval.

3.3 Comparison of Econen and Rototest IVAS

Econen does not permit the storage of previous journeys either internally or via an output data channel in an external medium. In order to compare the measurement data from Econen with Rototest IVAS, we have therefore been obliged to rely on the instructors' notes on a form that was specially designed for this trial. In some cases, however, these notes were not complete. Comparisons have been made of four points, specific fuel consumption, total fuel consumption, driving distance and average speed.

According to measurements made with Econen, the specific fuel consumption (litres/10 km) decreases by an average of 11.2% for every journey. The same average for IVAS is 10.9%. The difference between Econen and IVAS could be due to calibration. Unlike IVAS, Econen is only calibrated at one point. The calibration of Econen is performed by dividing the logged volume of the fuel that is added (during refuelling) by the total measured injection time. It is then assumed that the relationship is linear and intersects the zero point, which it does not. As a result, Econen shows fuel consumption that is too low for short injection times and too high for long ones. In addition, the IVAS calibration is based on mass flow, while the Econen calibration is based on volume flow. If the density is changed, the results will deviate.

When calculating the total consumption (litres), all the journeys were used for IVAS, while only 22 of 32 were used for Econen. Information on the total consumption after instruction was missing for one journey. Total consumption was not noted for any of the four journeys in Solna. According to measurements with Econen, the total fuel consumption declined by an average of 12.1%. The same average for IVAS was 10.9%.

The first time the data was processed, it emerged that the measurement instructions had not be complied with satisfactorily for eight of the 16 individuals. It appeared that the car had not been turned off in connection with the test. After manual inspection, all the files have been changed so that the test began when the car started moving. The journeys in Solna were exceptionally poorly documented and this made it difficult to define the actual starting point of the test.

A calculation of the difference in driving distance between Econen and IVAS reveals that there is a difference of ± 2% between the measurements. The journeys from Solna also differ on this point.

The average speed was calculated inclusive of idling and these measurements reveal that Econen deviates from IVAS by ± 2%.

4 Discussion

Relatively comprehensive material relating to the effect economical driving styles have on fuel consumption is available (Ahlvik et al., 1999). When it comes to emissions, however, very little knowledge of the effects of economical driving styles (with the exception of carbon dioxide) has been available. This pre-study represents the first step in a process of obtaining a greater knowledge and understanding of the effects economical driving styles and EcoDriving in particular have on emissions.

It is important to point out that this study is only based on measurements made using one car. Even if the same emission standards are set for all the new cars that are sold within the EU, independent tests reveal that emissions vary very sharply (see Teknikens Värld (1999) and What Car? (1999)). This applies in particular to conditions that are not included in the European driving cycle. Surveys of driving styles in real-life traffic reveal that a significant part of the driving falls outside the European driving cycle (Johansson et al., 1999 and Ny Teknik, 1999). So the results relating to emissions should be regarded as more of an indication than an average value for the whole car population.

Although the basic vehicle material is very limited, the number of trial subjects is much larger. The number of trial subjects offers some opportunity to study the changes instruction brings about in terms of driving style, emissions and fuel consumption for a given vehicle. It also provides an opportunity to study the differences in behaviour between individuals and differences in the changes in behaviour that result from instruction.

The reduction in fuel consumption and the emission of carbon dioxide as a result of instruction was 10.9%. This result must be regarded as typical of the results produced by training in EcoDriving.

When it came to the change in emissions as a result of instruction, it was not possible to demonstrate any of the changes statistically. The emission levels were, however, in some cases very high both before and after instruction. If an ”environmentally-sound” driving style is to be offered, it is important to establish the causes of these high emissions.

4.1 Formation of emissions in an Otto engine with a catalytic converter

The conditions that are usually sought in an Otto engine (petrol engine) are that the amount of air is just right to ensure complete combustion, which is known as stoichiometric combustion. The surplus air is usually described using the letter λ (Lambda). In conjunction with stoichiometric combustion, $\lambda = 1$. If there is surplus air (lean), $\lambda > 1$ and, if there is surplus fuel (rich), $\lambda < 1$. A Lambda close to one (1) is also essential if the level of emission control in a catalytic converter is to be optimal (see Figure 4.1).

In the event of a fuel surplus in an Otto engine with catalytic emission control, the emissions of carbon monoxide and hydrocarbons are considerably higher than they are in situations in which stoichiometric combustion takes place. During lean combustion, on the other hand, the emissions of nitrogen oxides are higher. This only applies, however, if the combustion air is sufficiently hot. At a Lambda of more than 1.1, the formation of nitrogen oxides is reduced as a result of the lower temperature of the combustion air. The extreme case involves engine braking at engine speeds at more than 1,300 to 1,500 rpm when fuel injection is (usually) shut off in a modern petrol engine. In these conditions, no combustion takes place and nitrogen oxides is therefore unable to form. On the other hand, oxygen is stored in the catalytic converter during engine braking. The positive effect of this oxygen storage is that the conversion of hydrocarbons and carbon monoxide is extremely efficient. The disadvantage is that the conversion of nitrogen oxides is blocked to a greater or lesser degree. When combustion begins again, the oxygen stores are gradually utilised and the conversion level for nitrogen oxides increases. As engine braking is used on a large scale in EcoDriving, it is likely that the emission of nitrogen oxides in these conditions increases. Judging from the results, it would, however, appear that these emissions are not of any great significance (see Chapter 3.2).

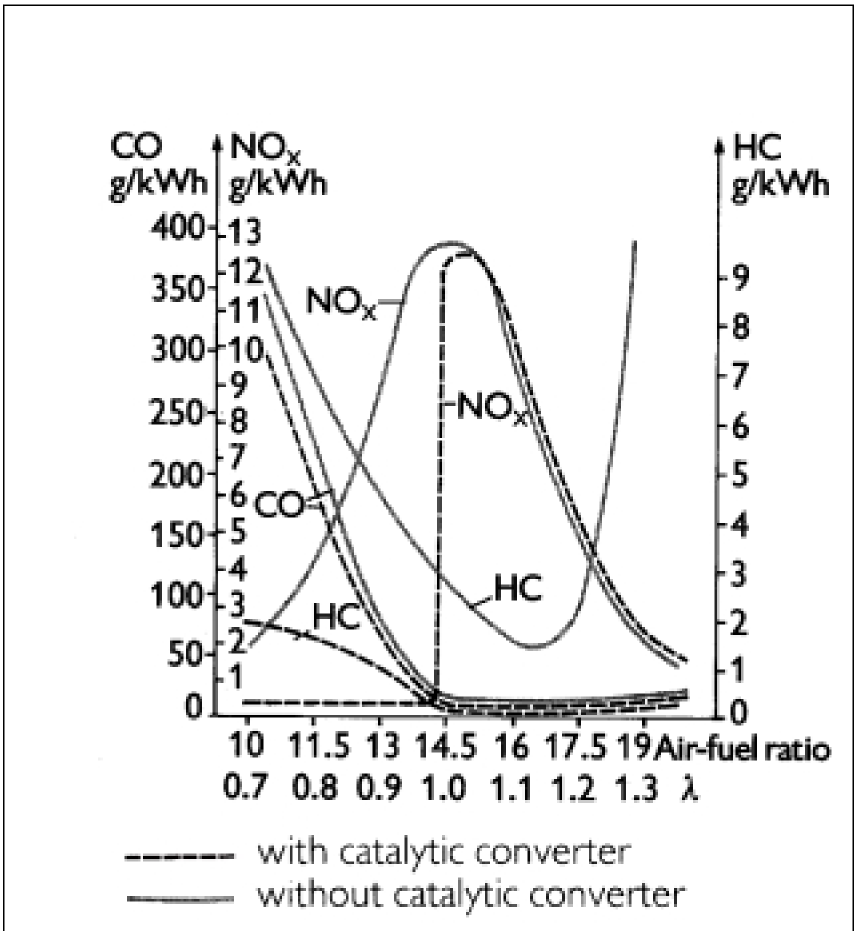

Figure 4.1 Emission control using a three-way catalytic converter (Bauman, 1988).

To obtain the cleanest possible emissions, the engine is equipped with what is known as Lambda control. This is a closed-loop control system which senses the oxygen concentration in the exhaust system and regulates the supply of fuel so that Lambda stays at around one. In conjunction with rapid changes in load, it is, however, difficult to keep Lambda at around one. The fuel mix is also often enriched, in conjunction with high loads and engine speeds which are frequently outside the driving cycles that are used for emission approval.

An indication of the way emission control functions in the vehicle in question is given in Figure 4.2. It shows how much output can be developed at different engine speeds in static conditions while maintaining full emission control, compared with the maximum output that can be obtained at the corresponding engine speed. By way of comparison, the results for another car model are also shown. In the case of the Golf, it is not possible to obtain completely full output from 3,000 rpm while maintaining a high level of emission control. The Volvo, on the other hand, is able to produce full output up to 4,000 rpm. At higher engine speeds, it is, however, possible to obtain more output from the Golf while maintaining emission control than from the Volvo. This demonstrates that emission control reacts in different ways in different car models.

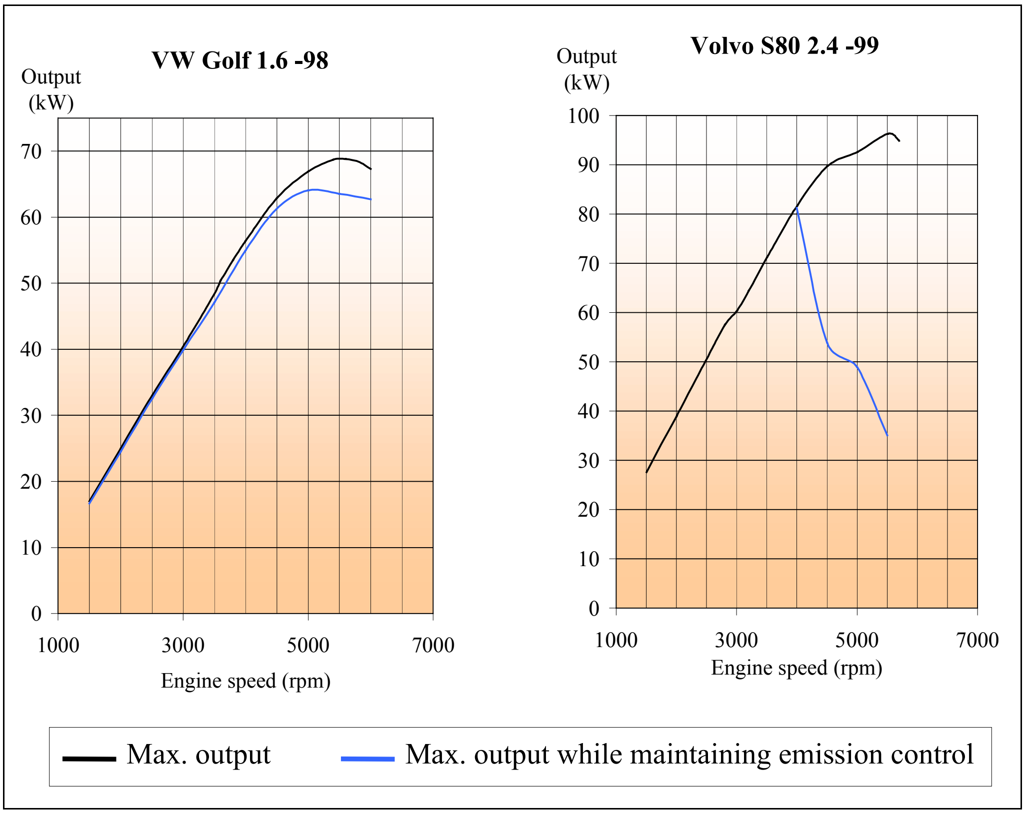

Figure 4.2 Maximum performance while maintaining emission control for a 1998 VW Golf 1.6 and a 1998 Volvo S80 2.4. The figure shows how much output can be obtained at different engine speeds in static conditions while maintaining full emission control, compared with the maximum output obtained at the corresponding engine speed. N.B. Different scales (source Rototest AB).

When the concept for EcoDriving was designed, an attempt was made to take account of emissions by issuing recommendations for maximum engine speed and maximum throttle. It is not within the framework of this study to investigate whether the limits for maximum throttle and engine speed have been correctly set. If recommendations of this kind are to be optimal, they must also be adapted to suit each individual car model, which is virtually impossible. The recommendations that exist must be regarded as a compromise based on knowledge of the vehicles that are used most frequently. The above results clearly demonstrate that these recommendations did not reach the students – at least when it came to maximum throttle. The percentage of driving that took place at more than half-throttle (pedal position) increased from an average of 1.4% before instruction to 3% after.

4.2 Causes of higher emissions of hydrocarbons and carbon monoxide

To identify the possible causes of the high emissions of hydrocarbons and carbon monoxide, we are going to study one of the journeys with high emission levels. We are primarily interested in the effects of EcoDriving and therefore choose a journey that produced higher emissions after instruction compared with before. Figure 4.3 shows the driving pattern and emissions of hydrocarbons for a student in Köping before and after instruction.

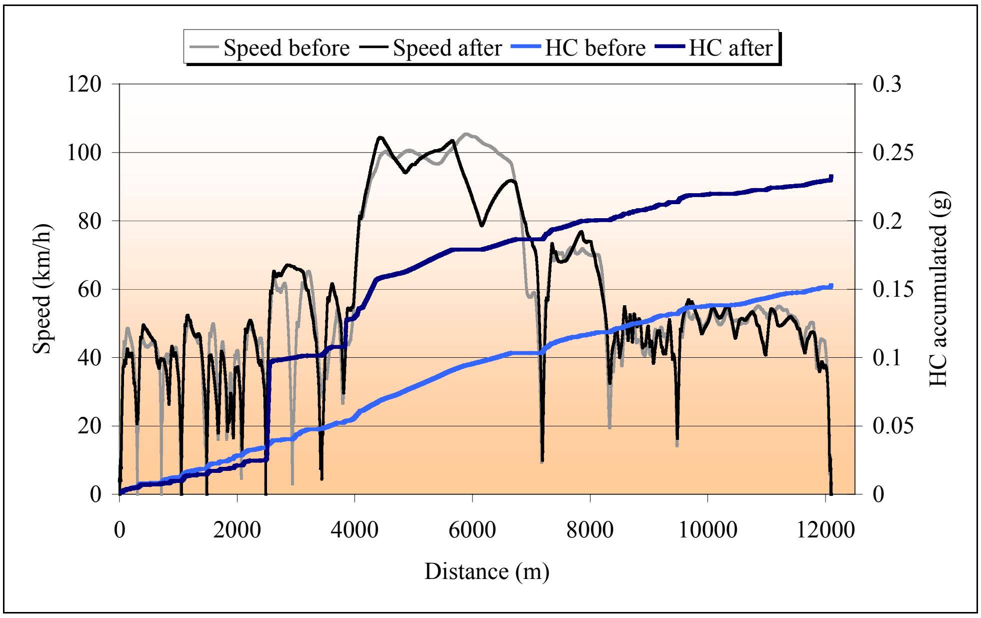

Figure 4.3 Driving pattern and emissions of hydrocarbons for a student in Köping before and after instruction.

The emissions can be divided into two components, a more continuous part and a part which tends to take the form of pulses. These pulses are a result of driving in the rich area. It is the part in pulses which causes the emissions to be higher after instruction compared with before. Figure 4.4 gives a detailed presentation of the part in which the pulsed emissions are produced.

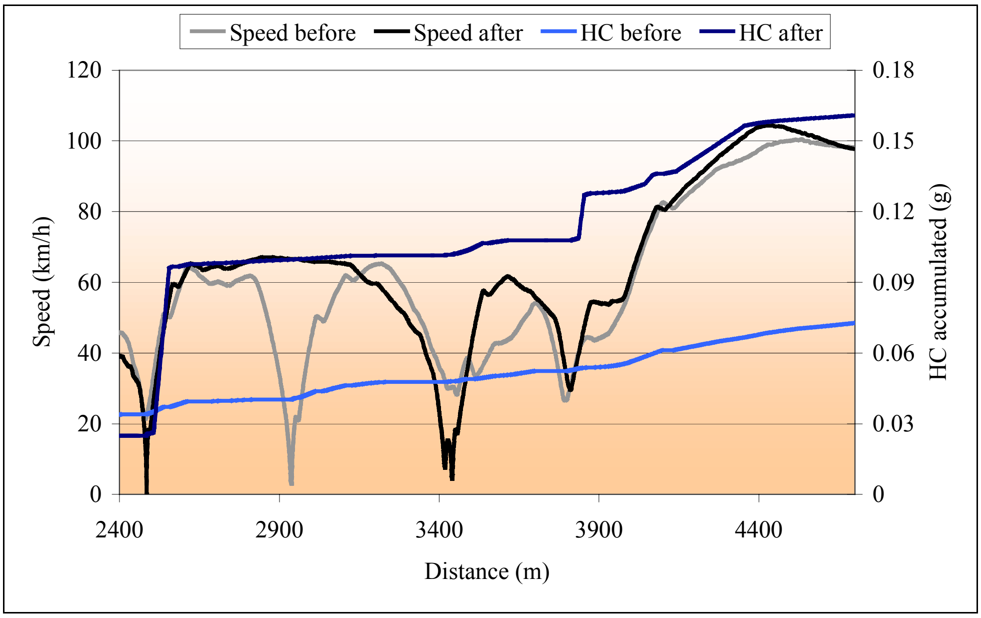

Figure 4.4 Details of driving pattern and emissions of hydrocarbons for a student in Köping before and after instruction.

The figure shows that the largest emissions are produced during acceleration. There could be several reasons for the increase in emissions. Chapter 4.1 mentions three causes, high engine speed, rapid changes in load and high engine load. In this case with the same vehicle and driving environment before and after instruction, the last two of these causes can be equated with rapid changes in throttle and full use of the throttle.

Figure 4.5 shows the engine speeds and emissions of hydrocarbons for the driving patterns in Figure 4.4.

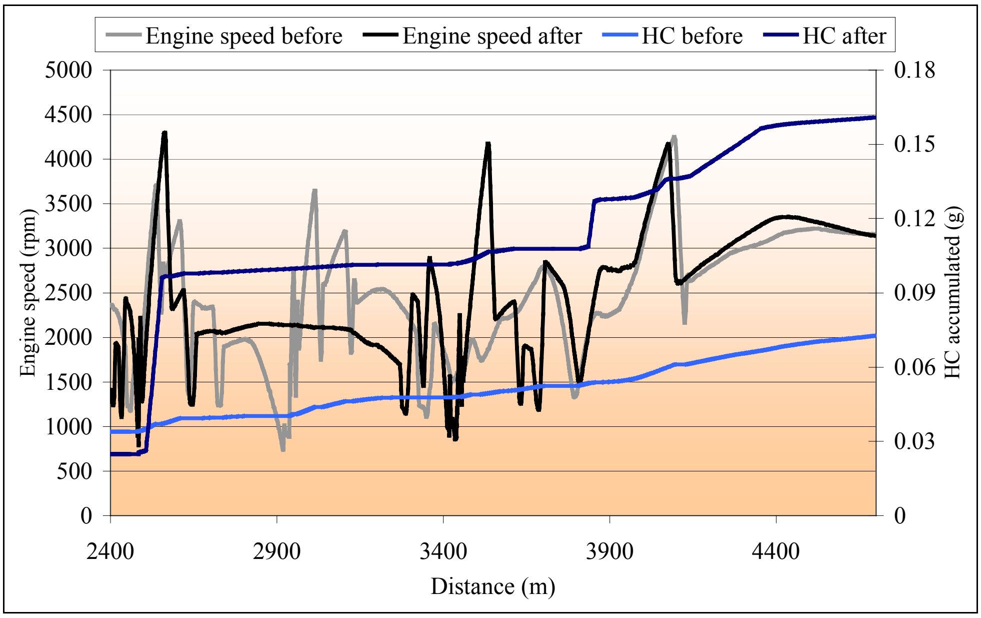

Figure 4.5 Engine speeds and emissions of hydrocarbons for the driving patterns in Figure 4.4.

As Figure 4.5 shows, there is some agreement between engine speed and emissions at 2,500, 3,500 and 4,000 metres. However, there are also occasions on which high emissions are discharged even though the engine speed is low, at 3,800 metres, for example, and to some degree between 4,100 and 4,400 metres.

Figure 4.6 shows the throttle (pedal position) and emissions of hydrocarbons for the driving patterns in Figure 4.4.

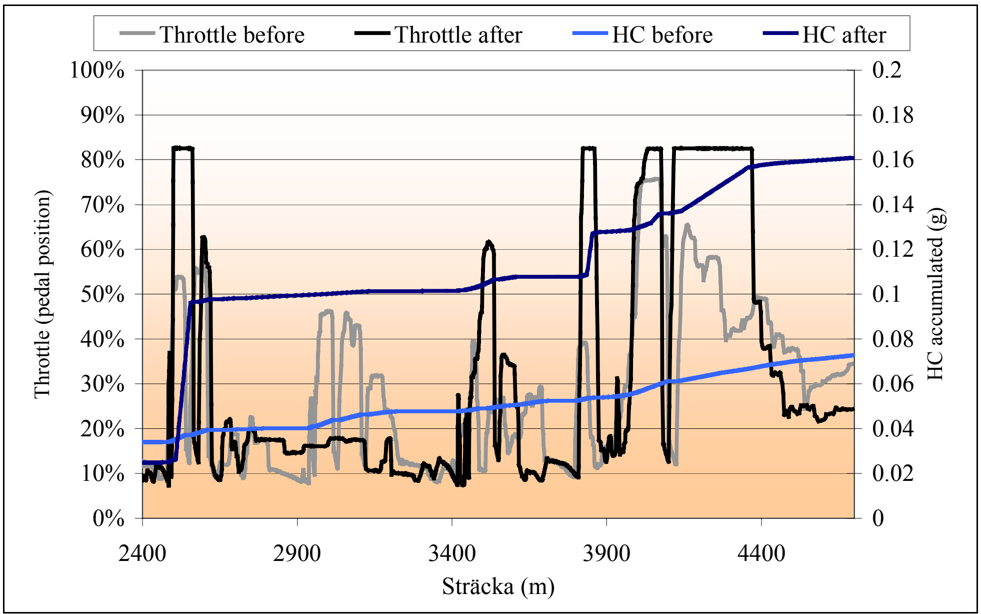

Figure 4.6 Throttle and emissions of hydrocarbons for the driving patterns in Figure 4.4.

In Figure 4.6, the high throttle after instruction is particularly striking. In actual fact, 82% throttle with the accelerator corresponds to a fully open throttle. Pressing the accelerator even closer to the floor has no effect in the car in question. Instead of using a maximum of half-throttle, this student has repeatedly driven at full throttle! The connection between the high throttle and the emission of hydrocarbons is far more clear cut than the connection with engine speed. The situation for carbon monoxide is virtually the same. The figure also shows that it is primarily the high throttle rather than the rapid changes in throttle that produces the large emissions. This is particularly clear when it comes to the distance between 4,100 and 4,400 metres. It is important to point out that, over the distance in question in Figures 4.4-4.6, no gains are made in the form of reduced fuel consumption after instruction compared with before instruction. Fuel consumption before instruction was 10.7 l/100 km, whereas it was 10.8 l/100km after instruction (over this distance).

The above results indicate that there is a connection between high throttle and the emission of hydrocarbons and carbon monoxide, at least as far as these journeys are concerned. To obtain a better picture of the effect of high throttle, it is also necessary to examine the remaining journeys. Figure 4.7 shows the relationship between the percentage of time spent at more than half-throttle and the average emission of hydrocarbons for all the journeys before and after instruction. The figure clearly demonstrates that there is a connection between a large percentage of time at more than half-throttle and large emissions of hydrocarbons. The same thing applies to carbon monoxide. It is interesting to note that there are journeys, especially before instruction, during which a relatively small percentage of time was spent driving at more than half-throttle. This shows that it is perfectly possible to drive at moderate throttle. This applies to all three test sites.

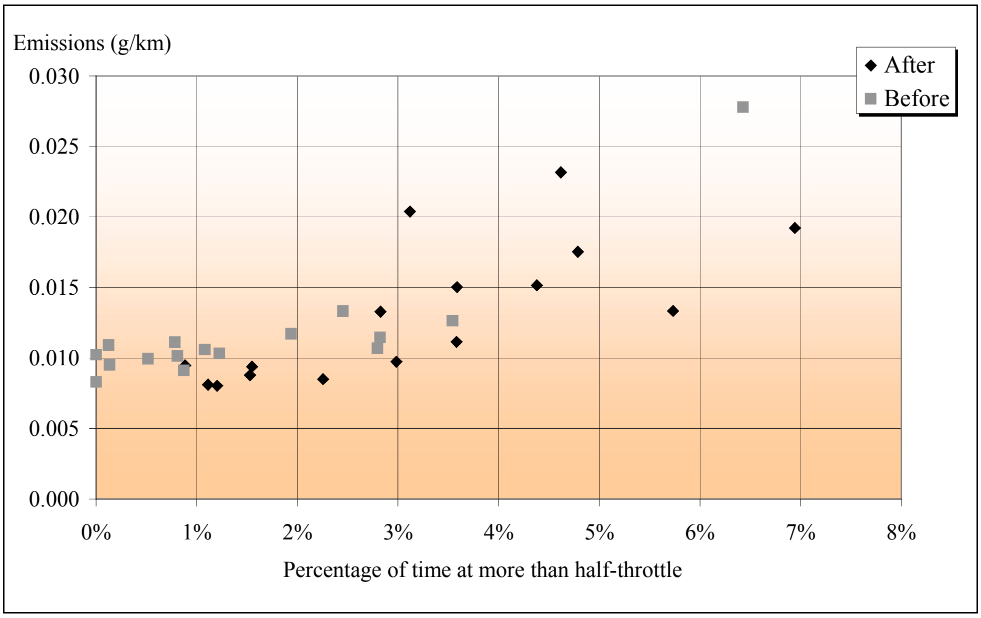

Figure 4.7 Relationship between percentage of time at more than half-throttle and emissions of hydrocarbons for complete journeys.

If only driving done at more than three-quarter throttle is taken into account, the relationship between high throttle and the emission of hydrocarbons becomes even clearer (see Figure 4.2).

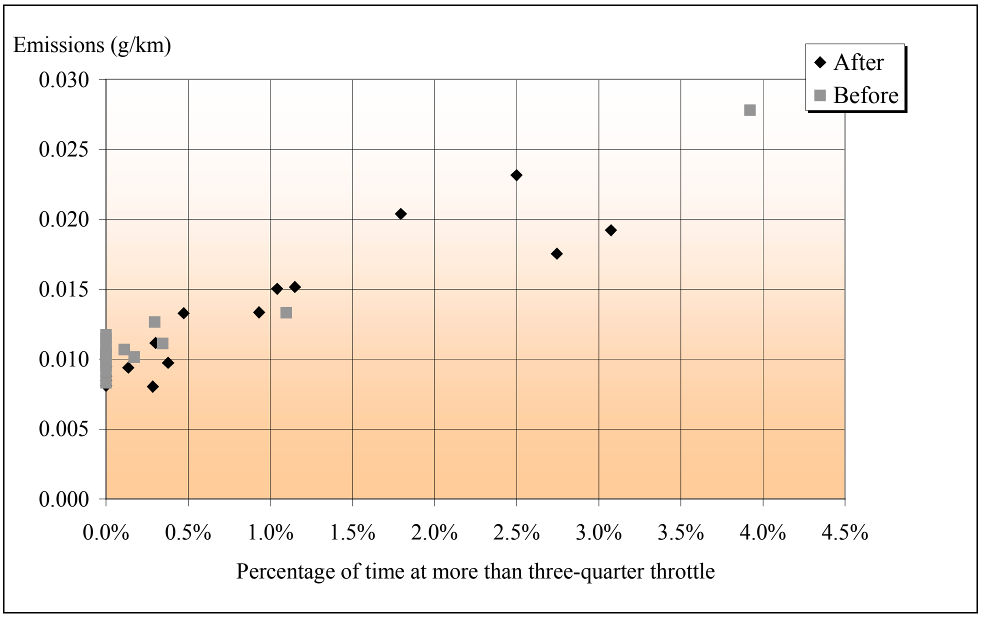

Figure 4.8 Relationship between percentage of time at more than three-quarter throttle and emissions of hydrocarbons for complete journeys.

4.3 Causes of higher emissions of nitrogen oxides

Figure 4.9 shows the relationship between the percentage of time at more than half-throttle and the emission of nitrogen oxides. As the figure shows, there is neither a positive nor a negative relationship between high throttle and nitrogen oxides emissions. The same thing applies to the relationship between the percentage of time at more than half-throttle and fuel consumption. This is an important conclusion as it indicates that the emission of hydrocarbons and carbon monoxide can be reduced by decreasing the amount of throttle, without any increase in fuel consumption and nitrogen oxides emissions.

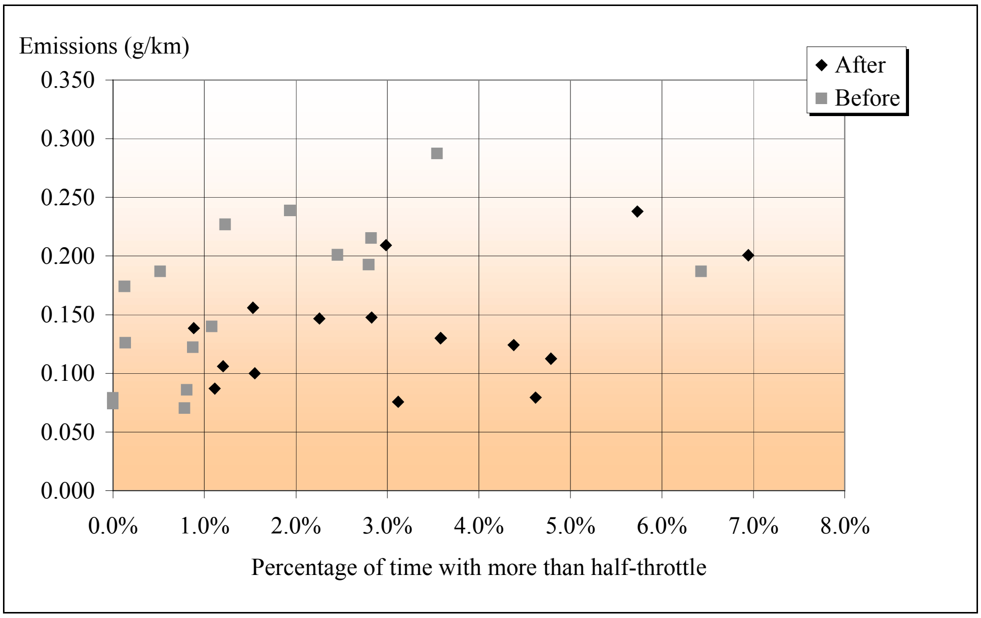

Figure 4.9 Relationship between percentage of time at more than half-throttle and emissions of nitrogen oxides for complete journeys.

Figure 4.10 shows the emission of nitrogen oxides for the same driving patterns and students as in Figure 4.3. As expected, the emissions of nitrogen oxides and hydrocarbons could be described as counterparts – high emissions of hydrocarbons do not occur at the same time as high emissions of nitrogen oxides and vice versa.

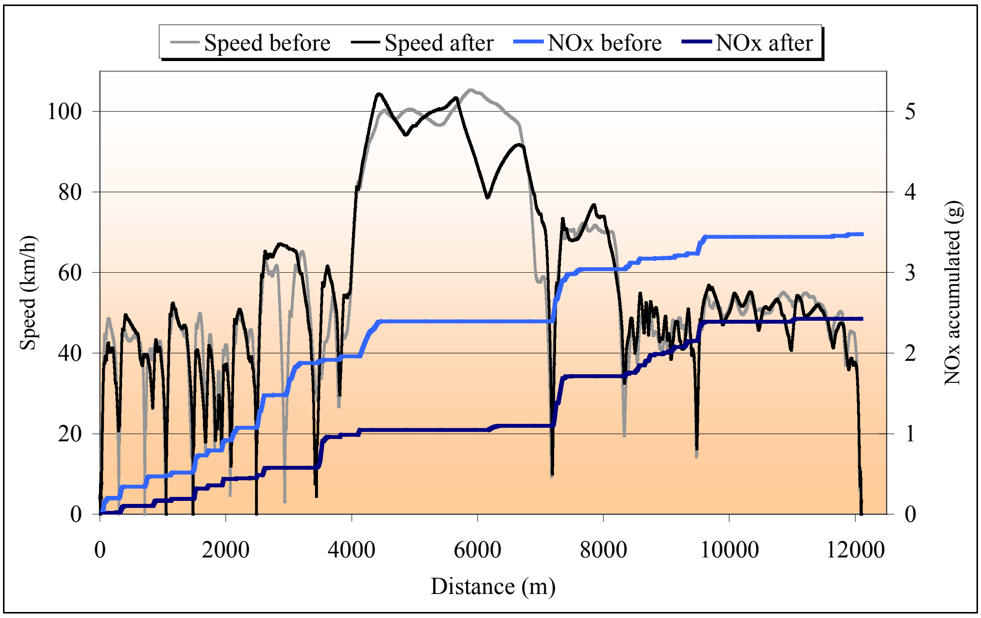

Figure 4.10 Emission of nitrogen oxides for the same driving patterns and students as in Figure 4.3.

Figure 4.11 shows a detail of the driving pattern and emissions in Figure 4.10. It shows that emissions are produced both when the driver accelerates hard and when driving is not smooth.

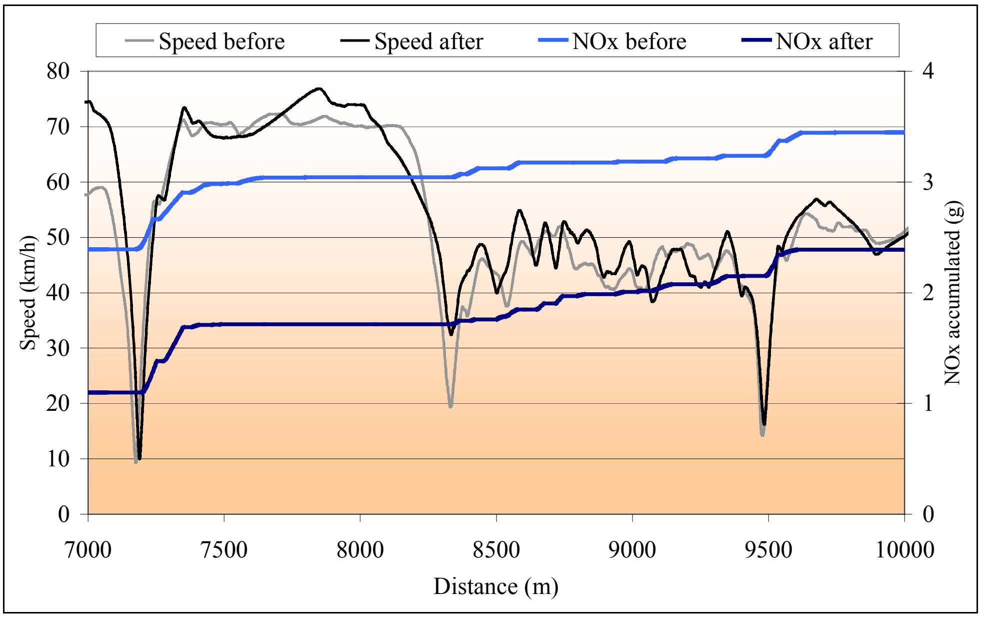

Figure 4.11 Details of driving pattern and emissions of nitrogen oxides in Figure 4.10.

The formation of nitrogen oxides in an Otto engine is a complicated problem which, in addition to being governed by the oxygen concentration and thereby by Lambda, is dependent on the combustion temperature. Emission control also plays a role. A number of different explanatory variables for the emission of nitrogen oxides were tested and engine speed was the one which best explained these emissions. An example of this is shown in Figure 4.12 for the driving patterns in Figure 4.11.

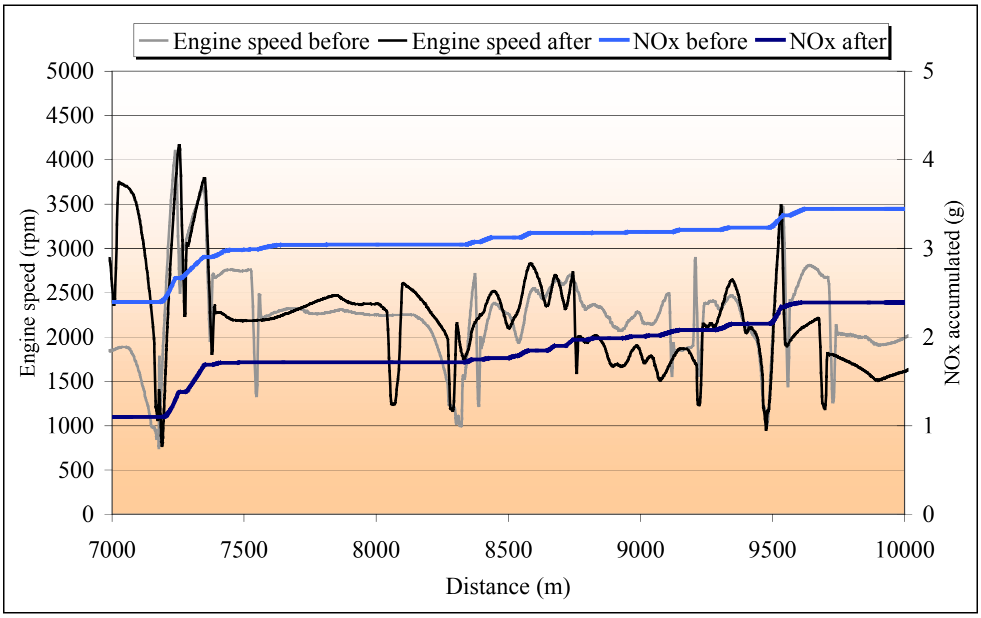

Figure 4.12 Engine speeds and emissions of nitrogen oxides for the driving patterns in Figure 4.11.

Figure 4.12 shows that engine speed primarily explained the higher emissions of nitrogen oxides at 7,200-7,400 metres and at 9,500-9,600 metres. The other emissions had other causes. There is no scope for an analysis of these causes within this pre-study.

Figure 4.13 shows the relationship between average engine speed and the emission of nitrogen oxides for the journeys before and after instruction in Köping. It should be pointed out that the relationship is not as clear cut in the other towns.

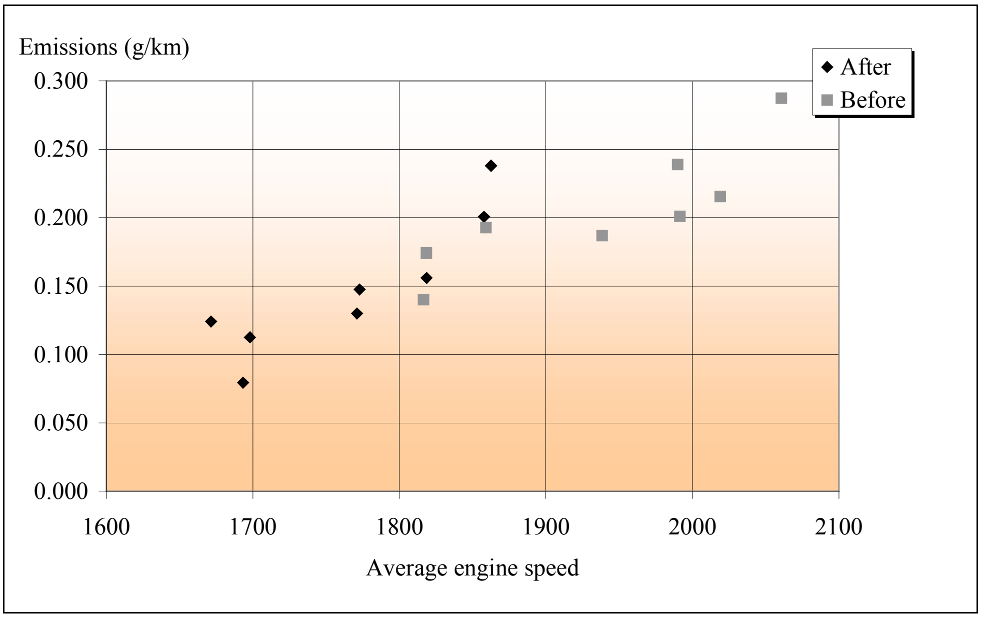

Figure 4.13 Relationship between emission of nitrogen oxides and average engine speed for the journeys before and after instruction in Köping.

4.4 Impact of EcoDriving

Chapters 3.1 and 4.2 both demonstrate that the driving style of several of the students deviated from the EcoDriving concept when it came to maximum throttle. There were large variations in the students' driving styles, however. Needless to say, it would have been best to have been able to divide the students into those who followed the concept and those who did not. However, no student followed the concept in every detail after instruction. To enable us to say something about the impact of EcoDriving on emissions, we have chosen to divide the students into two groups. The first group (Group 1) is made up of students who followed the concept to a large extent, while the second group (Group 2) comprises the students who followed it to a lesser extent. A definition of the two groups can be found in Table 4.1.

The idea is not that the recommendation of a maximum engine speed of 3,000 rpm should apply when driving in top gear on highways and motorways with high maximum permissible speeds. On the vehicle in question, 3,000 rpm was exceeded at 93 km/h in top gear. So, in the case of Köping, the percentage of driving that took place at 93 km/h or more in fifth gear has been excluded from the calculations of the percentage of time at which the engine speed exceeded 3,000 rpm.

Table 4.1 Definition of Group 1 who followed the EcoDriving concept to a large extent and Group 2 who followed it to a lesser extent. When calculating the percentage of time at which certain engine speeds were reached, the part of the driving in Köping that took place at more than 3,000 rpm in fifth gear has been excluded.

	Percentage of time after instruction at engine speeds of more than 3,000 rpm	**Percentage of time after instruction at more than half-throttle (pedal position)**
Group 1	< 2%	< 2%
Group 2	≥ 2%	≥ 2%

Figures 4.14-4.17 show the fuel consumption and emissions for the two groups both before and after instruction. By way of comparison, the effects in the form of an average value for the group are shown. Both groups contained students from all three towns, but they were not evenly distributed. Group 1 comprised one student from Köping, three from Jönköping and one from Solna. The results are, however, largely the same if the differences between the two groups are taken into account by means of weighting. In both groups, the percentage of time at more than half-throttle increased, while the percentage of time at more than 3,000 rpm decreased.

Two findings emerge from the figures.

1) Fuel consumption and emissions after instruction are lower on average for Group 1, the students who followed the recommendations relating to throttle and engine speed to a greater extent than those in Group 2. In the case of carbon monoxide and hydrocarbons, the emissions are significantly lower.

2) The average emissions are lower in Group 1 than in Group 2, even before instruction.

The second of these findings reveals that any interpretation of EcoDriving is influenced by the students' previous driving style. To rectify this situation, it is important to focus more heavily on training students who have a tendency to use more throttle and high engine speeds before instruction compared with students who already display good driving behaviour in this respect. While working on this report, this conclusion has also been passed on to the EcoDriving instructors.

It is difficult to say anything about the impact of EcoDriving on emissions on the basis of these results. One indication for the vehicle in question can be obtained by comparing the emissions after instruction for Group 1, who almost complied with the recommendations, with the emissions for all the students before instruction. On average, all the emissions are lower for the students who followed the recommendations after instruction compared with those for all the students before instruction. However, the limited material and the large distribution make it impossible to demonstrate any reduction statistically, with the possible exception of hydrocarbon emissions. The degree to which drivers who over-use the throttle can be re-trained is also uncertain.

More material is needed in order to demonstrate statistically the impact of EcoDriving on emissions. It would also have been advantageous if a control group had driven the routes twice without receiving any instruction on EcoDriving.

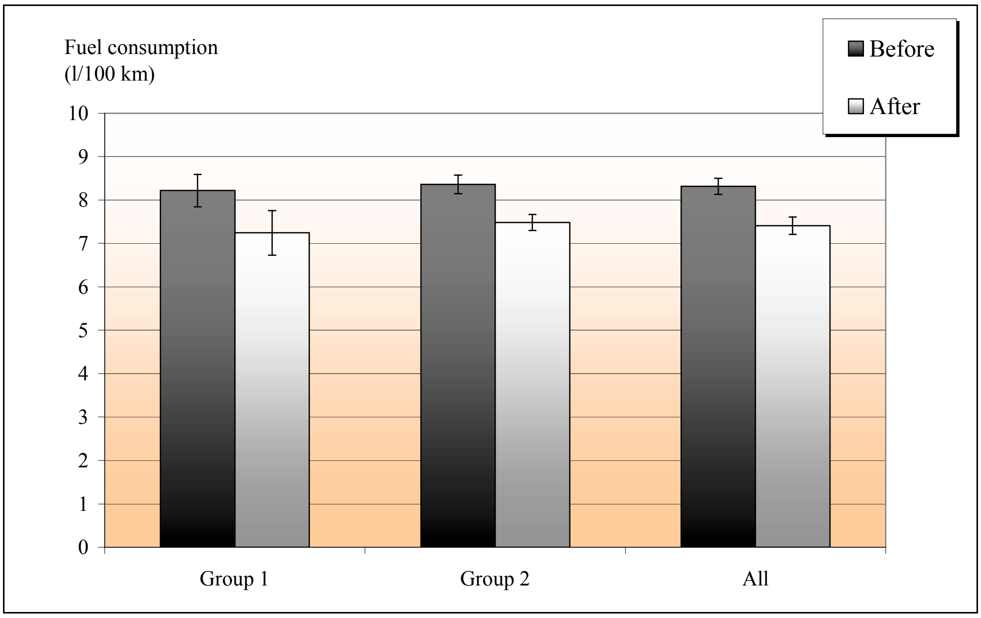

Figure 4.14 Fuel consumption before and after instruction for the two groups and the average for all the students. The lines mark the limits for 95 per cent confidence intervals for the average value.

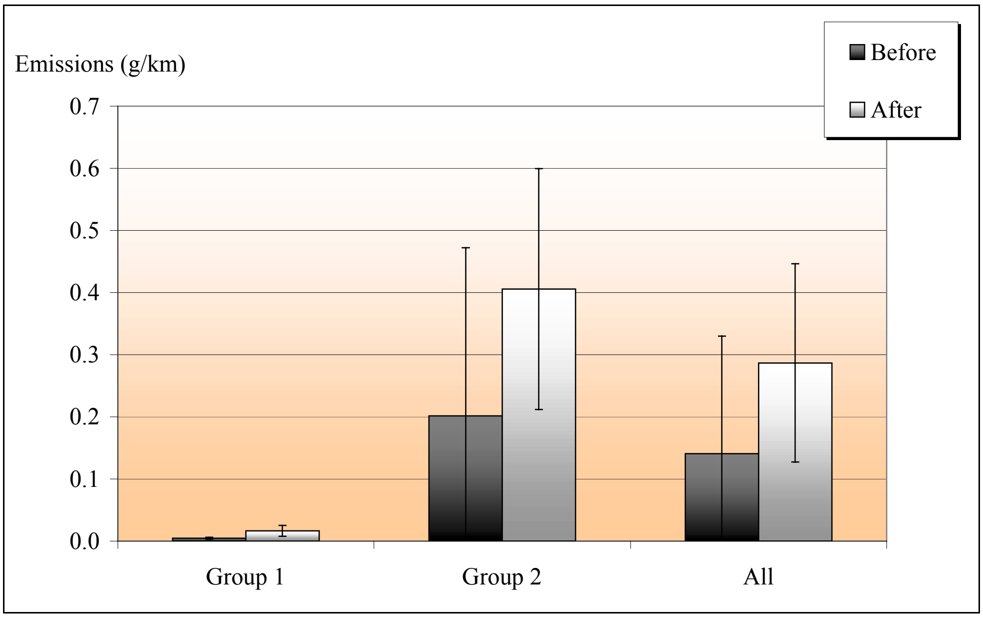

Figure 4.15 Emission of carbon monoxide before and after instruction for the two groups and the average for all the students. The lines mark the limits for 95 per cent confidence intervals for the average value.

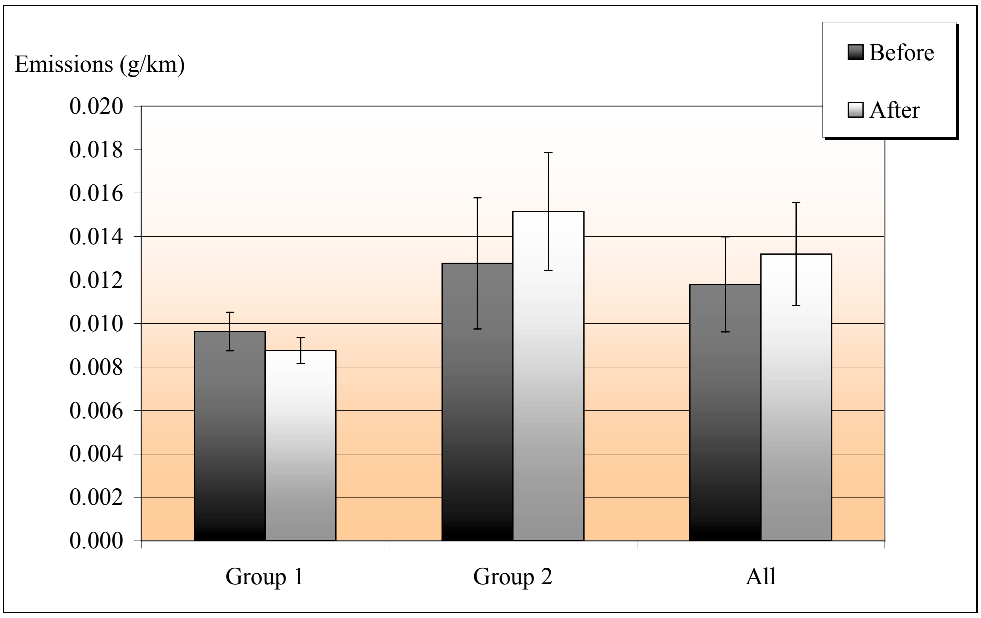

Figure 4.16 Emission of hydrocarbons before and after instruction for the two groups and the average for all the students. The lines mark the limits for 95 per cent confidence intervals for the average value.

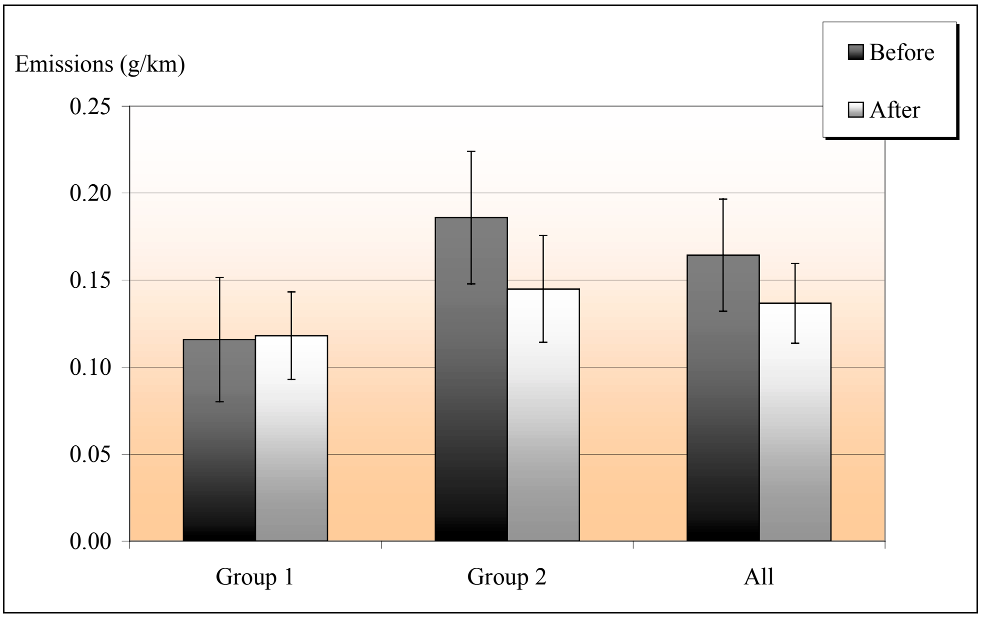

Figure 4.17 Emission of nitrogen oxides before and after instruction for the two groups and the average for all the students. The lines mark the limits for 95 per cent confidence intervals for the average value.

4.5 Further development of the measurement equipment used in training

The results in Chapter 3 reveal that Econen offers satisfactory precision when it comes to determining fuel consumption, driving distance and average speed. The prerequisite for this is, however, that it is calibrated with a sufficient volume of fuel.

The results for emissions reveal that emission control is very sensitive to driving style. As a first approximation, the recommendations in EcoDriving for a maximum of half-throttle and a maximum engine speed when accelerating of 3,000 rpm will definitely help, provided that the recommendations are complied with. The disadvantage of Econen and the present training set-up is that the students do not receive sufficient feedback on whether their driving has or has not resulted in low emission levels. It would therefore be beneficial if the vehicles that are used in the training could at least have some simple form of less complex measurement equipment to provide an indication of low or high emission levels.

One way of achieving this would be to use the signal from the Lambda sensor as an entry to a measurement instrument which shows the time or distance spent driving in rich areas and relevant lean areas. The second of these could be slightly more difficult using the kind of Lambda sensor which is normally fitted in standard cars, as it has basically only two values. Figure 4.18 presents a comparison between an original Lambda sensor and the Rototest IVAS broadband Lambda sensor. To simplify the comparison between the two sensors, the values for the original Lambda sensor have been adapted using a function. The figure shows that it should be possible to use the signal from the original Lambda sensor to provide some indication of the emission of hydrocarbons. This also applies to carbon monoxide.

In the case of nitrogen oxides, on the other hand, this is not as straightforward, as the original Lambda sensor senses no difference between a Lambda of just over one and the clean air that is produced when braking via the engine. Then there is the problem of oxygen storage. More research is therefore needed to obtain an indication when it comes to nitrogen oxides emissions.

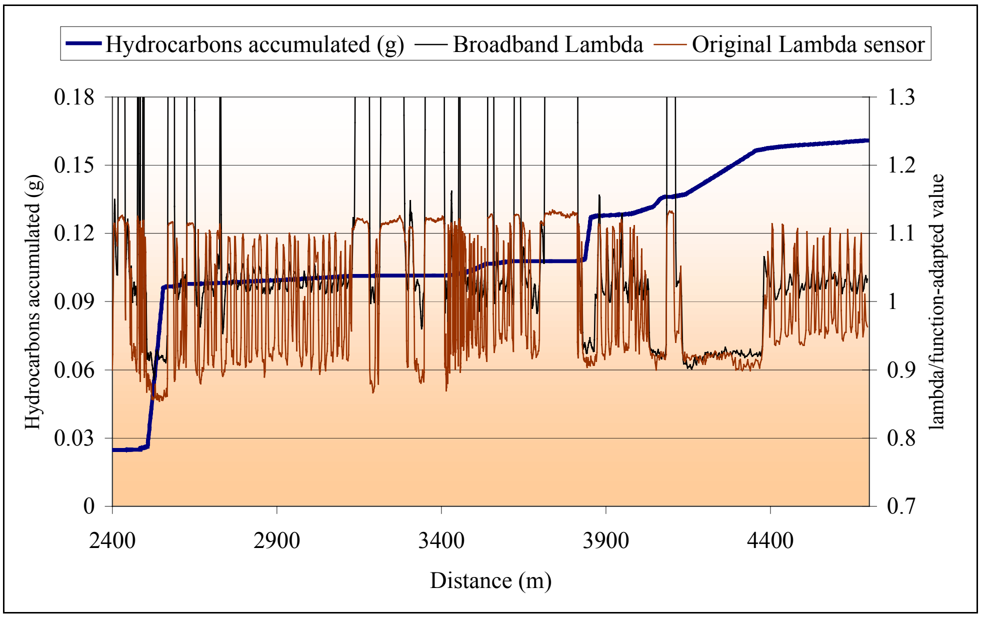

Figure 4.18 Comparison of a broadband Lambda sensor (Rototest IVAS) and an original Lambda sensor. To facilitate the comparison, the value from the original Lambda sensor has been adapted according to (-1(original +0.85).

5 Conclusions

- In the study, fuel consumption was reduced by an average of 10.9%, which should be regarded as typical for training in EcoDriving.

- Provided that the students follow the recommendations relating to maximum engine speed and throttle, emissions can be reduced by EcoDriving in the vehicle in question. The level of uncertainty is, however, high and these reductions cannot be demonstrated statistically, with the possible exception of hydrocarbon emissions.

- It is not actually possible to say anything about the way emissions would have been changed if another car with other emission characteristics had been used; the emissions could have both increased and decreased. It is, however, highly probable that the instructions relating to maximum engine speed and throttle increase the potential for reducing emissions.

- To demonstrate the impact of EcoDriving on emissions statistically, more extensive material than that used in this study is required.

- The students did not follow the recommendations in EcoDriving which relate to maximum throttle when accelerating. The percentage of driving at more than half-throttle (pedal position) doubled from before instruction to after. The recommendations relating to maximum engine speed when accelerating were also exceeded. This percentage did, however, decrease after instruction.

- There is a clear-cut relationship between the percentage of time at more than half-throttle and higher emissions of hydrocarbons and carbon monoxide. It was not, however, possible to demonstrate any relationship between the percentage of time at more than half-throttle and fuel consumption and the emission of nitrogen oxides. This indicates that the throttle can be reduced, thereby decreasing the emission of hydrocarbons and carbon monoxide, without increasing fuel consumption and the emission of nitrogen oxides.

- There is a clear-cut relationship between higher engine speed and an increase in the emission of nitrogen oxides.

- The students who had an aggressive driving style before instruction usually also retained this style after instruction. To rectify this situation, it is necessary to focus more heavily on the recommendations relating to maximum throttle and engine speed for these students.

- Econen provides sufficient precision when it comes to determining fuel consumption, driving distance and average speed.

- To provide the students with feedback on whether their driving has or has not resulted in low emission levels, the instructors' cars should contain equipment which provides some indication of emissions. In the case of hydrocarbon and carbon monoxide emissions, the signal from the Lambda sensor can probably be used for this purpose. In the case of nitrogen oxides, it is probably somewhat more difficult to obtain an indication of emissions.

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