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EXHAUST EMISSIONS AT HIGH SPEEDS FROM ADVANCED TECHNOLOGY CARS

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CONTENTS

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ABSTRACT

New legislation in the European Community (EC) will significantly reduce allowable exhaust emissions from cars and include higher speeds in the emission test cycle. These changes will make it necessary for cars to be equipped with more effective emission control systems. This report describes the measurement of exhaust emissions from three types of car at steady speeds up to 130 km/h. One type of car was built to comply with EC directive 83/351/EEC and had no specific emission control system, another had a controlled three-way catalyst and the third had a lean-burn engine with an oxidation catalyst. At speeds over 110 km/h all cars emitted substantially increased rates of hydrocarbons and carbon monoxide, with a decrease in the rate of emission of oxides of nitrogen. Overall, the emission controlled cars produced substantially lower emissions at high speeds than the car without catalyst. The fuel consumption of the lean-burn cars was consistently lower than that of the other cars.

1 INTRODUCTION

Within the European Community (EC), agreed amendments to current legislation will significantly reduce the allowable exhaust emissions from cars. Substantially lower limits for the emission of carbon monoxide, hydrocarbons and oxides of nitrogen will apply from the end of 1992 and an extra-urban cycle will be included in the type approval test procedure to provide a means of testing vehicle emissions at speeds up to 120 km/h, supplementing the existing low speed urban cycle.

Until now, it has been possible for manufacturers to satisfy emissions requirements by relatively minor adjustments such as better control of fuelling and ignition timing, but the agreed changes in the regulations will make it necessary for cars to have superior emission control systems. The most effective available technology for exhaust emission control is the three-way catalyst, which may be used with engine control systems of varying complexity to reduce carbon monoxide, hydrocarbons and oxides of nitrogen.

There has also been considerable interest and research into lean-burn engines, which potentially reduce fuel consumption as well as emissions of carbon monoxide and oxides of nitrogen. These engines operate at air/fuel ratios of 20–25:1, compared to the ratios 14–18:1 used in conventional engines. Because the exhaust contains surplus oxygen, they may be equipped with an oxidation catalyst to give further control of hydrocarbon and carbon monoxide emissions, but they cannot be used with a three-way catalyst to obtain the reduction of oxides of nitrogen.

The exhaust emissions from six medium-sized (1.6 Litre) cars have been studied over 50,000 miles. Two of the cars had lean-burn engines and oxidation catalysts and two were fitted with fully-controlled three-way catalysts. Both of these types of car were manufactured for sale in Japan. The remaining two cars had no special emissions control equipment and were manufactured to comply with EC Directive 83/351/EEC. All three types of car were powered by variants of the same engine and engine management system so that a direct comparison could be made between the emission control methods.

These cars were also used in work contributing to the development of the new high-speed test cycle, and, in order to provide information on their emissions performance at high speed, a series of special tests was carried out on one of each type of car. This report gives details of these high-speed tests to supplement the results for lower steady speed tests. Reports on the other aspects of the study of these vehicles are in preparation.

2 EXPERIMENTAL PROCEDURE

For the overall test programme two examples of each type of car were used. They were driven for official duties and personal activities by many members of TRRL staff. Each car was subjected to a wide range of emissions tests on a chassis dynamometer at TRRL every 5000 km. The specifications of the cars are given in Table 1.

The cars were tested in early 1988, near the end of the main test programme, when they had covered between 45,000 and 49,000 miles. The tests were carried out at the Motor Industries Research Association (MIRA) because the dynamometer at TRRL was subject to a speed limitation of 100 km/h.

The relationship between speed and vehicle drag for the dynamometer was set to provide coastdown times measured at TRRL and listed in

TABLE 1

Vehicle Specifications

Model	Toyota Carina SG (car 1)	Toyota Carina ST (car 2)	Toyota Corolla (car 3)
Engine type	4A-ELU (Lean burn)	4A-ELU (3 way cat)	4A-GE
Engine size (L)	1.6	1.6	1.6
Power DIN kW	NA	NA	89 @ 6600rpm
SAE (net) kW	73.5 @ 5600rpm	73.5 @ 5600rpm	86 @ 6600rpm
Fuel consumption			
(L/100 km) ECE15	NA	NA	8.8
Japanese 10 mode	5.9	6.9	8.1
Fuel injection	Sequential	Parallel	Parallel
Compression ratio	9.3:1	9.0:1	10.0:1
Exhaust treatment	Oxidation catalyst	Three-way catalyst	None

Table 2. Cars 1 and 2 were very similar and hence the same data (actually measured on car 2) were applicable. For car 3, the measured coastdown times, when used with a standard curve-fitting program, gave an anomalous coastdown curve that did not decrease in gradient with a decrease in speed. The difference in coastdown data for cars 2 and 3 was small, and because of the limited time available for the project, it was decided to use the same coastdown data, those for car 2, for all three cars.

During the main programme sets of tests were carried out on these cars at intervals of approximately 5000 km. Emissions were measured at steady speeds between 60 and 100 km/h in the laboratory during each test sequence. Each test lasted approximately five minutes, and was preceded by a five minute conditioning period at the same speed. The tests were all carried out with the vehicles fully warmed up and in fifth gear. The high-speed tests were designed to supplement this information and followed the same format. In order to confirm the consistency of results obtained at TRRL during the main programme and during these tests, measurements were made at 60, 80 and 100 km/h, as well as at the higher speeds of 110, 120 and 130 km/h.

Sampling was carried out using a constant volume sampler and the exhaust emissions were analysed using a flame ionisation detector for hydrocarbons, the chemiluminescent method for oxides of nitrogen and non-dispersive infrared gas analysers for carbon monoxide and carbon dioxide. Fuel consumption was calculated by the carbon balance method. It was initially intended to test all the cars at speeds up to 160 km/h. Above 130 km/h overheating of the exhaust system, tyres and sampling equipment became a serious problem, and the speed range was curtailed.

TABLE 2

Load setting data

Coastdown times	
100.0 – 80.0 km/h =	11.5 s
80.0 – 70.0 km/h =	7.3 s
55.0 – 45.0 km/h =	10.4 s
Inertias	
Car 1&2	= 2500 lbs
Car 3	= 2250 lbs

3 RESULTS

Six tests at each test speed were carried out on each car. Some of the results from similar tests showed considerable variation, giving rise to high standard deviations. In some cases this was caused by one very high value in the set rather than more general variation of the results. In these cases, the test records were re-examined to ensure that no sampling or analysis errors had caused the inconsistencies and any dubious results were discarded. The mean results thus obtained, with standard deviations, are shown in Table 3. Similar effects have been observed in other tests during the main test programme, confirming that these vehicles did, on occasion, display anomalous behaviour, and these outlying results have not been discarded. The reason is not known with certainty but, because the engine timing and fuelling of these cars were electronically controlled, it is likely that the changes in emission rate reflect a stepwise change in one or more engine parameters when the test condition was near to a transitional point.

In order to check consistency, the results of steady speed tests at 60, 80 and 100 km/h that were carried out at TRRL immediately before the high-speed tests were compared with those shown in Table 3. The results at both TRRL and MIRA for the tests at these speeds were in general very similar. Figure 1 shows a comparison of these steady speed tests at 60, 80 and 100 km/h.

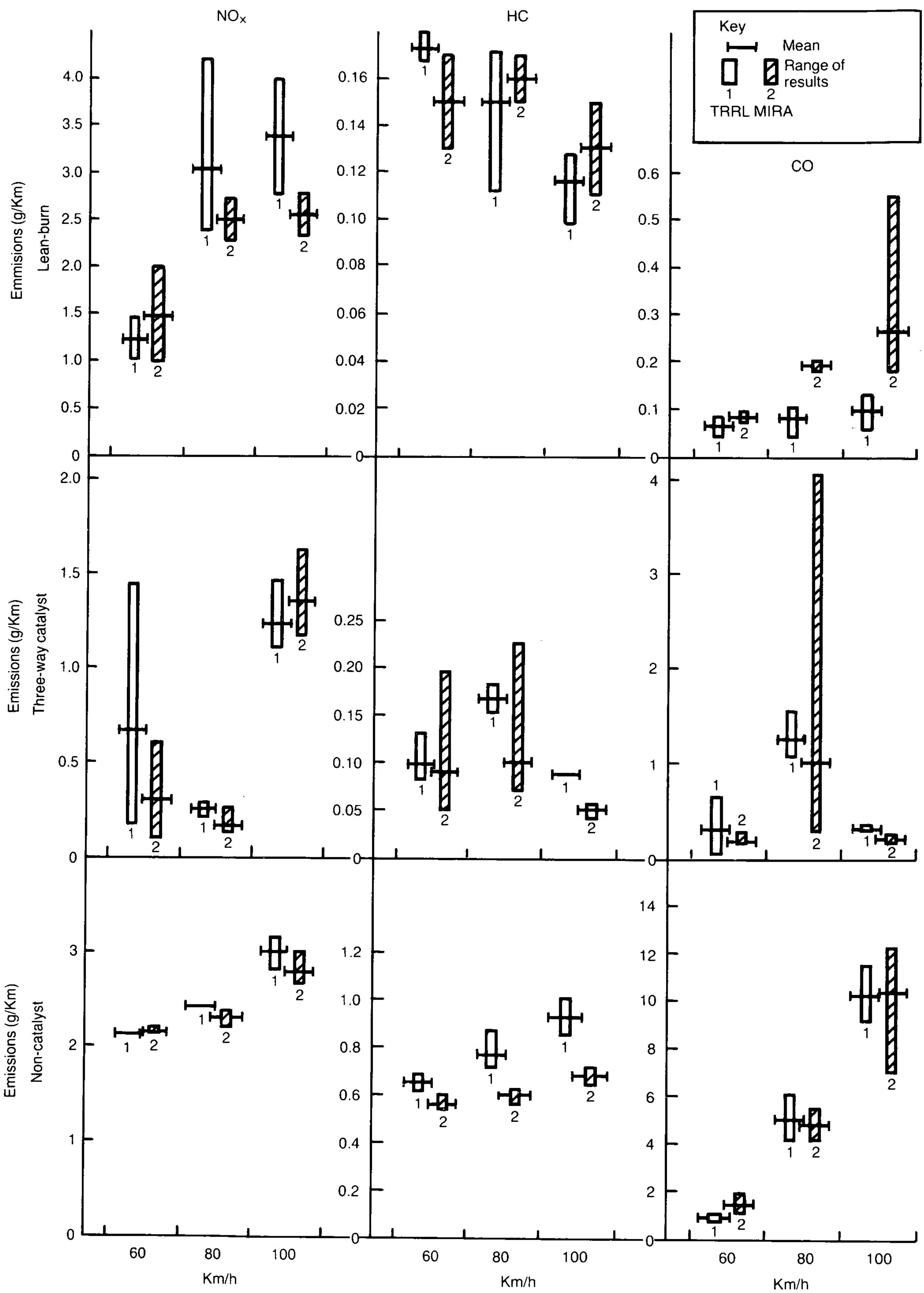

Fig. 1 Comparison of steady speed tests at TRRL with those at MIRA

TABLE 3

Means and standard deviations of emission and fuel consumption measurements

Test speed (km/h)	Emission rates (g/km)			Fuel cons (L/100 km)
	NOx	HC	CO	
Car 1. Lean-burn engine plus oxidation catalyst				
60km/h	1.45 (0.37)	0.15 (0.015)	0.08 (0.010)	3.78 (0.10)
80km/h	2.50 (0.18)	0.16 (0.009)	0.19 (0.012)	4.55 (0.086)
100km/h	2.55 (0.15)	0.13 (0.015)	0.26 (0.14)	5.49 (0.13)
110km/h	3.34 (0.30)	0.15 (0.008)	0.23 (0.084)	6.33 (0.14)
120km/h	1.08 (1.14)	0.20 (0.090)	4.86 (3.62)	7.49 (0.18)
130km/h	0.96 (1.45)	0.47 (0.22)	29.5 (16.4)	8.91 (0.80)
Car 2. Three-way catalyst				
60km/h	0.30 (0.20)	0.09 (0.056)	0.18 (0.046)	4.50 (0.088)
80km/h	0.17 (0.048)	0.10 (0.061)	1.02 (1.50)	5.36 (0.080)
100km/h	1.35 (0.18)	0.05 (0.005)	0.21 (0.027)	6.15 (0.27)
110km/h	1.73 (1.02)	0.06 (0.003)	0.21 (0.097)	7.17 (0.084)
120km/h	0.76 (0.31)	0.57 (0.030)	34.1 (3.60)	9.16 (0.22)
130km/h	0.59 (0.15)	0.54 (0.050)	32.1 (3.44)	9.48 (0.28)
Car 3. Without catalyst				
60km/h	2.16 (0.029)	0.56 (0.021)	1.39 (0.31)	4.74 (0.076)
80km/h	2.30 (0.053)	0.60 (0.023)	4.81 (0.57)	5.63 (0.062)
100km/h	2.84 (0.13)	0.68 (0.025)	10.4 (1.89)	6.85 (0.24)
110km/h	3.86 (0.49)	0.62 (0.072)	6.94 (2.13)	7.84 (0.70)
120km/h	3.55 (0.93)	0.79 (0.29)	9.01 (1.07)	8.41 (0.091)
130km/h	1.80 (0.80)	1.12 (0.31)	43.5 (19.7)	9.62 (1.89)

Figures in parentheses are standard deviations.

4 DISCUSSION

The rates of emission from these cars are governed principally by the air/fuel ratio of the mixture entering the engine and, in the case of the two catalyst-controlled cars, the efficiency with which the catalyst operated under the particular test conditions.

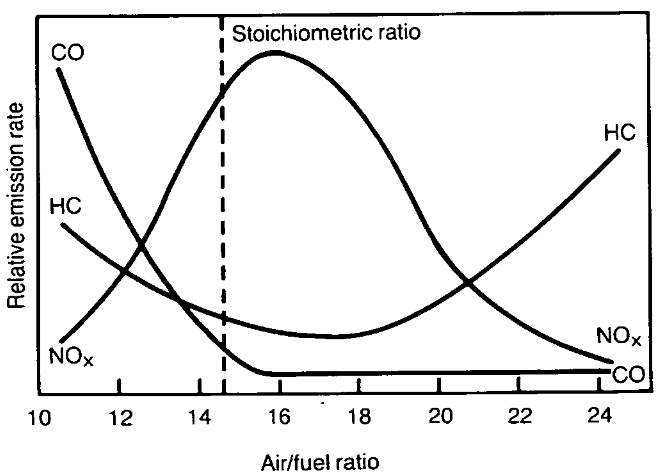

Fig. 2 Effect of air/fuel ratio on emissions from typical engines
(from Gruden, 1985)

Figure 2 (from Gruden, 1985) shows typical effects of air/fuel ratio on emissions of oxides of nitrogen, hydrocarbons and carbon monoxide. A stoichiometric air/fuel ratio produces a mixture in which the amounts of air and fuel are sufficient for each to react completely during combustion. The stoichiometric ratio is approximately 14.6:1. At this ratio, emissions of oxides of nitrogen are relatively high while carbon monoxide and hydrocarbon emissions are relatively low. As the mixture becomes richer than stoichiometric (lower air/fuel ratio), emissions of oxides of nitrogen decrease rapidly, while those of carbon monoxide and hydrocarbons increase. As the mixture becomes progressively leaner than stoichiometric, there is an initial increase in emissions of oxides of nitrogen but at ratios greater than approximately 17.5:1 they again decrease rapidly. Those of hydrocarbons and carbon monoxide decrease slightly, with carbon monoxide emissions remaining at a low value for all lean mixtures while hydrocarbon emissions increase when the ratio is greater than approximately 17.5:1.

Figure 3 shows the air/fuel ratio calibration map for the Toyota lean-burn system (Matsushita et al, 1985). For a large part of the map, the air/fuel ratio is greater than 20:1 and will result in low carbon monoxide and oxides of nitrogen emissions. However, under some circumstances, such as at idle, high load or high engine speeds, it is necessary to operate at a lower air/fuel ratio to obtain satisfactory performance and driveability from the car. Different rates of emission will result under these conditions.

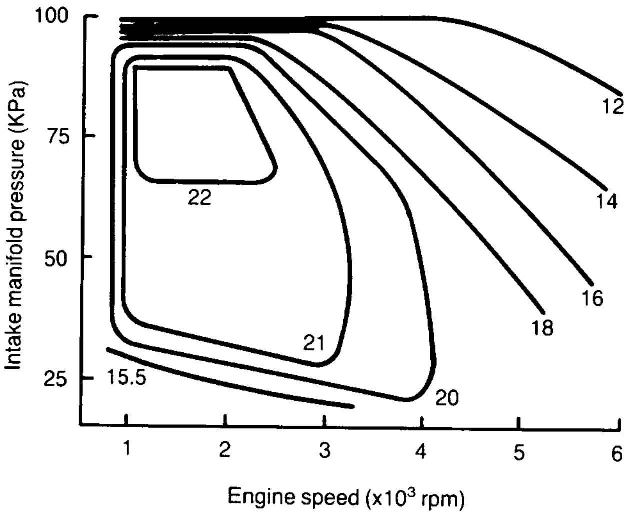

Fig. 3 Air/fuel ratio calibration map for the Toyota lean-burn system
(from Matsushita et al, 1985)

In addition to its direct effects on exhaust pollutant formation, the air/fuel ratio is also of primary importance for the effective operation of exhaust catalysts. Three-way catalysts operate by reducing oxides of nitrogen and oxidising both carbon monoxide and hydrocarbons, producing carbon dioxide, water and nitrogen. These reactions require the amount of oxygen in the exhaust to be carefully controlled. An excess of oxygen, caused by operating at a high air/fuel ratio, will prevent reduction of oxides of nitrogen, while insufficient oxygen, when the air/fuel ratio is low, means that oxidation will be incomplete. The optimum air/fuel ratio is stoichiometric, when the catalyst is able to react all the reducing agents (carbon monoxide, hydrogen and hydrocarbons) with all the oxidising agents (oxygen and oxides of nitrogen). For this reason the engine of a three-way catalyst system is controlled to operate within a very narrow region either side of stoichiometric. Oxidation catalysts operate in the presence of excess oxygen but are obviously ineffective in controlling oxides of nitrogen emissions.

The rates of emission measured durng these tests show variations that reflect changes in fuelling and exhaust oxygen content as the vehicles' operating conditions were varied. Because emissions from the non-catalyst car are not influenced by either a catalyst or lean operation of the engine they may be regarded as a standard against which to compare the other types of car.

4.1 OXIDES OF NITROGEN

The oxides of nitrogen results are shown in Figure 4 as a function of the test speed.

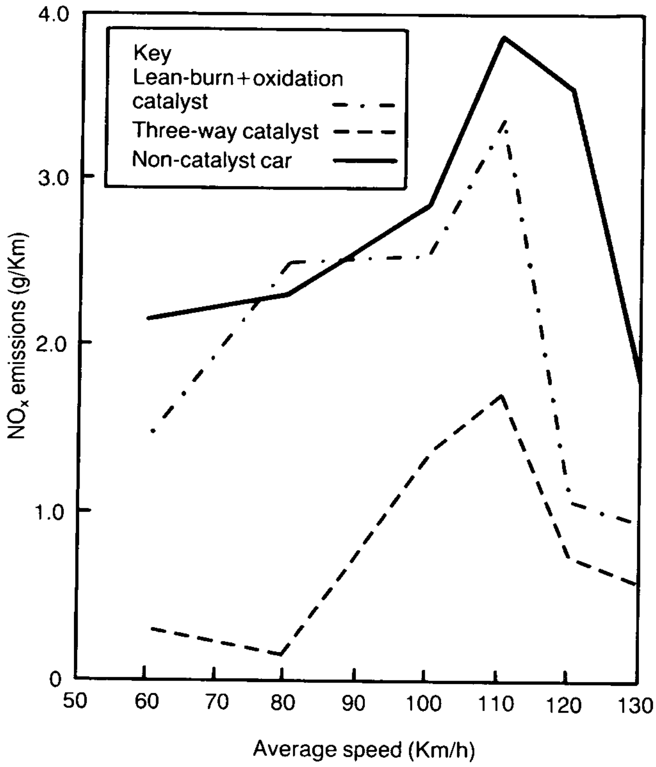

Fig. 4 Variation of exhaust emission rate with speed for oxides of nitrogen

At the lowest speed (60 km/h) the lean-burn car produced approximately 30% less oxides of nitrogen than the non-catalyst car but, as the speed increased, rates of emission became more similar. Clearly, as the speed of and load on the engine were increased, the air/fuel ratio of the lean-burn car was reduced in accordance with Figure 3, giving rise to increased oxides of nitrogen emissions. For speeds greater than 110 km/h, the lean-burn emissions were much lower than those of the non-catalyst car, approaching the levels produced by the three-way catalyst car. A number of factors may have contributed to this difference. As speeds increased, a progressively richer mixture was required. When the air/fuel ratio became stoichiometric, the 'oxidation' catalyst fitted to the lean-burn cars would behave as a three-way catalyst and oxides of nitrogen would decrease rapidly. If the mixture is further enriched, formation of oxides of nitrogen during combustion is reduced, as Figure 2 shows, and exhaust oxygen levels would also be very low, allowing the catalyst to continue to reduce oxides of nitrogen. Thus, while oxides of nitrogen emissions from the lean-burn car were lower, on average, than from the non-catalyst car, the difference is not considered to be a result of lean operation except at the lowest speed.

Rates of emission of oxides of nitrogen for the three-way catalyst car were considerably lower than for the other two cars. The car showed a drop in emission rates between 60 and 80 km/h, followed by a steep rise for speeds up to 110 km/h and a sharp decrease for speeds over 110 km/h. Again, the combined behaviour of the catalyst and the engine affects the emissions. As speeds increase, oxides of nitrogen production in the engine increases because the higher peak operating temperature promotes greater combination of oxygen and nitrogen. This behaviour was also seen in the results from the non-catalyst car in the speed range 80 to 110 km/h. However, as speeds continue to increase above a certain point, more power is demanded than is available with a stoichiometric air/fuel ratio, and the mixture becomes richer. As with the lean-burn car, this results in a large decrease in the formation of oxides of nitrogen in the engine and of oxygen in the exhaust, which aids the catalytic reduction.

4.2 HYDROCARBONS

Figure 5 shows that hydrocarbon emissions were fairly stable for all cars at speeds between 60 and 110 km/h. Emissions from the non-catalyst car were much higher than from either catalyst equipped car, indicating effective oxidation by the catalysts in this speed range. At speeds over 110 km/h there was a rise in emission rate for all cars, again reflecting the reduction in air/fuel ratio necessary to satisfy the increased power demand (Figure 2 shows that on a typical car, production of hydrocarbons increases with richer mixtures). The reduced exhaust oxygen content resulting from these richer mixtures would cause less efficient oxidation by the catalysts and therefore

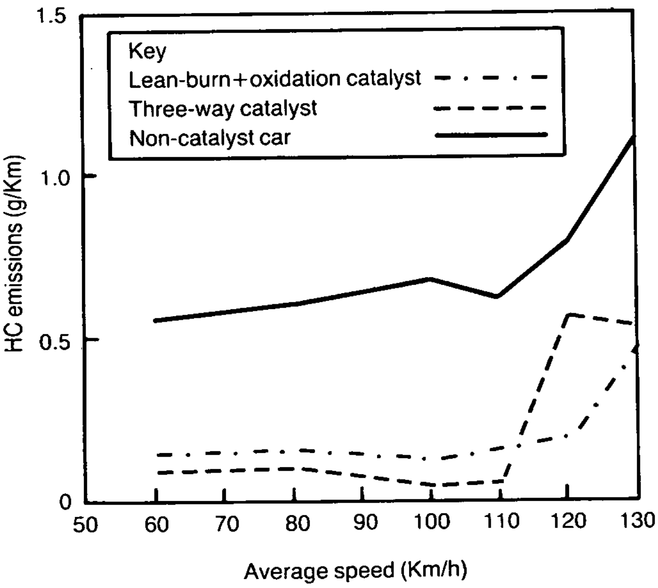

Fig. 5 Variation of exhaust emission rate with speed for hydrocarbons

higher hydrocarbon emissions. The rise in emission rate for the three-way catalyst car occurred before that for the lean-burn car. This indicates that the air/fuel ratio fell below stoichiometric at a lower speed for the three-way catalyst car than for the lean-burn car.

4.3 CARBON MONOXIDE

Carbon monoxide emission rates are shown in Figure 6. The results follow a pattern very similar to the hydrocarbon measurements and may be attributed to the same effects of engines and catalysts. The increase in emission rates at the highest speeds was considerably steeper than for hydrocarbons, as would be expected since the rate of increase of carbon monoxide formation as the air/fuel ratio is reduced is greater than for hydrocarbons. (See figure 2).

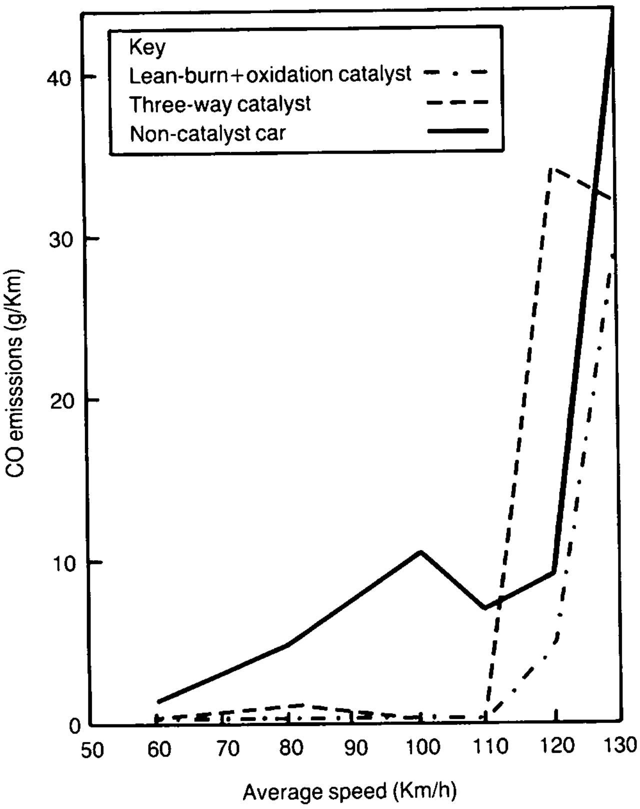

Fig. 6 Variation of exhaust emission rate with speed for carbon monoxide

4.4 FUEL CONSUMPTION

Figure 7 shows the carbon-balance fuel consumption as a function of test speed.

For all cars there was an overall increase of approximately 5 L/100 km as the speed increased

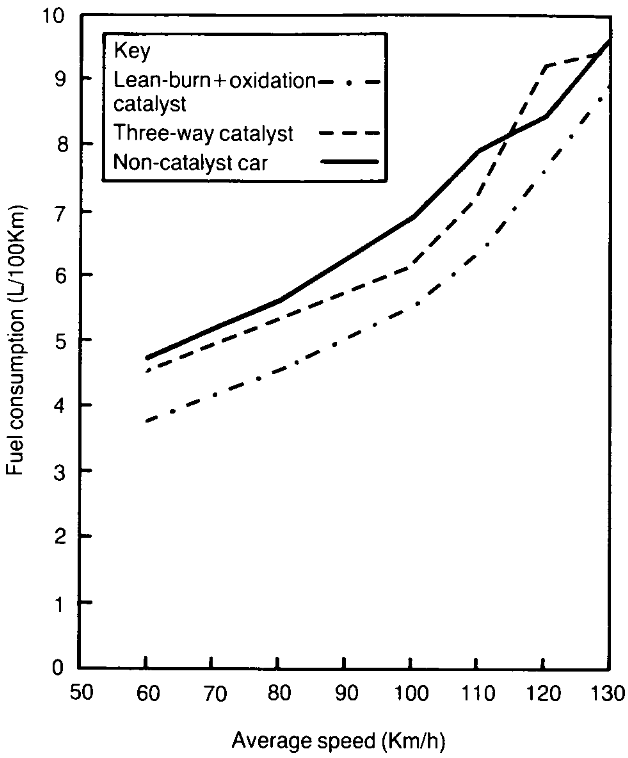

Fig. 7 Variation of carbon balance fuel consumption with speed

from 60 to 130 km/h. The fuel consumption of the lean-burn car was consistently lower than those of the other two cars by about 1 L/100 km. This result is in good agreement with fuel consumption measurements during other tests on these cars and overall fuel consumption rates calculated from records of fuel usage and distance covered over a two year period. It is perhaps somewhat surprising in view of the emission measurements discussed above, where it seemed that the lean-burn car was not operating with a lean mixture over much of the speed range of these tests. Therefore, the fuel economy benefit of lean combustion might be expected to be less apparent here than during other tests at lower speeds and during general use on the road. However, reduced fuel consumption can result from the use of air/fuel ratios which, while leaner than stoichiometric, are not sufficiently lean to influence exhaust emission rates significantly. Similarly, when the air/fuel ratio was richer than stoichiometric it was nevertheless leaner than that used by the other car types under the same conditions and resulted in a relative fuel saving. A further indication that this was so is provided by comparing emission rates of hydrocarbons and carbon monoxide from the catalyst equipped cars at the highest test speeds (120 and 130 km/h, Figures 5 and 6). For each pollutant the speed at which emission rates began to rise rapidly is lower for the three-way catalyst car, showing earlier enrichment of the mixture.

5 CONCLUSIONS

1. Rates of exhaust emission of oxides of nitrogen, hydrocarbons and carbon monoxide, together with rates of fuel consumption, were measured on three types of car during tests at steady speeds in the range 60 to 130 km/h. The car types were a non-catalyst car, a car with a lean-burn engine and oxidation catalyst, and a car with a controlled three-way catalyst.
2. Overall, the catalyst-controlled cars produced lower emissions than the non-catalyst car, although there was evidence that the emission control systems did not operate efficiently at speeds above 110 km/h. The catalyst-controlled cars were designed for use in Japan where a low speed test cycle is used and the maximum speed limit is 100 km/h. The engine managment systems would therefore have been designed to satisfy Japanese operating requirements. At speeds over 110 km/h there was a large increase in emissions of hydrocarbons and carbon monoxide and a decrease in emissions of oxides of nitrogen.
3. These changes in emission rates were the result of changes of the air/fuel ratio needed to provide sufficient power at the high test speeds. This had the dual effect of altering the primary emissions from the engines and of modifying the oxygen content of the exhaust and thus the efficiency of the catalysts. These changes in operation emphasize the need for regulatory test cycles to examine emissions at the highest legal speeds, as well as at lower speeds.
4. For all cars there was an overall increase in fuel consumption of approximately 5 L/100 km as the speed increased from 60 to 130 km/h. The fuel consumption of the lean-burn car was consistently lower than that of the three-way catalyst and non-catalyst cars by about 1 L/100 km.

6 ACKNOWLEDGEMENTS

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