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EMISSION TESTING OF FREIGHT RAIL LOCOMOTIVE 8154

by

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Report to Freight Rail

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SUMMARY

The influence of different blended diesel fuels on exhaust pollution emissions from an 81 class locomotive was evaluated at the Chullora test facility. The locomotive was subject to a multi-mode test cycle consisting of 30 min operation at low idle and at each of the throttle notch settings from 1 to 7, 60 mins in notch 8 then 30 mins per notch from 7 to low idle.

A portion of the exhaust gases was ducted to ground level, from which an aliquot was taken for determination of gas (carbon monoxide, carbon dioxide, nitrogen oxides, methane and non methane hydrocarbons and sulphur dioxide) and particle concentrations (both total and those with size < 2.5 μm) at each mode of the test cycle.

The report presents details of the exhaust gas composition in terms of its volumetric composition and in terms of specific fuel emission rates (the ratio of the a particular pollutant to the sum of the measured carbonaceous species).

No significant variations in specific emission rates was found between the six tests within the accuracy of the measurements, except that the particulate matter in test, 5 involving the last of the blended fuels, was largely > 2.5 μm, whereas, for all the other tests it was mostly in the fine portion ie < 2.5 μm. Possibly tests 4 and 5 produced higher emissions of sulphur dioxide than the other tests.

The results are reasonably similar to the data of Fritz (1994) for an engine used in the 82 class locomotives.

1 OBJECTIVE

To determine the emission rates of selected gaseous and particulate pollutants from Freight Rail locomotive 8154 as a function of engine load for a range of fuel qualities.

2 METHODOLOGY

2.1 Sampling Set-up

An exhaust sampling duct 180mm diameter and 20 m in length, was mounted so that its inlet was immediately above the centre of the exhaust stack of the locomotive. The purpose of the duct was twofold: 1) to allow easy access to the exhaust gases at ground level and 2) provide time for particles to agglomerate to sizes more typical of their ambient equilibrium size (circa 0.5 μm).

2.2 Sampling Procedures

2.2.1 Gaseous Constituents

An aliquot of the exhaust gases were continuously sampled for the determination of nitrogen oxides, (NOx ie NO + NO_2), carbon monoxide (CO), carbon dioxide (CO_2), volatile sulphur compounds (as sulphur dioxide, SO_2), methane (CH_4) and non-methane hydrocarbons (NMHC). Prior to measurement, water in the exhaust was removed by cooling to 0^oC by passing the aliquot through an ice-cooled condenser.

Concentrations of NOx were determined using a chemiluminescence instrument. CO and CO_2 concentrations were measured using non-dispersive infrared (NDIR) instruments. Concentrations of CH_4 and NMHC were determined using a heated flame ionization detector (HFID). SO_2 concentrations were measured using flame photometry (FP). Some of the important characteristics of the instruments are listed in Table 1.

Table 1. Typical Instrument Characteristics

Instrument	FSD (as used in tests)	Accuracy (% fsd)	Response time (s)
CO	500 ppmv	1	10
CO_2	15 %v	1	10
CH_4	50 ppmv	1	120
NMHC	50 ppmv	1	120
NO_x	1500 ppmv	3	10
SO_2	0.06 ppmv	3	20

To keep within the dynamic range of the SO_2 monitor, a portion of the sample stream was diluted 1:15 with bottled air. All others gases were analysed using raw exhaust, after removal of combustion-generated water.

2.2.2 Particulate Matter

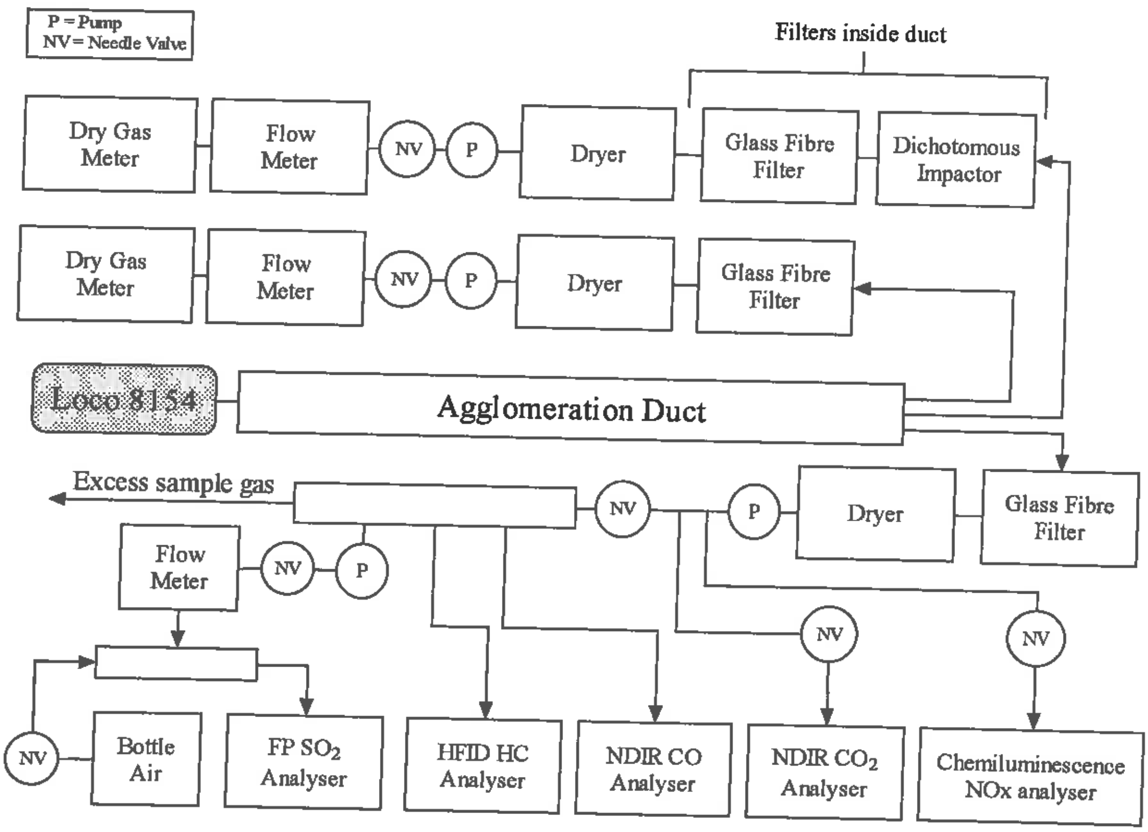
For test 1 (27/10/95), a cold filtering system was employed to collect particulate matter. This consisted of a 3/8 inch stainless steel intake tube connected to a 3/8 inch teflon tube which feed into a dryer. After drying, the cooled exhaust gas was drawn through two stainless steel filter holders containing 47 mm Whatman GF/A glass fibre filters capable of collecting particles greater than 0.1 μm diameter. One of the filters was preceded by a dichotomous impactor designed to remove particles greater than 2.5 μm in size. The total volume of the exhaust gas passing through each of the filters was determined by a dry gas meter.

The weights of the collected particles for test 1 were somewhat less than anticipated, raising the possibility of loss during gas cooling and drying. To overcome this, the filtration system was placed directly into the exhaust duct and allowed to heat up before sampling.

The glass fibre filters were weighed with an analytical balance purged with nitrogen to an accuracy of 0.1 mg. For tests 2-6 the filters were pre-treated in an oven at 180°C for 24 hours.

Figure 1 displays a schematic representation of the sampling system employed to monitor the composition of the exhaust gases and also the particulate concentrations.

Figure 1: Schematic of sampling system



2.3 Test Procedure

A multi-mode test procedure involving each of the throttle notch settings was used for evaluating fuel consumption and pollutant emission. This is shown in Table 2.

Table 2: Testing Procedure

Notch Setting	Sampling Time (minutes)
Low idle	30
1	30
2	30
3	30
4	30
5	30
6	30
7	30
8	60
7	30
6	30
5	30
4	30
3	30
2	30
1	30
Low idle	30

At the end of each test segment, CO_2 was zero calibrated with ambient air and span calibrated with 12% CO_2 in nitrogen. At the beginning and end of each test, CO_2 was multi-point calibrated with 2, 5.8 and 12% CO_2 in nitrogen.

Flow rates for the dilution system used for SO_2 measurements were determined at the end of each test segment using a digital bubble flow meter. SO_2 was calibrated using 53.2 ppm SO_2 in nitrogen sampled through the dilution system.

NOx calibrations were taken at regular intervals during test period for span using 1130/1100 ppm (NOx/NO) in nitrogen, for test 1-4 and 665/680 ppm (NOx/NO) for test 5-6. Multi-point calibrations were performed during the course of the experiment by dilution of the above stock gases with bottled air via a mass flow controller.

CO was zero calibrated with ambient air at the end of each test segment and span calibrated at the beginning and end of the experiment with 550 ppm CO.

CH_4 and NMHC was zero calibrated at the beginning and end of each test with ambient air, and was span calibrated using 10.1 ppm CH_4 and 4.9 ppm C_3H_8 at the beginning and end of the experiment.

Particulate samples were taken at each notch setting for a period of approximately 20 minutes, with duplicate samples taken for notch 8. Volumetric measurements were manually recorded from the dry gas meter gauges.

The data obtained from the instruments were recorded on chart and logged every 5 seconds on a computer.

3 RESULTS AND DISCUSSION

The volumetric concentrations of CO_2, CO, NMHC (as CH_4), CH_4, NO_x and SO_2 in the exhaust gas were measured at low idle and at each notch setting for a total of six tests. PM was measured as wt/vol of exhaust gas. Test 1 and 6, at the start and end of the campaign, involved the baseline fuel, the other four tests concerned fuels with proprietary additives. The pollutant emissions can be expressed as a volume fraction of the fuel carbon by summing CO_2, CO, NMHC, CH_4 and PM_{tot}. The PM_{tot} was converted to volume assuming that the PM was all carbon. These volume fractions can be converted to a specific mass emission rate by multiplying by the molecular weights assuming that the molecular weight of the diesel fuel corresponded to an elemental composition of $CH_{1.85}$. For this purpose, the NMHC was calculated as equivalent CH_4 and NO_x as NO.

The volumetric concentrations and the specific mass emission rates (denoted as ratios of FC) for each of the test cycle modes are shown in Tables 3 to 8 for tests 1 to 6 respectively. It should be noted that the measured volumetric concentrations varied slightly within the duration of a single notch setting presumably because of a changing engine temperature, the values reported here are the average values recorded during each notch setting. The variations in specific emission rates for each of the tests are listed in Tables 9 to 15 for CO, NMHC, CH_4, NO_x, SO_2, PM_{tot} and $PM_{2.5}$ respectively. The data are also shown in the same sequence in Figures 2-7 along with the results of Fritz (1994), obtained for a 12 cylinder engine, type EMD 12-710 G3A, used in the 82 class locomotives.

There were no significant differences in the CO/FC ratios between any of the tests, except at the starting low idle point, when CO emissions were relatively high (see Table 9 and Figure 2). Engine warm-up was probably the major factor in the differences between the individual tests as at the end low idle the emissions were close together, although higher than at other notch settings. A repeatable feature was a slight increase in CO levels going from notch 5 to notch 6 dropping again at notch 7, in both the throttle up and throttle down parts of the multi-mode cycle. The data of Fritz (1994) are very similar except for the rise from notch 6 to notch 8. Perhaps this reflects different engine operation characteristics. Values for CO/FC varied between 1.47 and 4.01 g/kg for notches 1 to 8 and across the six tests.

Similarly, as shown in Table 10 and Figure 3, NMHC/FC ratios are not significantly different between the six tests and all showed a small decrease from notch 1 to notch 4 followed by a slight increase from notch 4 to notch 8. Again at starting low idle the emissions were higher and more scattered for the same reasons as suggested for the CO emissions. Average values varied between 0.18 and 0.59 over the eight notches and the six tests. The results of Fritz (1994) are about a factor of three higher. This may reflect the differences in the fuel volatilities or the loss of the less volatile exhaust NMHC in our measurements when cooling the gases to remove water. Also we note that his NMHC monitor was calibrated with propane, which has a molecular weight about three times that of CH_4. Fritz's experimental methodology is not sufficiently detailed to ascertain whether this is a possible reason.

Values of CH_4/FC are smaller than NMHC and show the same trends (Table 11, Figure 4). There are no data from Fritz (1994).

The specific emissions of NO_x displayed more scatter for those results obtained going down from notch 8 than those for the first half of the test cycle (see Table 12 and Figure 5). We have no explanation for this, except to note that difficulties were experienced in keeping within the operational requirements for the NO_x monitor due to filter clogging. Test 5 seemed to produce somewhat less NO_x at the lower notch settings, otherwise there were little differences between the six tests. Values of NO_x/FC varied from 28.2 to 44.8 g/kg from notches 1 to 8 and across the six tests. The results of Fritz (1994) were distinctly higher than ours, however he did not specify whether his data was as NO or as NO_2. If the latter, then on conversion to NO, his results fall in the range 43.7 to 54.9 g/kg.

Specific SO_2 emission rates are listed in Table 13 and depicted in Figure 6. The rates decreased markedly from notch 1 to notch 3 thereafter remaining fairly constant until increasing again after reaching notch 3 on the down throttle part of the test cycle. Tests 4 and 5 emitted somewhat higher amounts of SO_2 than the others particularly during the second half of the cycle. Part of this was due to higher ambient SO_2 which would have been in the combustion air, however, it did appear that these two tests produced slightly more SO_2 than the others. Values of SO_2/FC varied from 0.02 to 0.13 g/kg fuel corresponding to 0.001 to 0.0065% S in the fuel. The fuel contained 0.17% S, so that only a small portion of the S appeared in the gaseous form in the exhaust. There may be some loss when passing through the drier another route being through oxidation. Sooty carbon, which makes up a significant if not a major part of diesel exhaust particulate matter, is known to catalyse the oxidation of SO_2 by air to particle sulphate (Brodzinsky et al., 1980). Also NO_2 can act as the oxidiser in the absence of O_2 (Britton and Clarke 1980). Heterogeneous oxidation of SO_2 is often facilitated by higher temperatures which occur in the agglomeration duct at high notch settings. This may at least provide part of the explanation. The PM in test 5 had different size characteristics than in the other tests (see below) which may influence the extent of any catalytic oxidation.

The fuel specific amounts of total PM in the exhaust for all the tests are shown in Table 14 and Figure 7. Those for the fine fraction ie < 2.5 μm aerodynamic diameter are listed in Table 15 and Figure 8. The percentage of the total PM that was found to be < 2.5 μm is shown in Table 16 and Figure 9. All the tests generated similar quantities of PM ranging from 0.4 to 1.4 g/kg fuel, although test 4 may have produced slightly more but the precision is such that no firm conclusion can be formed.. The only significant, and intriguing, difference was that PM generated in test 5 was largely in the coarse fraction (83 %), whereas in the remainder only 18%, on average was > 2.5 μm.

Finally, it is customary when dealing with automobile pollution to evaluate the ratios NMHC/CO, CO/NO_X and NMHC/NO_X. These are presented without comment in Tables 17-19 respectively and shown in Figures 10 to 12.

4 CONCLUSIONS

There was little difference in any of the pollutant emission rates between any of the fuels tested at any of the modes in the test cycle, within in the accuracy of the measurements, except for the fraction of fine PM emitted in test 5. In this test, the bulk of the PM was found to be have an aerodynamic diameter > 2.5 µm, whereas in the other tests most of the PM was < 2.5 µm. The SO_2 emissions in tests 4 and 5 appeared to be slightly higher, but not significantly so.

CO emissions exhibited a slight peak at notch 6, possibly a function of engine operation changes at this point.

5 REFERENCES

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Brodzinsky R., Chang S-G, Markowitz s.s and Novakov T. 1980. Kinetics and mechanism for the catalytic oxidation of sulfur dioxide on carbon in aqueous suspensions. J Phys. Chem, 84, 3354-3358.

Fritz S.G. 1994. Exhaust emissions from two intercity passenger locomotives. J Eng for Gas Turbines and Power. (Trans ASME), 116, 774- 783.

Table 3. Exhaust gas composition and specific emission rates for test 1 as a function of throttle settting.

Test 1	CO_2 (ppm)	CO (ppm)	NMHC (ppm)	CH_4 (ppm)	PMtotal (ppm)	PM<2.5um (ppm)	NO_x (ppm)	SO_2 (ppm)
Low Idle	7400	61	11	3	14	10	113	
1	22700	28	9	2	25	21	398	0.367
2	30600	32	9	2	27	24	510	0.388
3	43200	31	10	2	45	36	772	0.414
4	50000	49	11	2	44	40	859	0.435
5	57100	69	14	2	51	45	938	0.451
6	64000	127	18	2	46	38	1046	0.445
7	66000	93	21	2	45	42	1129	0.450
8	67000	84	22	2	48	39	1158	0.456
7	65800	89	19	3	43	32	1127	0.454
6	64000	122	16	3	35	31	1032	0.455
5	57600	67	11	3	14	11	860	0.449
4	50600	46	9	3	30	27	794	0.423
3	43700	37	9	3	23	22	708	0.420
2	30600	40	8	3	20	13	456	0.396
1	23200	31	8	3	17	12	379	0.380
Low Idle	7000	33	8	3	13	10	128	0.340
	CO_2/FC (kg/kg)	CO/FC (g/kg)	NMHC/FC (g/kg)	CH_4/FC (g/kg)	PMtotal/FC (g/kg)	PM<2.5/FC (g/kg)	NO_x/FC (g/kg)	SO_2/FC (g/kg)
Low Idle	3.14	16.36	1.76	0.47	1.61	1.21	32.7	
1	3.17	2.44	0.45	0.12	0.96	0.79	37.9	0.075
2	3.17	2.11	0.33	0.08	0.78	0.69	36.1	0.058
3	3.17	1.47	0.27	0.05	0.90	0.72	38.6	0.044
4	3.17	1.97	0.26	0.04	0.77	0.70	37.2	0.040
5	3.17	2.42	0.28	0.04	0.77	0.68	35.5	0.036
6	3.17	4.01	0.33	0.04	0.62	0.52	35.3	0.032
7	3.17	2.84	0.37	0.04	0.59	0.54	37.0	0.031
8	3.17	2.52	0.38	0.04	0.61	0.51	37.4	0.031
7	3.17	2.74	0.33	0.05	0.57	0.42	37.0	0.032
6	3.17	3.83	0.28	0.05	0.47	0.42	34.8	0.033
5	3.17	2.34	0.23	0.05	0.21	0.17	32.3	0.036
4	3.17	1.85	0.20	0.06	0.52	0.46	33.9	0.039
3	3.17	1.73	0.23	0.07	0.46	0.43	35.0	0.044
2	3.17	2.62	0.31	0.10	0.56	0.37	32.2	0.060
1	3.17	2.73	0.39	0.13	0.64	0.45	35.3	0.076
Low Idle	3.15	9.34	1.35	0.45	1.58	1.23	39.3	0.223

Table 4. Exhaust gas composition and specific emission rates for test 2 as a function of throttle settting.

Test 2	CO_2	CO	NMHC	CH_4	PMtotal	PM<2.5um	NO_x	SO_2
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Low Idle	8200	43	11	2	7	6	137	0.267
1	24200	37	10	1	19	11	388	0.309
2	30900	40	10	1	27	23	515	0.326
3	42500	37	11	0	31	29	747	0.367
4	49900	51	12	0	38	32	911	0.381
5	57000	57	14	0	35	33	976	0.394
6	64600	102	18	0	42	34	1130	0.408
7	66800	75	20	1	31	28	1221	0.417
8	67300	71	21	1	32	28	1261	0.420
7	66400	74	20	1	24	16	1249	0.300
6	64900	108	17	1	40	36	1108	0.297
5	58400	58	12	1	31	29	1003	0.296
4	50500	46	11	1	38	32	913	0.282
3	43000	37	10	2	28	20	823	0.272
2	29800	37	9	2	29	26	517	0.251
1	23100	31	9	2	23	15	398	0.237
Low Idle	7100	26	9	2	7	6	140	0.214

	CO_2/FC	CO/FC	NMHC/FC	CH_4/FC	PMtotal/FC	PM<2.5/FC	NO_x/FC	SO_2/FC
	(kg/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	3.15	10.63	1.49	0.24	0.77	0.66	35.8	0.149
1	3.17	3.08	0.47	0.05	0.67	0.41	34.6	0.059
2	3.17	2.62	0.37	0.03	0.76	0.63	36.0	0.049
3	3.17	1.75	0.30	0.01	0.64	0.59	38.0	0.040
4	3.17	2.06	0.29	0.01	0.66	0.55	39.5	0.035
5	3.17	2.00	0.28	0.01	0.52	0.50	37.0	0.032
6	3.17	3.17	0.32	0.01	0.57	0.46	37.8	0.029
7	3.17	2.27	0.35	0.01	0.40	0.36	39.5	0.029
8	3.17	2.13	0.37	0.01	0.41	0.36	40.5	0.029
7	3.17	2.24	0.34	0.02	0.31	0.21	40.7	0.021
6	3.17	3.36	0.30	0.02	0.53	0.48	36.9	0.021
5	3.17	2.01	0.24	0.02	0.47	0.43	37.1	0.023
4	3.17	1.85	0.24	0.03	0.65	0.54	39.1	0.026
3	3.17	1.74	0.26	0.04	0.56	0.41	41.4	0.029
2	3.17	2.48	0.34	0.07	0.84	0.75	37.5	0.039
1	3.17	2.73	0.43	0.09	0.85	0.58	37.2	0.047
Low Idle	3.16	7.31	1.49	0.34	0.89	0.77	42.5	0.139

Table 5. Exhaust gas composition and specific emission rates
for test 3 as a function of throttle settting.

Test 3	CO_2 (ppm)	CO (ppm)	NMHC (ppm)	CH_4 (ppm)	PMtotal (ppm)	PM<2.5um (ppm)	NO_x (ppm)	SO_2 (ppm)
Low Idle	7100	95	14	3	22	16	101	0.196
1	21300	34	10	2	34	24	383	0.243
2	27100	38	8	3	29	24	483	0.258
3	38700	37	10	2	32	29	729	0.275
4	46700	52	12	2	29	26	852	0.280
5	53700	54	13	2	34	32	912	0.315
6	57200	94	16	2	42	38		0.330
7	58800	64	18	2	23	16	1063	0.347
8	63900	71	22	2	22	16	1270	0.366
7	61000	65	19	2	22	16	1226	0.373
6	58000	92	15	2	35	31	1199	0.390
5	53300	44	12	2	32	27	997	0.346
4	45900	42	10	2	29	24	896	0.343
3	38800	34	9	2	18	16	785	0.329
2	25800	35	9	2	17	13		0.301
1	20800	29	9	2	16	12	368	0.291
Low Idle	6600	27	10	2	10	6		0.242

	CO_2/FC (kg/kg)	CO/FC (g/kg)	NMHC/FC (g/kg)	CH_4/FC (g/kg)	PMtotal/FC (g/kg)	PM<2.5/FC (g/kg)	NO_x/FC (g/kg)	SO_2/FC (g/kg)
Low Idle	3.12	26.51	2.16	0.53	2.62	1.94	30.3	0.126
1	3.17	3.20	0.52	0.10	1.38	0.96	38.8	0.052
2	3.17	2.81	0.33	0.12	0.92	0.77	38.5	0.044
3	3.17	1.94	0.29	0.07	0.71	0.66	40.7	0.033
4	3.17	2.26	0.30	0.06	0.53	0.49	39.4	0.028
5	3.17	2.04	0.28	0.04	0.55	0.51	36.7	0.027
6	3.17	3.32	0.32	0.04	0.63	0.57		0.027
7	3.17	2.19	0.35	0.04	0.34	0.21	39.1	0.027
8	3.17	2.25	0.40	0.03	0.30	0.21	43.0	0.026
7	3.17	2.16	0.37	0.03	0.31	0.22	43.5	0.028
6	3.17	3.22	0.31	0.04	0.52	0.47	44.7	0.031
5	3.17	1.65	0.26	0.04	0.53	0.44	40.4	0.030
4	3.17	1.86	0.26	0.04	0.54	0.46	42.2	0.034
3	3.17	1.79	0.28	0.06	0.40	0.35	43.8	0.039
2	3.17	2.77	0.39	0.08	0.56	0.42		0.054
1	3.17	2.80	0.52	0.10	0.65	0.49	38.2	0.065
Low Idle	3.15	8.31	1.75	0.36	1.36	0.82		0.168

Table 6. Exhaust gas composition and specific emission rates for test 4 as a function of throttle settting.

Test 4	CO_2	CO	NMHC	CH_4	PMtotal	PM<2.5um	NO_x	SO_2
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Low Idle	5900	101	16	2	23	19		
1	20700	26	11	1	25	23	430	
2	25800	36	10	0	19	17	526	0.438
3	39700	36	12	0	33	28	725	0.453
4	47800	49	12	0	54	41	752	0.461
5	52200	73	15	0	60	48	945	0.478
6	62000	119	18	0	69	57	1051	0.554
7	66000	120	20	1	46	41	1223	0.817
8	66400	95	21	1	29	25	1272	1.167
7	62400	97	19	1	39	30	1138	0.661
6	58800	109	16	1	47	45	960	0.674
5	53900	63	13	1	47	43	1033	0.631
4	46700	37	10	1	41	39	866	0.609
3	41700	32	10	1	29	24	810	0.594
2	27900	30	8	1	23	18	520	0.586
1	20800	26	8	2	14	12	383	0.551
Low Idle	6000	26	9	2	11	10	135	0.509
	CO_2/FC	CO/FC	NMHC/FC	CH_4/FC	PMtotal/FC	PM<2.5/FC	NO_x/FC	SO_2/FC
	(kg/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	3.10	33.67	3.15	0.30	3.36	2.67		
1	3.17	2.57	0.59	0.04	1.06	0.96	44.8	
2	3.17	2.79	0.45	0.01	0.64	0.56	44.0	0.078
3	3.17	1.83	0.34	-0.01	0.73	0.60	39.5	0.053
4	3.17	2.07	0.30	0.00	0.98	0.75	34.0	0.044
5	3.17	2.83	0.32	0.00	0.99	0.79	39.1	0.042
6	3.17	3.86	0.34	0.01	0.96	0.80	36.6	0.041
7	3.17	3.65	0.36	0.01	0.60	0.54	40.0	0.057
8	3.17	2.87	0.37	0.01	0.38	0.32	41.4	0.081
7	3.17	3.15	0.34	0.02	0.54	0.42	39.4	0.049
6	3.17	3.73	0.32	0.02	0.69	0.66	35.3	0.053
5	3.17	2.36	0.27	0.02	0.75	0.70	41.4	0.054
4	3.17	1.61	0.25	0.03	0.76	0.72	40.1	0.060
3	3.17	1.55	0.27	0.04	0.60	0.51	42.0	0.066
2	3.17	2.17	0.35	0.06	0.71	0.55	40.3	0.097
1	3.17	2.55	0.45	0.09	0.58	0.48	39.7	0.122
Low Idle	3.15	8.76	1.72	0.39	1.55	1.40	48.4	0.389

Table 7. Exhaust gas composition and specific emission rates for test 5 as a function of throttle settting.

Test 5	CO_2	CO	NMHC	CH_4	PMtotal	PM<2.5um	NO_x	SO_2
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Low Idle	6300	56	10	2	9	2		0.567
1	20600	34	8	1	28	5		0.576
2	27700	33	8	1	27	6	400	0.470
3	42300	36	9	1	32	6	648	0.495
4	48600	41	9	1	39	4	891	0.524
5	56100	61	11	1	52	8	1009	0.543
6	60800	95	14	1	48	5	1089	0.564
7	63100	78	17	1	29	3	1209	0.583
8	63300	79	19	2	27	2	1170	0.702
7	62300	83	17	2	28	2	1211	0.720
6	59300	97	15	2	43	7	974	0.719
5	53900	57	10	2	41	3	758	0.711
4	46800	37	8	2	40	9	611	0.694
3	41700	33	7	2	27	4	574	0.594
2	27800	31	6	2	16	3	353	0.614
1	20700	29	6	2	13	4	276	0.576
Low Idle	6200	31	7	2	9	3	94	0.491
	CO_2/FC	CO/FC	NMHC/FC	CH_4/FC	PMtotal/FC	PM<2.5/FC	NO_x/FC	SO_2/FC
	(kg/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	3.14	17.67	1.75	0.35	1.28	0.28		0.411
1	3.17	3.33	0.43	0.05	1.17	0.21		0.129
2	3.17	2.39	0.35	0.03	0.85	0.19	31.2	0.078
3	3.17	1.71	0.25	0.02	0.65	0.12	33.2	0.054
4	3.17	1.71	0.21	0.02	0.69	0.08	39.6	0.050
5	3.17	2.21	0.23	0.02	0.80	0.12	38.9	0.045
6	3.17	3.14	0.26	0.02	0.68	0.07	38.7	0.043
7	3.17	2.50	0.31	0.02	0.39	0.04	41.4	0.043
8	3.17	2.52	0.34	0.03	0.37	0.03	40.0	0.051
7	3.17	2.69	0.32	0.03	0.39	0.03	42.0	0.053
6	3.17	3.30	0.29	0.03	0.63	0.11	35.5	0.056
5	3.17	2.14	0.22	0.03	0.65	0.05	30.4	0.061
4	3.17	1.60	0.21	0.04	0.75	0.17	28.2	0.068
3	3.17	1.58	0.19	0.05	0.57	0.08	29.8	0.066
2	3.17	2.23	0.26	0.08	0.51	0.10	27.5	0.102
1	3.17	2.83	0.36	0.11	0.53	0.18	28.8	0.128
Low Idle	3.15	9.98	1.28	0.43	1.30	0.46	32.6	0.363

Table 8. Exhaust gas composition and specific emission rates for test 6 as a function of throttle settting.

Test 6	CO_2	CO	NMHC	CH_4	PMtotal	PM<2.5um	NO_x	SO_2
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Low Idle	5800	61	6	2	12	7		
1	19200	28	5	1	15	11	301	
2	28800	31	6	2	27	22	429	
3	42200	35	7	3	31	29	714	0.420
4	49100	50	8	3	37	34	782	0.475
5	56200	71	11	3	34	31	935	0.492
6	63100	125	14	3	54	46	1039	0.522
7	63000	78	17	3	21	17	1149	0.521
8	66200	77	18	3	52	32	1176	0.546
7	64900	79	16	3	19	12	1024	0.526
6	62500	119	14	3	36	31	924	0.538
5	56000	67	9	3	35	29	991	0.527
4	48800	45	8	3	27	21	882	0.508
3	43000	37	7	3	23	20	805	0.503
2	28200	39	6	3	20	17	482	0.454
1	21500	32	7	3	17	10	379	0.428
Low Idle	6800	29	7	3	12	8	126	0.350

	CO_2/FC	CO/FC	NMHC/FC	CH_4/FC	PMtotal/FC	PM<2.5/FC	NO_x/FC	SO_2/FC
	(kg/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	3.13	20.84	1.19	0.38	1.75	1.02		
1	3.17	2.89	0.32	0.08	0.68	0.48	33.9	
2	3.17	2.19	0.23	0.06	0.81	0.66	32.2	
3	3.17	1.68	0.20	0.07	0.63	0.59	36.6	0.046
4	3.17	2.04	0.19	0.06	0.65	0.59	34.4	0.045
5	3.17	2.54	0.22	0.05	0.53	0.48	36.0	0.040
6	3.17	4.01	0.26	0.05	0.73	0.62	35.6	0.038
7	3.17	2.51	0.30	0.05	0.29	0.24	39.4	0.038
8	3.17	2.34	0.32	0.05	0.68	0.42	38.4	0.038
7	3.17	2.47	0.28	0.05	0.25	0.16	34.1	0.037
6	3.17	3.84	0.26	0.05	0.50	0.43	31.9	0.040
5	3.17	2.42	0.19	0.06	0.54	0.45	38.3	0.043
4	3.17	1.87	0.18	0.07	0.49	0.38	39.1	0.048
3	3.17	1.72	0.20	0.07	0.46	0.41	40.5	0.054
2	3.17	2.80	0.26	0.11	0.61	0.51	36.9	0.074
1	3.17	3.00	0.36	0.14	0.69	0.38	38.1	0.092
Low Idle	3.15	8.45	1.24	0.49	1.56	0.96	39.8	0.236

Table 9. Specific emission rates of CO as a function of throttle setting (Test 1-6, Fritz).

	Test 1 CO/FC (g/kg)	Test 2 CO/FC (g/kg)	Test 3 CO/FC (g/kg)	Test 4 CO/FC (g/kg)	Test 5 CO/FC (g/kg)	Test 6 CO/FC (g/kg)	Fritz CO/FC (g/kg)
Low Idle	16.36	10.63	26.51	33.67	17.67	20.84	5.67
1	2.44	3.08	3.20	2.57	3.33	2.89	3.71
2	2.11	2.62	2.81	2.79	2.39	2.19	3.23
3	1.47	1.75	1.94	1.83	1.71	1.68	1.67
4	1.97	2.06	2.26	2.07	1.71	2.04	1.66
5	2.42	2.00	2.04	2.83	2.21	2.54	2.82
6	4.01	3.17	3.32	3.86	3.14	4.01	2.56
7	2.84	2.27	2.19	3.65	2.50	2.51	4.95
8	2.52	2.13	2.25	2.87	2.52	2.34	7.62
7	2.74	2.24	2.16	3.15	2.69	2.47	
6	3.83	3.36	3.22	3.73	3.30	3.84	
5	2.34	2.01	1.65	2.36	2.14	2.42	
4	1.85	1.85	1.86	1.61	1.60	1.87	
3	1.73	1.74	1.79	1.55	1.58	1.72	
2	2.62	2.48	2.77	2.17	2.23	2.80	
1	2.73	2.73	2.80	2.55	2.83	3.00	
Low Idle	9.34	7.31	8.31	8.76	9.98	8.45	

Table 10. Specific emission rates of NMHC as a function of throttle setting (Test 1-6, Fritz).

	Test 1 NMHC/FC (g/kg)	Test 2 NMHC/FC (g/kg)	Test 3 NMHC/FC (g/kg)	Test 4 NMHC/FC (g/kg)	Test 5 NMHC/FC (g/kg)	Test 6 NMHC/FC (g/kg)	Fritz NMHC/FC (g/kg)
Low Idle	1.76	1.49	2.16	3.15	1.75	1.19	5.51
1	0.45	0.47	0.52	0.59	0.43	0.32	2.76
2	0.33	0.37	0.33	0.45	0.35	0.23	2.30
3	0.27	0.30	0.29	0.34	0.25	0.20	2.01
4	0.26	0.29	0.30	0.30	0.21	0.19	1.73
5	0.28	0.28	0.28	0.32	0.23	0.22	1.65
6	0.33	0.32	0.32	0.34	0.26	0.26	1.48
7	0.37	0.35	0.35	0.36	0.31	0.30	1.47
8	0.38	0.37	0.40	0.37	0.34	0.32	1.86
7	0.33	0.34	0.37	0.34	0.32	0.28	
6	0.28	0.30	0.31	0.32	0.29	0.26	
5	0.23	0.24	0.26	0.27	0.22	0.19	
4	0.20	0.24	0.26	0.25	0.21	0.18	
3	0.23	0.26	0.28	0.27	0.19	0.20	
2	0.31	0.34	0.39	0.35	0.26	0.26	
1	0.39	0.43	0.52	0.45	0.36	0.36	
Low Idle	1.35	1.49	1.75	1.72	1.28	1.24	

Table 11. Specific emission rates of CH_4 as a function of throttle setting (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	CH_4/FC	CH_4/FC	CH_4/FC	CH_4/FC	CH_4/FC	CH_4/FC
	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	0.47	0.24	0.53	0.30	0.35	0.38
1	0.12	0.05	0.10	0.04	0.05	0.08
2	0.08	0.03	0.12	0.01	0.03	0.06
3	0.05	0.01	0.07	0.01	0.02	0.07
4	0.04	0.01	0.06	0.00	0.02	0.06
5	0.04	0.01	0.04	0.00	0.02	0.05
6	0.04	0.01	0.04	0.01	0.02	0.05
7	0.04	0.01	0.04	0.01	0.02	0.05
8	0.04	0.01	0.03	0.01	0.03	0.05
7	0.05	0.02	0.03	0.02	0.03	0.05
6	0.05	0.02	0.04	0.02	0.03	0.05
5	0.05	0.02	0.04	0.02	0.03	0.06
4	0.06	0.03	0.04	0.03	0.04	0.07
3	0.07	0.04	0.06	0.04	0.05	0.07
2	0.10	0.07	0.08	0.06	0.08	0.11
1	0.13	0.09	0.10	0.09	0.11	0.14
Low Idle	0.45	0.34	0.36	0.39	0.43	0.49

Table 12. Specific emission rates of NO_X as a function of throttle setting (Test 1-6, Fritz).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Fritz
	NO_x/FC	NO_x/FC	NO_x/FC	NO_x/FC	NO_x/FC	NO_x/FC	NO_x/FC
	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	32.7	35.8	30.3				93.9
1	37.9	34.6	38.8	44.8		33.9	84.2
2	36.1	36.0	38.5	44.0	31.2	32.2	93.0
3	38.6	38.0	40.7	39.5	33.2	36.6	92.7
4	37.2	39.5	39.4	34.0	39.6	34.4	76.4
5	35.5	37.0	36.7	39.1	38.9	36.0	68.2
6	35.3	37.8		36.6	38.7	35.6	67.0
7	37.0	39.5	39.1	40.0	41.4	39.4	67.4
8	37.4	40.5	43.0	41.4	40.0	38.4	80.7
7	37.0	40.7	43.5	39.4	42.0	34.1	
6	34.8	36.9	44.7	35.3	35.5	31.9	
5	32.3	37.1	40.4	41.4	30.4	38.3	
4	33.9	39.1	42.2	40.1	28.2	39.1	
3	35.0	41.4	43.8	42.0	29.8	40.5	
2	32.2	37.5		40.3	27.5	36.9	
1	35.3	37.2	38.2	39.7	28.8	38.1	
Low Idle	39.3	42.5		48.4	32.6	39.8	

Table 13. Specific emission rates of SO_X as a function of throttle setting (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	SO_2/FC	SO_2/FC	SO_2/FC	SO_2/FC	SO_2/FC	SO_2/FC
	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle		0.149	0.126		0.411	
1	0.075	0.059	0.052		0.129	
2	0.058	0.049	0.044	0.078	0.078	
3	0.044	0.040	0.033	0.053	0.054	0.046
4	0.040	0.035	0.028	0.044	0.050	0.045
5	0.036	0.032	0.027	0.042	0.045	0.040
6	0.032	0.029	0.027	0.041	0.043	0.038
7	0.031	0.029	0.027	0.057	0.043	0.038
8	0.031	0.029	0.026	0.081	0.051	0.038
7	0.032	0.021	0.028	0.049	0.053	0.037
6	0.033	0.021	0.031	0.053	0.056	0.040
5	0.036	0.023	0.030	0.054	0.061	0.043
4	0.039	0.026	0.034	0.060	0.068	0.048
3	0.044	0.029	0.039	0.066	0.066	0.054
2	0.060	0.039	0.054	0.097	0.102	0.074
1	0.076	0.047	0.065	0.122	0.128	0.092
Low Idle	0.223	0.139	0.168	0.389	0.363	0.236

Table 14. Specific emission rates of PM_{total} as a function of throttle setting (Test 1-6, Fritz).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Fritz
	PMtotal/FC	PMtotal/FC	PMtotal/FC	PMtotal/FC	PMtotal/FC	PMtotal/FC	PMtotal/FC
	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	1.61	0.77	2.62	3.36	1.28	1.75	1.26
1	0.96	0.67	1.38	1.06	1.17	0.68	0.73
2	0.78	0.76	0.92	0.64	0.85	0.81	0.84
3	0.90	0.64	0.71	0.73	0.65	0.63	1.17
4	0.77	0.66	0.53	0.98	0.69	0.65	1.14
5	0.77	0.52	0.55	0.99	0.80	0.53	1.20
6	0.62	0.57	0.63	0.96	0.68	0.73	1.12
7	0.59	0.40	0.34	0.60	0.39	0.29	1.16
8	0.61	0.41	0.30	0.38	0.37	0.68	1.39
7	0.57	0.31	0.31	0.54	0.39	0.25	
6	0.47	0.53	0.52	0.69	0.63	0.50	
5	0.21	0.47	0.53	0.75	0.65	0.54	
4	0.52	0.65	0.54	0.76	0.75	0.49	
3	0.46	0.56	0.40	0.60	0.57	0.46	
2	0.56	0.84	0.56	0.71	0.51	0.61	
1	0.64	0.85	0.65	0.58	0.53	0.69	
Low Idle	1.58	0.89	1.36	1.55	1.30	1.56	

Table 15. Specific emission rates of $PM_{<2.5\mu m}$ as a function of throttle setting (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	PM<2.5um/FC	PM<2.5um/FC	PM<2.5um/FC	PM<2.5um/FC	PM<2.5um/FC	PM<2.5um/FC
	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
Low Idle	1.21	0.66	1.94	2.67	0.28	1.02
1	0.79	0.41	0.96	0.96	0.21	0.48
2	0.69	0.63	0.77	0.56	0.19	0.66
3	0.72	0.59	0.66	0.60	0.12	0.59
4	0.70	0.55	0.49	0.75	0.08	0.59
5	0.68	0.50	0.51	0.79	0.12	0.48
6	0.52	0.46	0.57	0.80	0.07	0.62
7	0.54	0.36	0.19	0.54	0.04	0.24
8	0.51	0.36	0.21	0.32	0.03	0.42
7	0.42	0.21	0.22	0.42	0.03	0.16
6	0.42	0.48	0.47	0.66	0.11	0.43
5	0.17	0.43	0.44	0.70	0.05	0.45
4	0.46	0.54	0.46	0.72	0.17	0.38
3	0.43	0.41	0.35	0.51	0.08	0.41
2	0.37	0.75	0.42	0.55	0.10	0.51
1	0.45	0.58	0.49	0.48	0.18	0.38
Low Idle	1.23	0.77	0.82	1.40	0.46	0.96

Table 16. Percent of particulate matter less than 2.5μm diameter (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	PM<2.5/PMt	PM<2.5/PMt	PM<2.5/PMt	PM<2.5/PMt	PM<2.5/PMt	PM<2.5/PMt
	(%)	(%)	(%)	(%)	(%)	(%)
Low Idle	75	86	74	80	22	58
1	82	61	69	90	18	71
2	89	83	84	89	22	81
3	80	92	93	83	18	95
4	91	83	92	76	11	91
5	89	95	93	80	15	92
6	84	80	90	83	10	85
7	92	89	70	89	9	83
8	82	88	71	85	9	61
7	74	67	72	76	7	64
6	90	91	90	95	17	87
5	82	92	84	93	8	83
4	88	83	85	95	22	77
3	95	73	86	84	14	89
2	66	89	75	77	19	83
1	71	68	75	82	34	56
Low Idle	77	86	60	91	35	62
Average	83	83	80	85	17	78

Table 17. Ratio of NMHC/CO as a function of throttle setting (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	NMHC/CO	NMHC/CO	NMHC/CO	NMHC/CO	NMHC/CO	NMHC/CO
	(g/g)	(g/g)	(g/g)	(g/g)	(g/g)	(g/g)
Low Idle	0.108	0.140	0.082	0.094	0.099	0.057
1	0.183	0.151	0.164	0.230	0.131	0.112
2	0.155	0.141	0.119	0.160	0.145	0.106
3	0.183	0.169	0.150	0.186	0.144	0.117
4	0.133	0.139	0.131	0.143	0.123	0.094
5	0.115	0.139	0.137	0.114	0.105	0.086
6	0.081	0.101	0.096	0.088	0.083	0.066
7	0.129	0.153	0.158	0.098	0.124	0.120
8	0.149	0.173	0.178	0.128	0.137	0.135
7	0.119	0.152	0.170	0.109	0.119	0.116
6	0.074	0.088	0.095	0.085	0.087	0.067
5	0.097	0.120	0.154	0.116	0.105	0.080
4	0.110	0.130	0.139	0.156	0.130	0.097
3	0.131	0.147	0.154	0.171	0.122	0.114
2	0.119	0.137	0.142	0.161	0.119	0.094
1	0.143	0.158	0.187	0.177	0.127	0.119
Low Idle	0.145	0.203	0.210	0.197	0.129	0.147

Table 18. Ratio of CO/NO_X as a function of throttle setting (Test 1-6).

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
	CO/NO_x	CO/NO_x	CO/NO_x	CO/NO_x	CO/NO_x	CO/NO_x
	(g/g)	(g/g)	(g/g)	(g/g)	(g/g)	(g/g)
Low Idle	0.501	0.297	0.874			
1	0.065	0.089	0.082	0.057		0.085
2	0.059	0.073	0.073	0.063	0.077	0.068
3	0.038	0.046	0.048	0.046	0.051	0.046
4	0.053	0.052	0.057	0.061	0.043	0.059
5	0.068	0.054	0.056	0.072	0.057	0.071
6	0.113	0.084		0.105	0.081	0.113
7	0.077	0.057	0.056	0.091	0.060	0.064
8	0.067	0.053	0.052	0.069	0.063	0.061
7	0.074	0.055	0.050	0.080	0.064	0.072
6	0.110	0.091	0.072	0.106	0.093	0.120
5	0.072	0.054	0.041	0.057	0.070	0.063
4	0.054	0.047	0.044	0.040	0.057	0.048
3	0.049	0.042	0.041	0.037	0.053	0.042
2	0.081	0.066		0.054	0.081	0.076
1	0.077	0.073	0.073	0.064	0.098	0.079
Low Idle	0.238	0.172		0.181	0.306	0.212

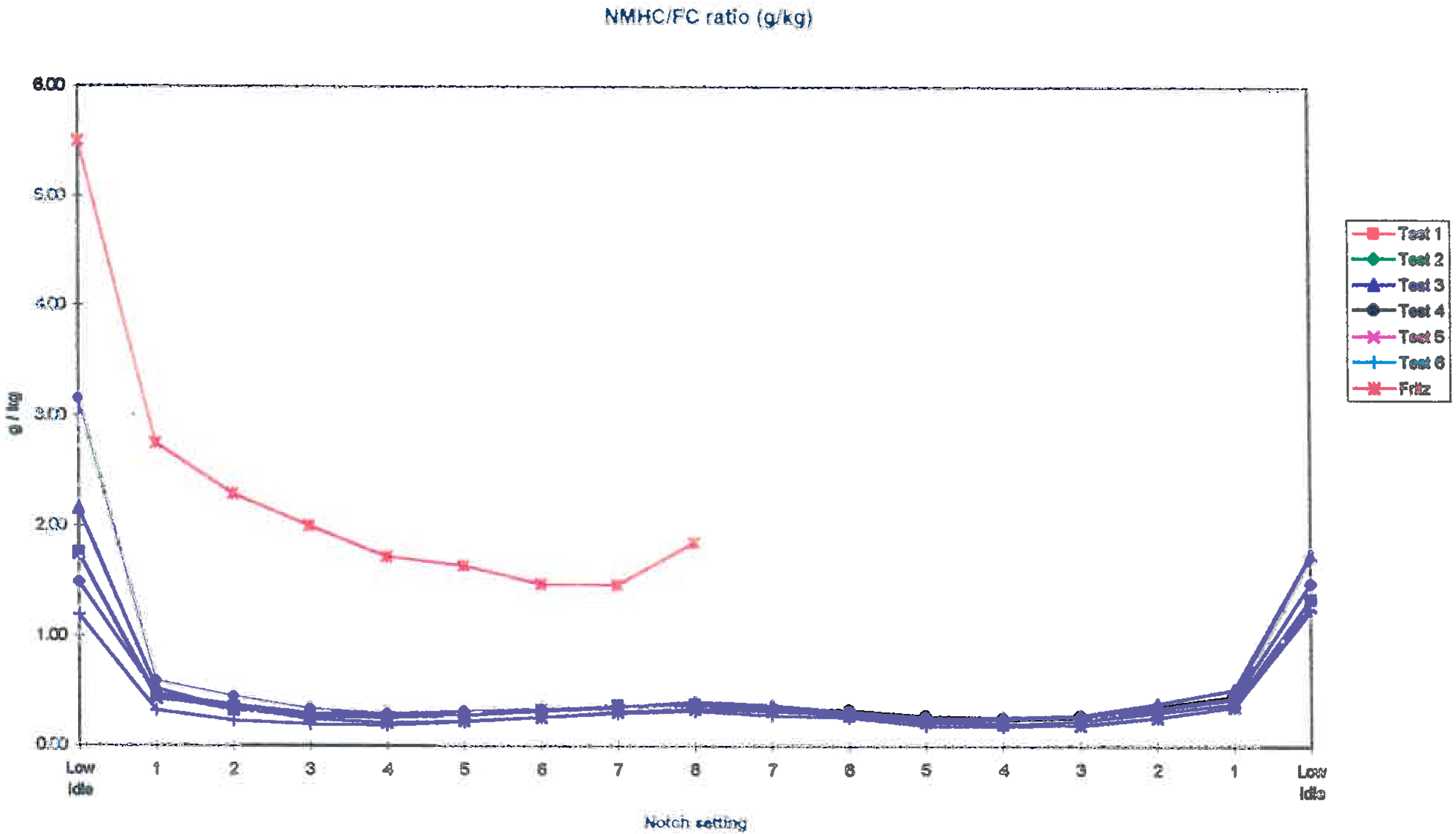

Figure 3. Specific emission rates of NMHC as a function of throttle setting (Test 1-6, Fritz).

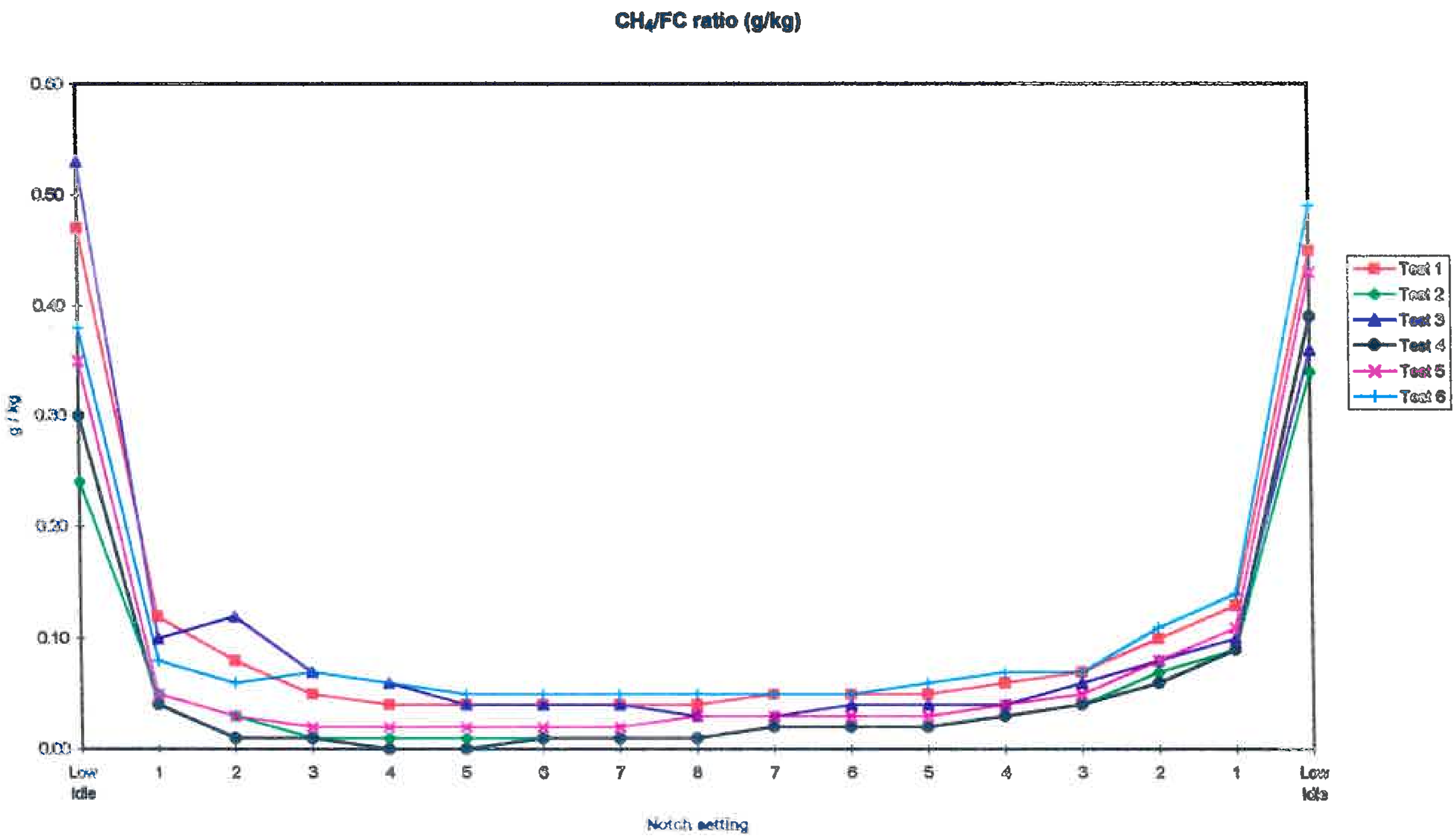

Figure 4. Specific emission rates of CH_4 as a function of throttle setting (Test 1-6).

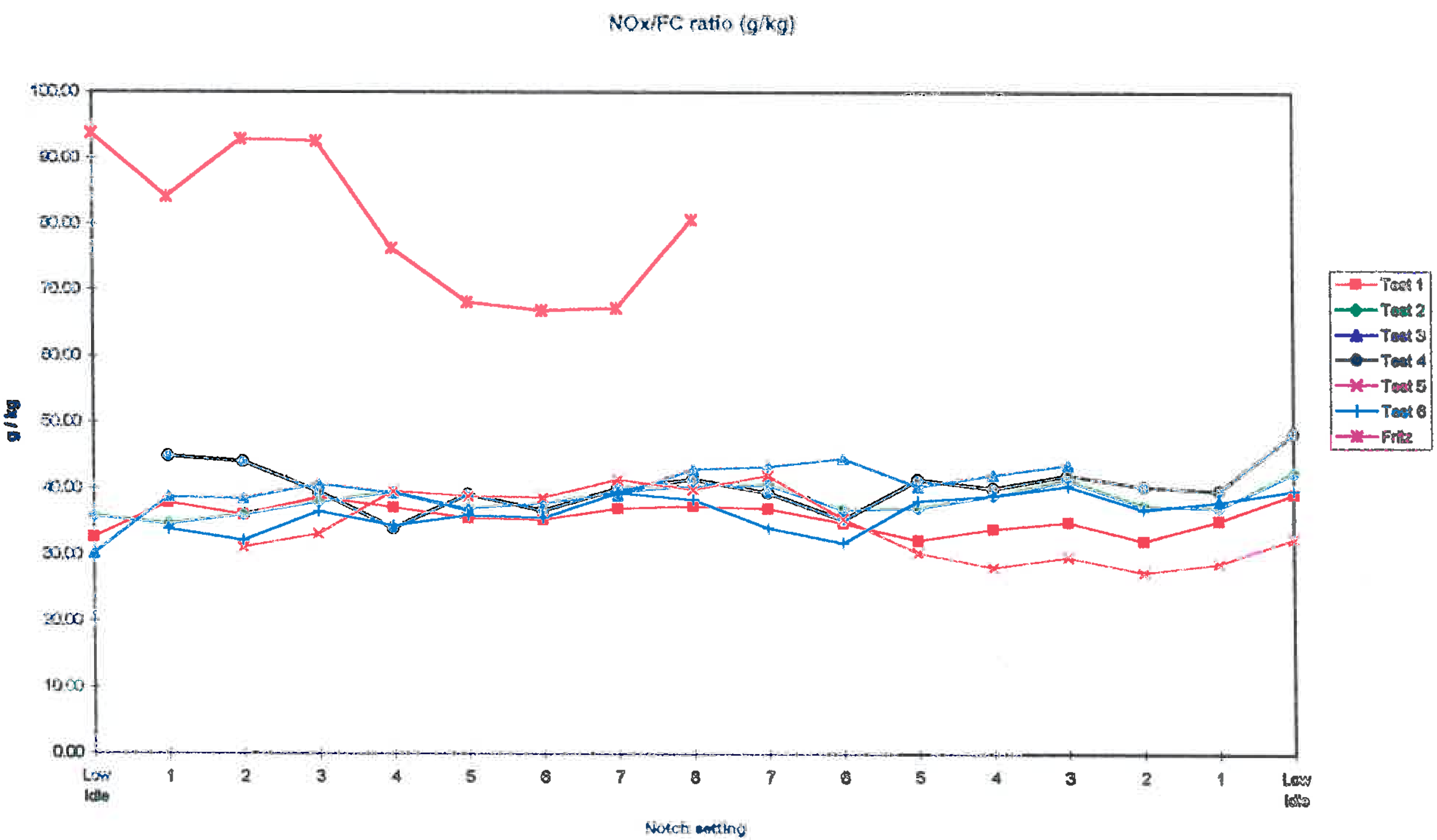

Figure 5. Specific emission rates of NO_X as a function of throttle setting (Test 1-6, Fritz).

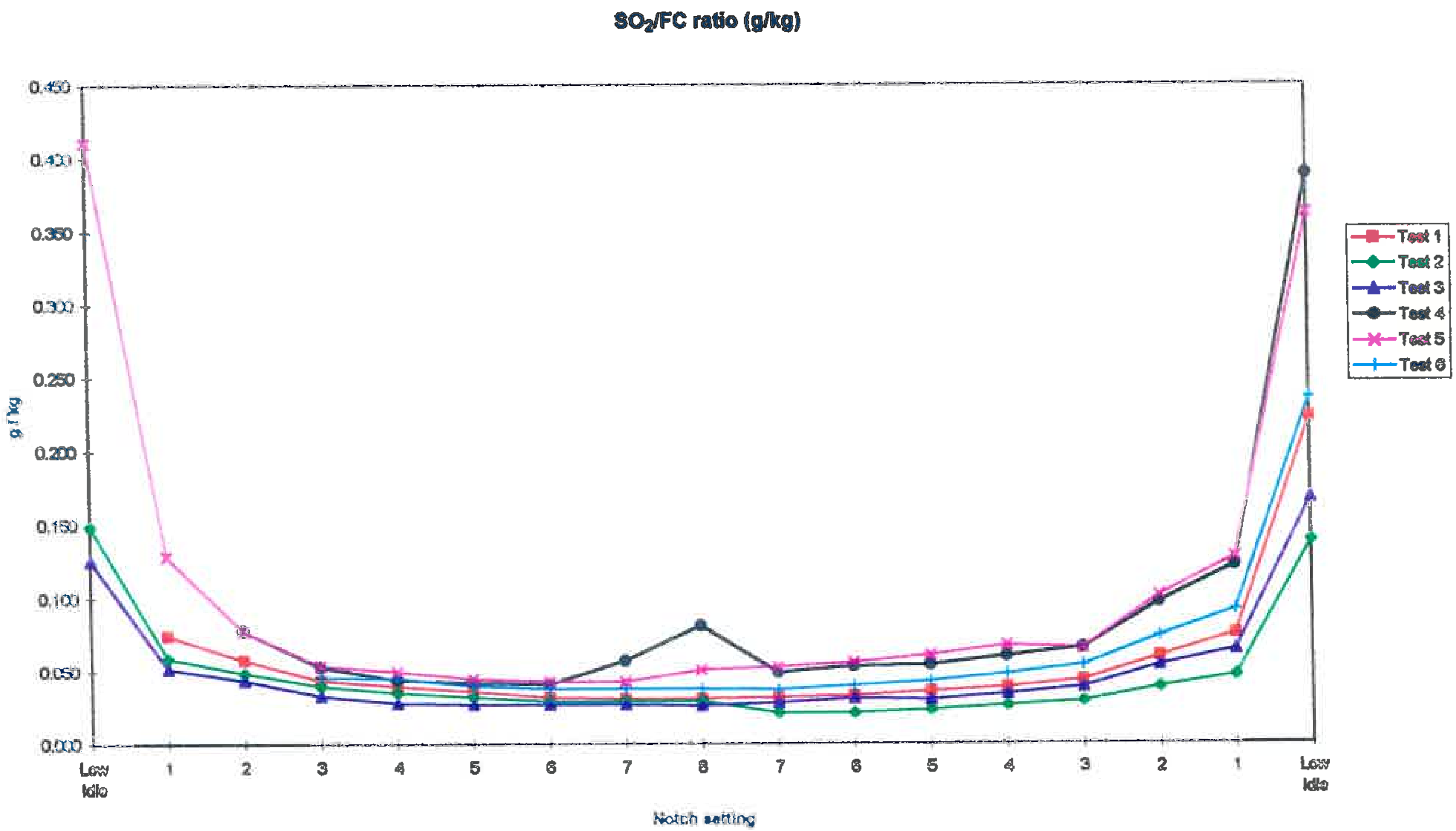

Figure 6. Specific emission rates of SO_2 as a function of throttle setting (Test 1-6).

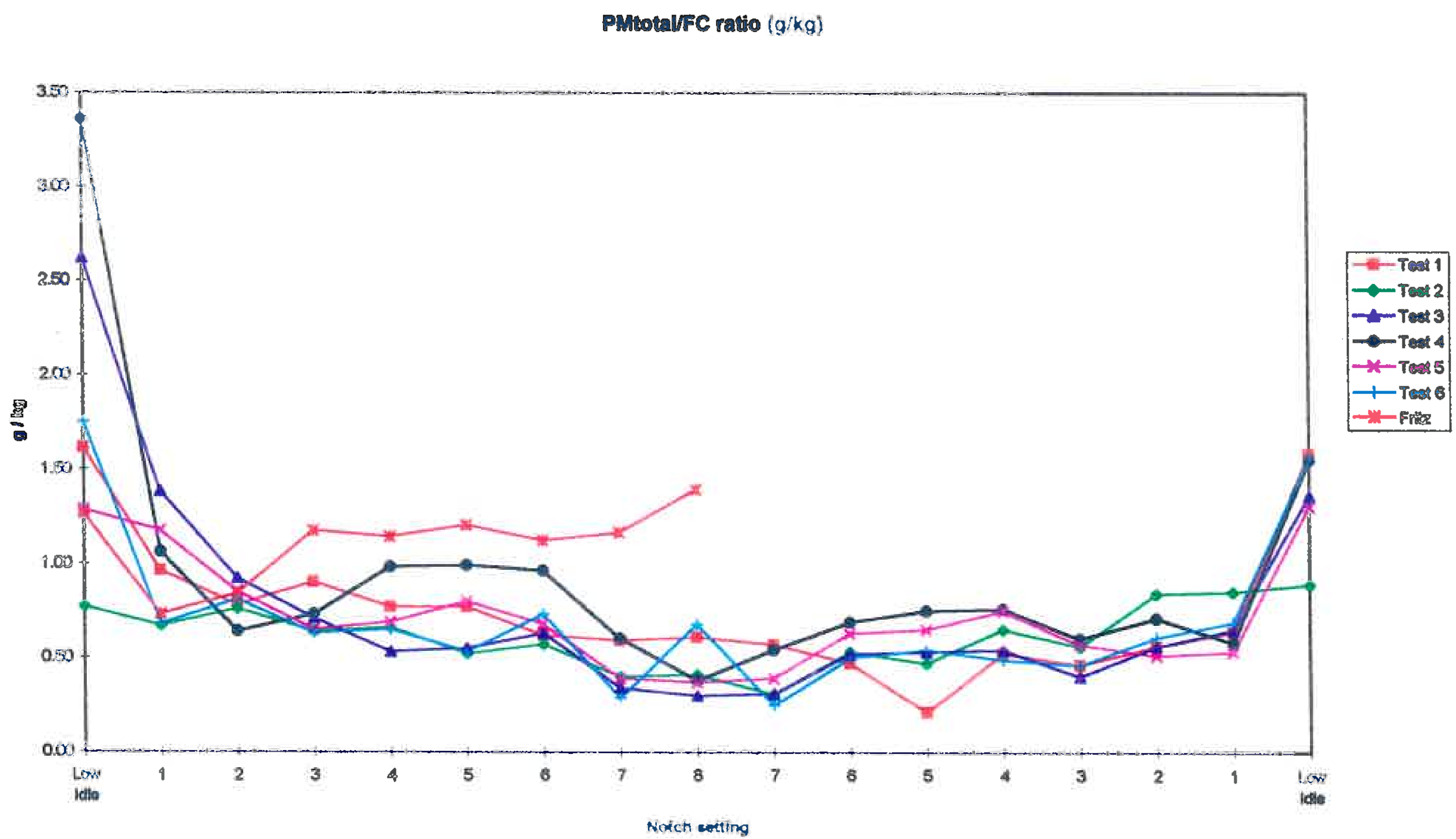

Figure 7. Specific emission rates of PM_{total} as a function of throttle setting (Test 1-6, Fritz).

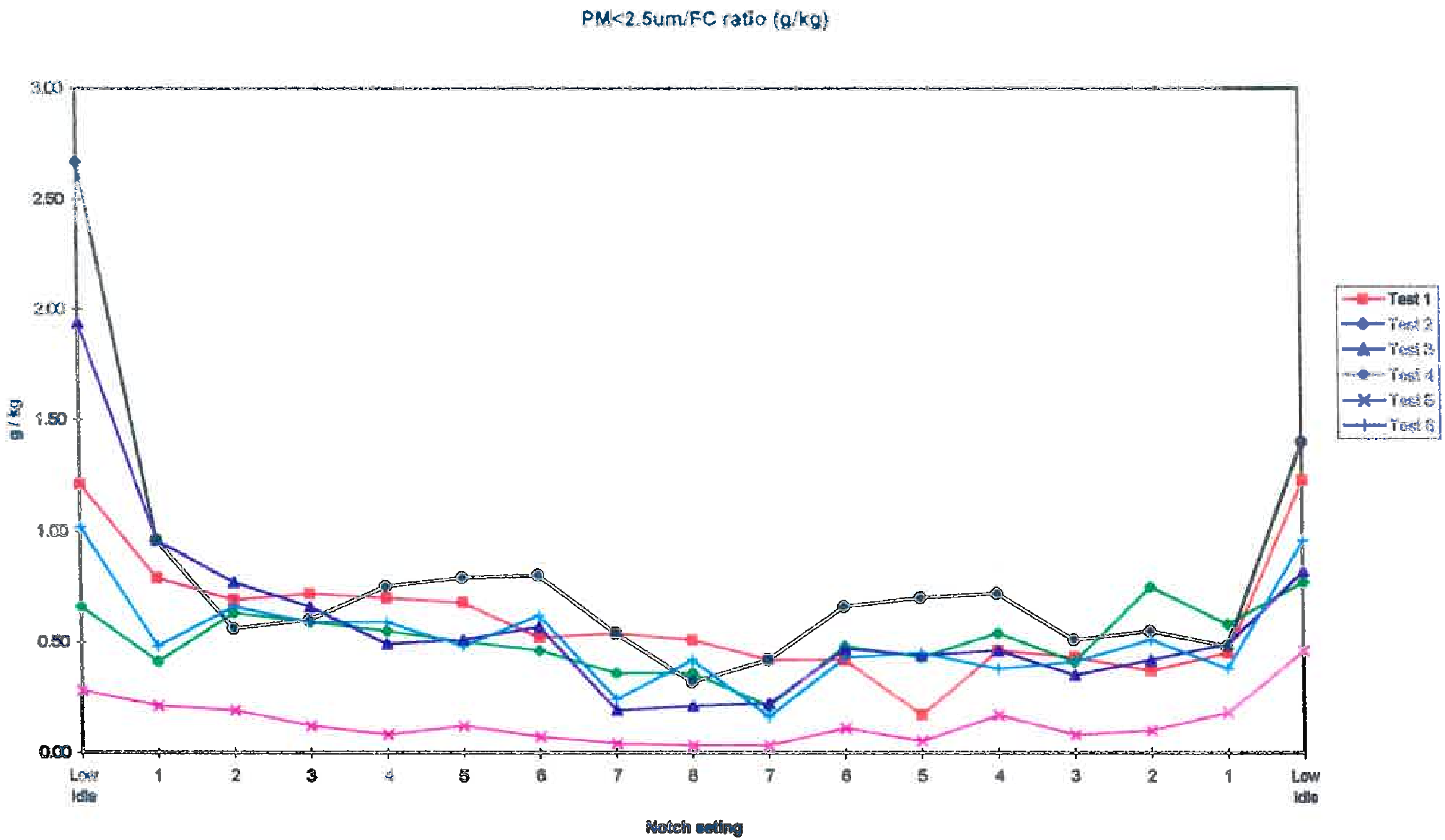

Figure 8. Specific emission rates of $PM_{<2.5\ \mu m}$ as a function of throttle setting (Test 1-6).

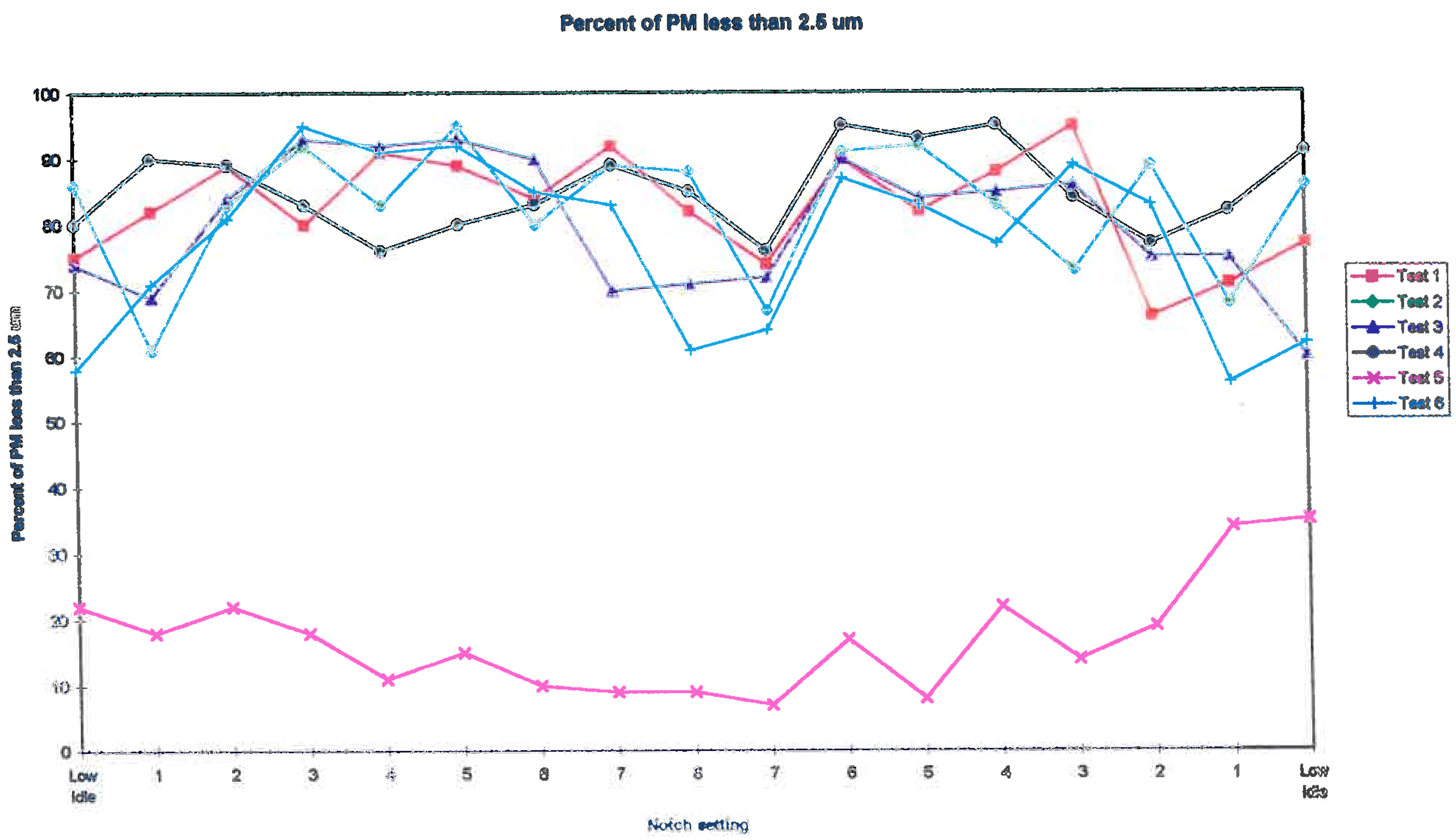

Figure 9. Percent of particulate matter less than 2.5 μm diameter (Test 1-6).

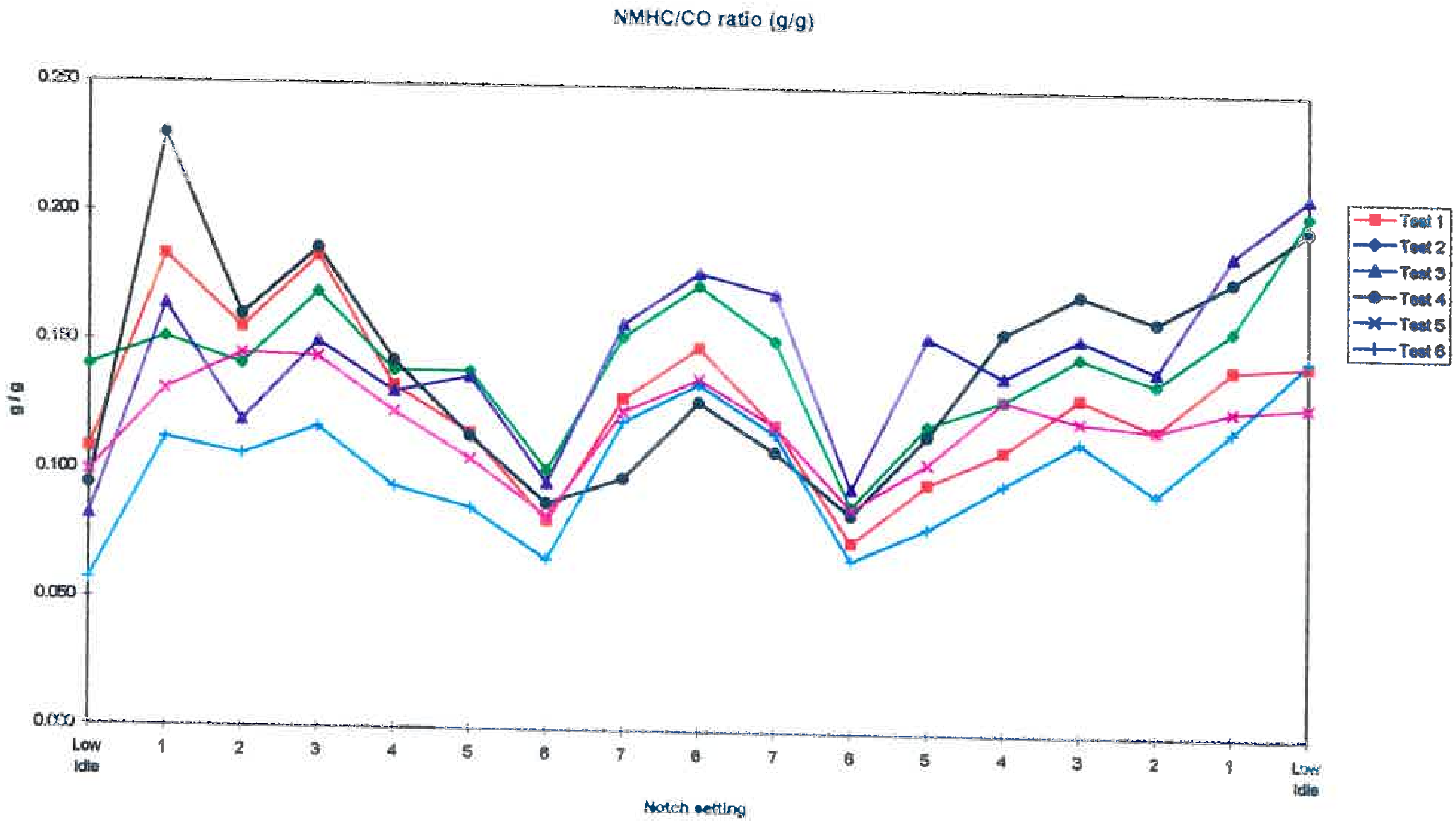

Figure 10. Ratio of NMHC/CO (Test 1-6).

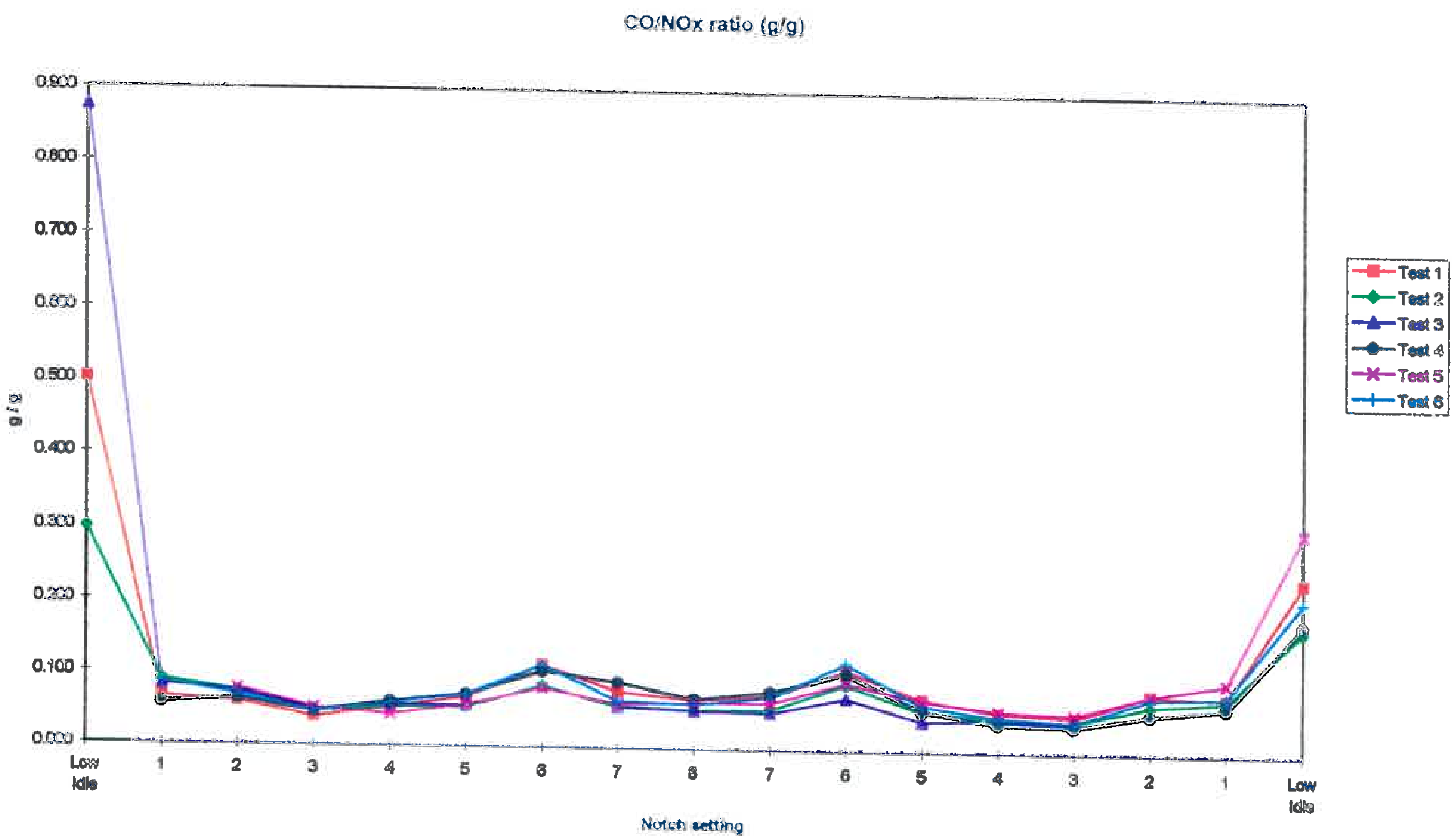

Figure 11. Ratio of CO/NO_X (Test 1-6).

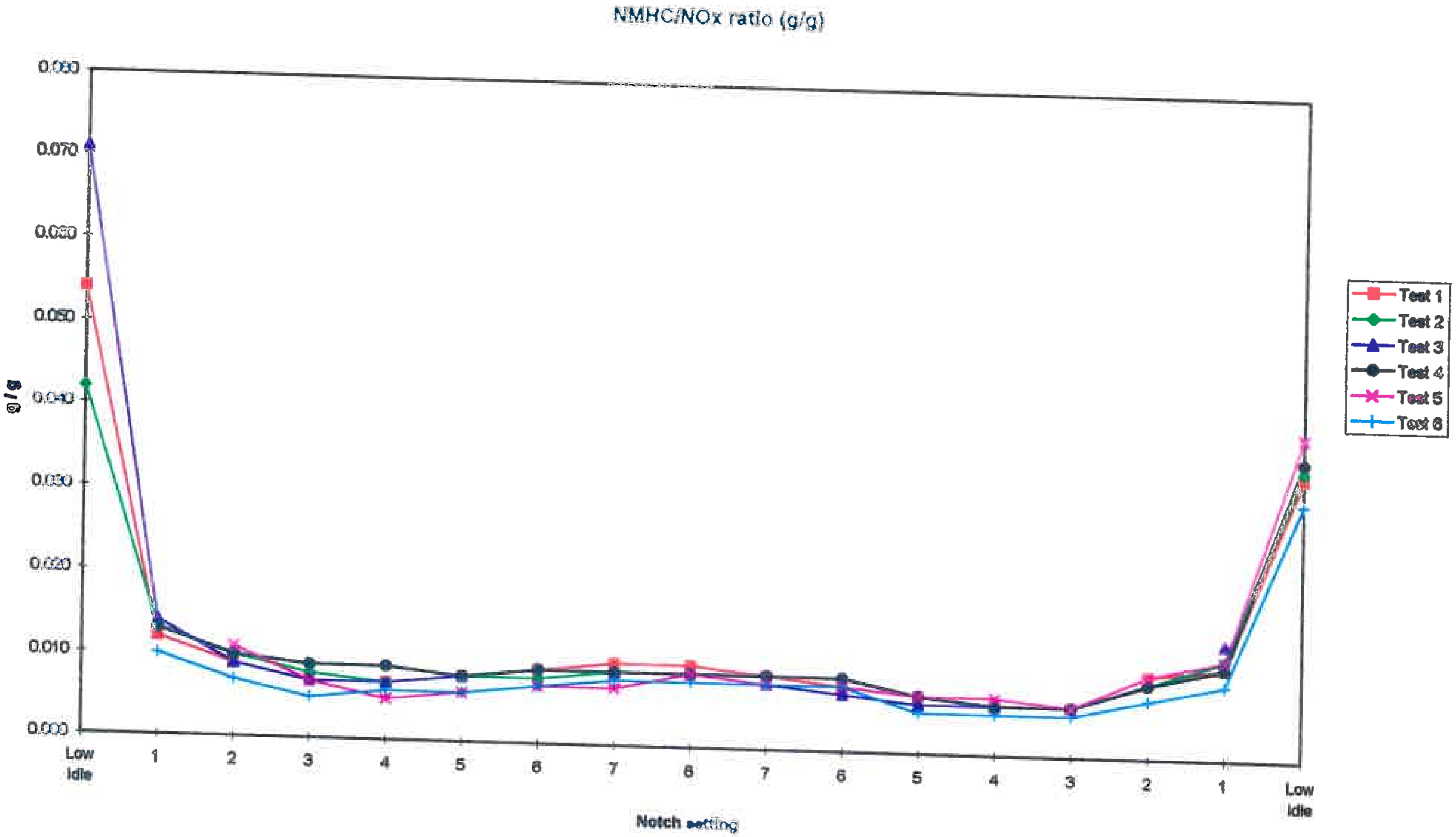

Figure 12. Ratio of NMHC/NOx (Test 1-6).