12th International Symposium "Transport and Air Pollution" / 12° Colloque international "Transports et pollution de l'air", Avignon, 16 - 18 *June* / juin 2003
proceedings / actes, n°92, tome / Vol. 2, Inrets ed., Arcueil, France, 2003, p. 183-190

Regulated and unregulated exhaust emissions from nine passenger cars

Bernhard Mittermaier, Dieter Klemp & Hermann-Josef Buers
FZ Jülich, Institut für Chemie und Dynamik der Geosphäre, ICG II: Troposphäre, D-52425 Jülich
Fax +49 24 61 61 32 40 - email: b.mittermaier@fz-juelich.de

Abstract
Nine different cars with latest exhaust gas treatment systems were tested on a chassis dynamometer in the certification cycles MVEG and FTP-75 as well as in two more demanding driving cycles. The cars had different engine concepts, i.e. conventional gasoline engine, gasoline engine with direct fuel injection and diesel engine. While all cars fulfilled the exhaust limits in the certification cycle, some severe exceedances were found in other cycles, especially for carbon monoxide in the case of gasoline engines. High emissions of NO_x - and here especially nitrogen dioxide - from diesel engines and gasoline engines with direct fuel injection are especially interesting from the perspective of air quality due to their relevance for ozone chemistry.
Keys-words: *exhaust, emissions, gasoline, diesel, ozone.*

Résumé
Émissions de gaz d'échappement régulées et non-régulées de neuf voitures
Neuf voitures différentes avec les systèmes les plus modernes de traitement de gaz d'échappement ont été testées sur un banc d'essai à dynamomètre sous les conditions des cycles de certification MVEG et FTP-75 et dans deux cycles de conduite encore plus exigeants. Les véhicules avaient des concepts de propulsion différents, à savoir des moteurs Otto conventionnels, des moteurs Otto à injection directe ainsi que des moteurs Diesel. Dans le cycle de certification, les véhicules étaient conformes aux normes pour les gaz d'échappement, mais dans d'autres cycles de test des dépassements considérables ont été constatés, notamment en ce qui concerne les monoxydes de carbone dans le cas des moteurs Otto. Les émissions élevées en NO_x – et ici notamment en NO_2 – des véhicules Diesel et des moteurs à injection directe ont une importance particulière du point de vue de la qualité de l'air dû à leur importance pour la chimie de l'ozone.
Mots clefs: *gaz d'èchappement, émissions, essence, diesel, ozone.*

Introduction

Emissions of passenger cars were first regulated at European level in the early 1970s by the directives 70/220/EEC (gasoline engines) and 72/306/EEC (diesel engines). Thereafter, several directives have sharpened the limits considerably. Today, the EURO3-limits are effective, and most new gasoline cars already fulfill the EURO4-limits, which is not mandatory before the year 2005. Nevertheless, the type approval figures do not necessarily reflect the real world emissions of vehicles because the approval testing cycle MVEG is quite undemanding (Hassel 1994), even though cold start emissions were included for EURO3- and EURO4-cars. Therefore it seems to be important to quantify the emissions of modern cars under rather realistic conditions.

Furthermore it has to be noted that from the perspectives of air quality and climate not only the regulated compounds CO, NO_x, HC and PM play major roles. For example, NO and NO_2 are recorded as sum NO_x although they play contrary roles in ozone chemistry. Therefore, several in-depth investigations beyond the regulated compounds seem to be necessary (Harrison 1996).

In this work, nine different cars were tested on a chassis dynamometer. The cars had different engine concepts, i.e. conventional gasoline engine, gasoline engine with direct fuel injection and diesel engine. Besides the well-known European and American driving cycles MVEG and FTP-75 which are used in type approvals, all cars were tested also in the "Autobahn-cycle", which represents the driving on German highways, and in the "MOBINET-cycle" which represents driving in the city of Munich. O_2, CO, CO_2, N_2O, NO, NO_2, HC, fuel consumption and air mass were recorded on a second-by-second basis. A brief overview of the literature was recently given by the authors (Mittermaier 2003).

1 - Experimental

Vehicles and driving conditions

The measuring program included eight different cars of the model years 2000 and later which were compliant with EURO3, EURO4, D3 or D4-exhaust regulation standard. For reasons of comparison to older cars, one EURO2 car (model year 1996) was tested either. Three cars had conventional gasoline engines (spark ignition, SI), three cars had SI-engines with direct fuel injection (SI-DI) and three cars had diesel engines (compression ignition, CI) with direct injection. All SI-engines had three-way-catalysts; the diesel engines were equipped with oxidative catalytic converters. For details see Table 1.

n°	Name	Engine type	Capacity [cm³]	Power [kW]	Model Year	Mileage [km]	Exhaust limit	Source
1	Ford Mondeo	SI	1796	85	2000	6.100	D4	FZ Jülich
2	VW Golf IV	SI	1984	85	2000	83.600	D4	FZ Jülich
3	Ford KA	SI	1299	44	2001	53.400	D4	car rental
4	VW Polo FSI	SI-DI	1390	63	2002	5.900	EURO4	Volkswagen AG
5	Mitsubishi GDI Space Star	SI-DI	1834	90	2001	38.200	D3	car rental
6	VW Golf FSI	SI-DI	1598	81	2002	13.300	EURO4	car rental
7	VW Golf III TDI	CI	1896	66	1996	146.800	EURO2	private
8	VW Golf IV TDI	CI	1896	85	2002	16.300	EURO3	car rental
9	Mercedes-Benz C220 CDI	CI	2148	105	2002	19.600	EURO3	car rental

Table 1: *Overview of the test vehicles. SI=spark ignition, SI-DI = spark ignition with direct fuel injection, CI=combustion ignition. D3 and D4 are special German exhaust limits. With regard to taxation such cars are treated like EURO3 and EURO4, respectively.*

Tableau 1 : Aperçu des véhicules testés. SI=moteur Otto, SI-DI=moteur Otto à injection directe, CI=moteur Diesel. D3 et D4 sont des normes de gas d'échappement allemandes spéciales, qui fiscalement correspondent à EURO3 et EURO4.

All cars were driven with commercial fuel according to the manufacturer's guidelines without further specification. The emission measurements were performed on the chassis dynamometer of RWTÜV Fahrzeug GmbH in Essen, Germany. They were carried out under the conditions of four different driving cycles (Figure 1 and 2):

MVEG: Certification cycle for all new cars in the EU. The cycle begins with a cold start. Therefore, the cars are pre-conditioned at 20 °C - 30 °C for at least 12 hours. The cold start is followed by 40 seconds with idle engine for EURO1/2 and D3/D4 cars. Sampling begins after these 40 seconds. For EURO3 and EURO4 cars the 40 seconds are omitted; sampling starts right from the beginning.

The cycle is divided into two phases. Phase 1 consists of 4 repetitive parts that shall reflect urban driving. The average speed is 19 km/h. The second phase reflects extra-urban driving with a speed up to 120 km/h at an average of 63 km/h. The MVEG cycle is quite undemanding due to low engine loads and moderate accelerations. For example, the beginning of the extra-urban part is an acceleration from 0 km/h to 70 km/h in 41 seconds.

FTP-75: Certification cycle for new cars in the US and several other countries. The FTP test is divided into three phases. The test begins with a cold start. In the first test phase an average speed of 41 km/h is driven. In the second test phase the average speed is only 26 km/h. After the second test phase the engine is shut off for 10 minutes and then the test continues with a warm start. The driving pattern of this third phase is identical with the first phase. By comparing the emissions obtained in the first and in the third test phase, the effects caused by the cold start procedure can be derived from the data. This cycle reflects the driving behavior in the US satisfactorily; engine load and maximum speed are comparable to the conditions in the US.

Autobahn-cycle: This cycle was developed by by Hassel (1994), TÜV Rheinland, Germany. It represents driving behavior on the German expressways "Autobahn". Again this cycle consists of three phases. After a running start at 95 km/h, the average velocity is increasing. In the third phase of the test cycle the cars have to accelerate from 127 km/h to the maximum speed of 162 km/h in 40 seconds. This means high engine loads which are neither covered in the FTP-75 cycle nor in the MVEG cycle.

MOBINET-cycle: This cycle was developed within the BMBF-funded project MOBINET by Klemp (2002). It is representative for the driving in the city of Munich because its distributions of velocity (v), acceleration (a) and engine load (v*a) are the same as the observed ones in Munich during 20 trips with a total of 70.000 second-by-second-values. The cycle consists of parts which were actually driven on a road, whereas MVEG and Autobahn are artificial. The MOBINET-cycle begins with a warm start, followed by normal urban driving controlled by traffic lights. This phase ends with one part recorded on a 4-lane-street with a speed maximum of 80 km/h. The second phase reflects stop-and-go with an average velocity of only 5 km/h, whereas the third phase shows the driving on a city-highway with a speed limit of 120 km/h. At the dynamometer, this phase is driven in duplicate in order to reach the detection limits for the sampling bags (cf. the next section).

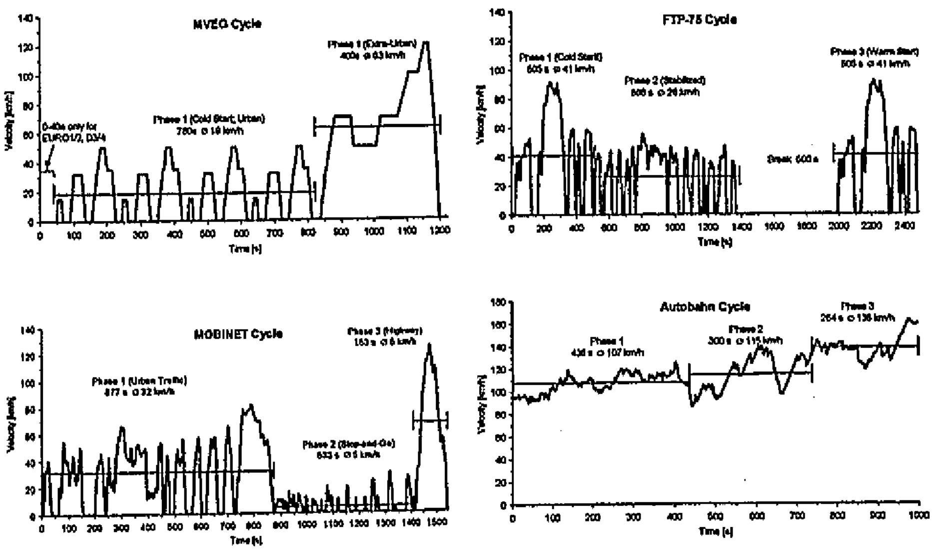

Figure 1: Driving cycles of the measuring program.

Figure 1: Cycles de conduite dans le programme de mesure

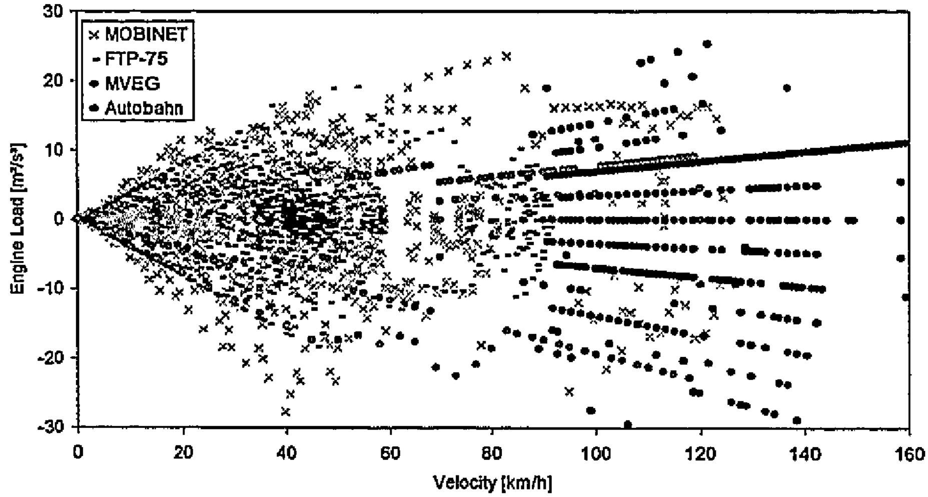

Figure 2: Distribution of engine load (velocity times acceleration) vs. velocity.
Figure 2: Répartition de la charge spécifique (produit de vitesse et d'accélération) vs. vitesse

Analysis

Fuel consumption (PLU 401-108, Pierburg Corp.), lambda value and the signal from the air mass sensor were recorded every second by our data acquisition system. As pointed out by Lenaers (1996), the current total exhaust gas mass flow can be calculated from the signals from the air mass sensor, the respective lambda value and the momentary fuel consumption. From the exhaust stream a flow of around 5 L/min is sucked in and analyzed by our gas analytics. NO, N_2O, CO and CO_2 mixing ratios in the exhaust gas are measured by means of commercially available gas analyzers (URAS, ABB Corp.) using non-dispersive infrared (NDIR) detection principle. The NO and NO_2 content of the exhaust gas is analyzed by UV-absorption (LIMAS, ABB Corp.). The total HC content is measured by a FID system (ABB Corp.). Low mixing ratios of CO were also measured by a modified trace gas analyzer (TE 48 C, Thermo Instruments). Emission values of CO, CO_2, NO, NO_2 and HC in g/s and g/km were calculated from the measured mixing ratios using the respective total exhaust gas mass flows, taking into account the individual time shifts between engine exhaust output and analyzing time for the different gas analyzers. Data of the vehicle velocities were provided by RWTÜV, together with measurements of the emissions with three independent devices. The four measurements (one by FZ Jülich, three by RWTÜV) generally agreed better than 10% (Klemp 2002). A detailed comparison will be published elsewhere. In this work, only the measurements of FZ Jülich are used.

2 - Results

Demand of the different driving cycles

A comparison of the three vehicles with conventional gasoline engines (No. 1-3 in Table 1), all compliant with the D4-exhaust regulation level, shows the bandwidth of emissions that exist in the broad range of velocities and engine loads which are present in the four different driving cycles. Table 2 shows the emissions of the regulated compounds of these cars in the respective driving cycle, together with the D4-exhaust limit. Except for a small excess in NO_x-emissions of the Ford Mondeo, all cars were compliant with the D4-limit in the MVEG-cycle. In the other driving cycles, considerable differences can be found:

- Only the Golf IV exceeded the D4-limits in neither driving cycle. Both the MOBINET-cycle with quite demanding urban driving and the Autobahn-cycle with its high velocities yield emissions comparable to the MVEG. Relatively large differences can be found only between MVEG and FTP-75. This might be due to the fact that the FTP-75 includes a whole cold start, whereas in the MVEG the first 40 seconds after the cold start are omitted. MOBINET and Autobahn do not include cold starts.

- In the Autobahn-cycle with velocities up to 160 km/h, both the Ford Mondeo and the Ford KA exceed the D4-limit for NO_x substantially. The emissions relative to distance exceed the ones from the MVEG by a factor of 2-3.

	Limit D4	MVEG	FTP-75	MOBINET	Autobahn
Ford Mondeo					
CO [g/km]	0.70	0.43	0.89	3.37	2.89
NO_x [g/km]	0.07	0.09	0.19	0.09	0.18
HC [g/km]	0.08	0.08	0.08	0.05	0.08
VW Golf IV					
CO [g/km]	0.70	0.20	0.74	0.50	0.47
NO_x [g/km]	0.07	0.04	0.06	0.06	0.04
HC [g/km]	0.08	0.02	0.04	0.01	0.01
Ford KA					
CO [g/km]	0.70	0.59	0.82	3.10	13.07
NO_x [g/km]	0.07	0.07	0.06	0.08	0.13
HC [g/km]	0.08	0.05	0.09	0.08	0.09

Table 2: Emissions of the cars with conventional gasoline engine in the different driving cycles (g/km).

Tableau 2 : Emissions des véhicules avec moteur Otto conventionnel dans les différents cycles de conduite (g/km).

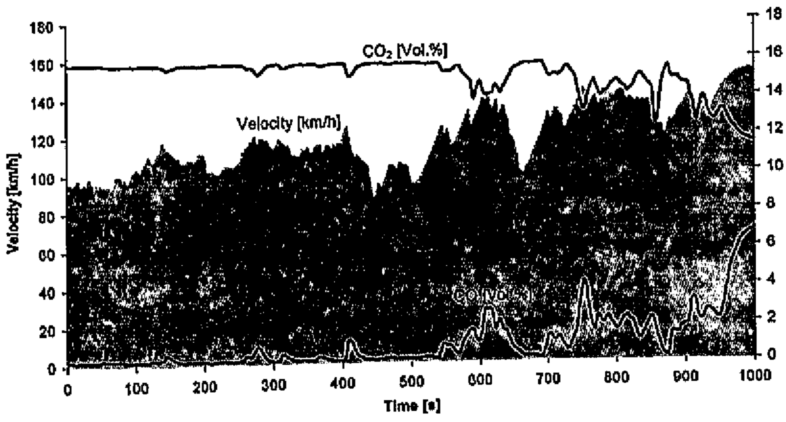

Figure 3: Emissions of carbon monoxide (CO) and carbon dioxide (CO_2) by the Ford KA in the Autobahn-cycle.

Figure 3: Emissions de monoxyde de carbone (CO) et de dioxyde de carbone (CO_2) de la Ford KA dans le cycle Autobahn.

- The most significant exceedances of the D4-limits happened for CO with the Ford Mondeo and Ford KA in the two demanding cycles MOBINET and Autobahn. The Ford Mondeo exceeded the D4-limits by a Factor of 5 in the MOBINET-cycle and by a factor of 4 in the Autobahn-cycle. For the Ford KA, who had the lowest-powered engine in the measuring program, CO-emissions in

MOBINET-cycle and Autobahn-cycle grew dramatically by a factor of 5 and 20, as compared to MVEG. In the last part of the Autobahn-cycle, CO-emissions reached 7 Vol. % (see Figure 3) probably due to full power enrichment. Such emission levels are expected to be reached by non-catalyst-cars.

Comparison of different model years / aged cars

The measuring program included one older car, a 6-years-old VW Golf III TDI with a mileage of almost 150.000 km. This car was compared to a VW Golf IV TDI from 2002 with little more than a tenth of the mileage. Both cars have engines with the same concept and the same capacity, but the Golf IV has more power (86 kW instead of 66 kW) and fulfills EURO3 instead of only EURO2.

	Limit	MVEG	FTP-75	MOBINET	Autobahn
VW Golf III TDI EURO2					
CO [g/km]	1.00	0.62	N/A	0.30	0.17
NO_x [g/km]	-	0.37	N/A	0.58	0.86
HC [g/km]	-	0.13	N/A	0.04	0.06
NO_x + HC [g/km]	0.90	0.50	N/A	0.62	0.92
VW Golf IV TDI EURO3					
CO [g/km]	0.64	0.13	0.10	0.11	0.09
NO_x [g/km]	0.50	0.39	0.39	0.46	0.69
HC [g/km]	-	0.01	0.01	0.00	0.00
NO_x + HC [g/km]	0.56	0.40	0.40	0.46	0.69

Table 3: *Emissions of the diesel-engine driven cars Golf III TDI and Golf IV TDI in the different driving cycles. Due to a handling error, no valid results were obtained for the Golf III TDI in the FTP-75 cycle.*

Tableau 3 : Emissions des voitures Diesel Golf III TDI et Golf IV TDI dans les différents cycles de conduite. A cause d'une erreur de manipulation, aucun résultat valable n'a pu être obtenu pour la Golf III TDI.

Both cars fulfilled the requirements of their respective emission limits in the MVEG (Table 3). The trends in the emissions in the perspective of technical progress seem to be interesting:

- CO emissions have been reduced considerably by 50-80%, depending on the driving cycle. The smallest reduction refer to the Autobahn-cycle which has the highest velocities.
- HC-emissions have been reduced by one order of magnitude to a very low level. The Golf IV TDI emits HCs almost exclusively during the cold start, which is part of MVEG and FTP-75. When the engine is warm (MOBINET and Autobahn), less than 10 mg HC are emitted per kilometer.
- NOx emissions practically remain on the same level. While there is even a slight increase in emissions during the MVEG (though not directly comparable due to the 40s-idle-period in the test for the Golf III, see Figure 1), emissions in the other cycles have been reduced by only 20%.

These findings lead to the conclusion that from the perspective of air chemistry and air quality a shift in the relevance of the exhaust compounds can be expected: While CO- and HC-levels will decrease in the future, NO_x-emissions will rather increase. This will take place especially because of the rising share of diesel cars in the fleet of passenger cars. Diesel cars emit approximately five times more NO_x than gasoline cars. The findings from these two cars have to be assured statistically.

Importance of speciated nitrogen oxide analysis

The nitrogen oxides NO (nitric oxide) and NO_2 (nitrogen dioxide) are usually recorded as sum value NO_x. Both species can be transformed into each other through the reaction with ozone:

$$NO + O_3 \Leftrightarrow NO_2 + O_2$$

For many conditions the Leighton relationship holds (Leighton 1961), according to which these species are in balance [$J(NO_2)$ is the photolysis rate of NO_2]:

$$\frac{[O_3][NO]}{[NO_2]} = const. \cdot J(NO_2)$$

This means that in dependence of the kind of nitrogen oxide emitted, ozone is either produced (from NO_2-emissions) or destroyed (from NO-emissions). While conventional gasoline engines almost exclusively emit NO (> 99%), the share of NO_2 from NO_x in DI-SI engines and in CI-engines is between 10% and 60%, see Figure 4 and Figure 5. Increasing shares of NO_2 lead to several effects:

- Less ozone coming from rural background air into the cities will be destroyed due to a smaller amount of NO. This is equivalent to rising ozone levels in the cities, which is consistent with the observation of increasing ozone levels in the last years, according to Umweltbundesamt (2002).

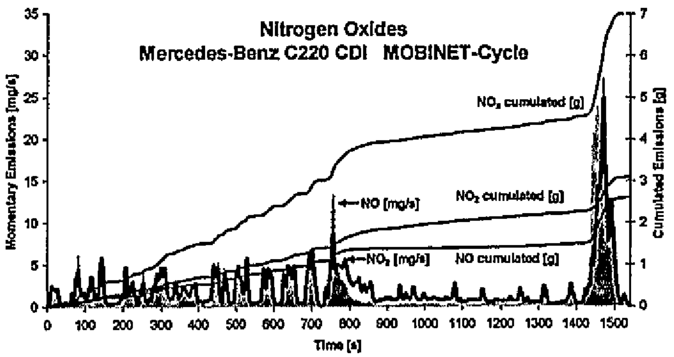

Figure 4: Emissions of nitrogen oxides by Mercedes-Benz C220 CDI in the MOBINET-cycle

Figure 4: Emissions d'oxydes d'azote de la Mercedes-Benz C220 CDI dans le cycle MOBINET

- Nitrous acid, HONO, is mainly formed heterogeneously on surfaces in the presence of water and NO_2 and is also directly emitted from diesel engines, as found by Kurtenbach (2001). HONO is a source of the most important daytime radical, the hydroxyl radical OH, which acts as initiator of multiple photochemical cycles.

$$2\,NO_2 + H_2O \rightarrow HNO_3 + HONO$$
$$HONO + h\nu \rightarrow OH + NO$$

- Increasing ozone levels and increasing HONO levels both result in higher OH concentrations and therefore in an acceleration of many photochemical reactions.

Worth mentioning is furthermore the emission of NO by the Polo FSI *after* the driving cycle (Figure 5). This car is equipped with a NO_x-storage catalyst, described by Glück (2000), which bases on the reversible reaction of NO with barium oxide:

$$BaO + 2\,NO + 1.5\,O_2 \Leftrightarrow Ba(NO_3)_2$$

It seems that after the cycle the back reaction took place, leading to the emission of NO. Other pollutants have not been emitted during that time.

Conclusion

In the last years, emissions of new cars have been reduced substantially. Nevertheless, a close look at the different pollutants is still necessary. While modern catalyst effectively convert hydrocarbons, NO_x and especially nitrogen dioxide stay a problem, aggregative due to the rising share of diesel engines and gasoline engines with direct fuel injection. They result in higher ozone levels and faster photochemistry. Furthermore, some cars emit high amounts of carbon monoxide during high engine loads and velocities. Therefore, not only the certification cycle MVEG but also more demanding driving cycles which rather realistic driving patterns must be taken into account.

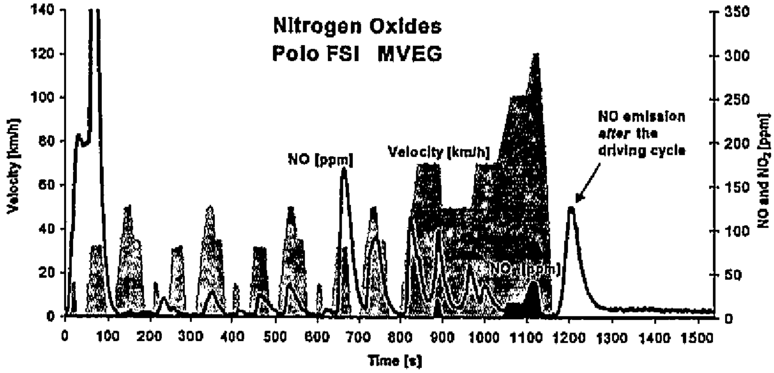

Figure 5: Emissions of nitrogen oxides by the Polo FSI in the MVEG
Figure 5: Emissions d'oxydes d'azote de la Polo FSI dans le MVEG

Acknowledgments

The authors wish to thank Volkswagen AG for providing the Polo FSI. This work was supported by BMBF in the project "MOBINET".

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