Reduction of Soot Emission from Diesel Fuelled Engine Using A Novel Diesel Particulate Filter

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***Abstract*—Malaysia is a rapidly developing country that is working hard towards achieving its Vision 2020, of becoming a developed country. The increase in economic activities has also resulted to an increase in the country air pollution problem. One of the main sources of the pollutants is emissions from motor vehicles, which is originated from incomplete fuel combustion; either diesel or gasoline. Among the emissions that are considered to be harmful to human health and environment are carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NO_X), sulphur oxide (SO_X) and carbon soot. Most emissions are equally contributed both gasoline and diesel fuelled vehicles. However, heavy duty diesel fuelled vehicles are the main contributor for the soot and NO_X emissions. At present, in Malaysia, there is no regulation that forces diesel fuelled vehicles to be installed with exhaust after treatment system, which is able to reduce soot emission. In this paper, an overview on the control of emissions from diesel fuelled vehicles in Malaysia will be presented. In addition to that, description of a novel exhaust after treatment system, based on porous medium, which aims to suppress soot emission from diesel fuelled vehicles, is also be included.**

***Keywords*:** diesel engines, soot emissions, exhaust after treatment

I. Introduction

Transportation sector is one of the important sectors that drive the country economy. Statistic from Malaysia Department of Transport shows that from 2003 until March 2008, the total number of vehicle registered is 4.7 million. These numbers will be definitely increasing in the coming years. The presence of these vehicles bring along the problem of air pollution because of the incomplete combustion by product that is emitted from engine exhaust pipe such as CO, HC, NO_X, SO_X and soot [1]

Air pollutant sources in Malaysia can be classified under four main sectors; motor vehicles, power stations, industries and other sources like open burning and trans-boundary sources [2]. The latest Malaysia environmental quality report by Department of Environment reported that emissions load from all sources has increased in year 2006 than 2005 as shown in Figure 1. If no action is taken to prevent this situation, it's becomes more serious because of the emissions effect day till days. It is such silent death to the human and environment. Although Malaysia have a good environment to stabilize the pollutant but it has reached a critical level as witnessed during the recent haze crisis [3] because of the effects to the public and the environment.

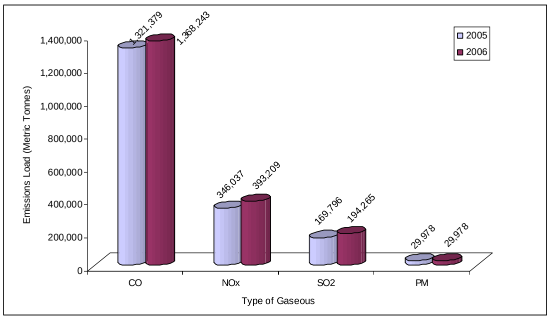

Figure 1: Air pollutant emission load from all sources, 2005-2006 [4]

Mobile sources or motor vehicles include passenger cars, motorcycles, goods vehicles, taxis and buses which are among the contributors to air pollution especially in major cities [2]. Motor vehicles are major contributor for NO_X (70%) and CO (98%) and the other gaseous about (9%) for SO_X and 8% for PM [4].

Figure 2 shows the air pollutant emissions load from motor vehicles between 2005 and 2006. Emissions load for the year 2006 has increase except for NO_2 and PM. In years 2005 and 2006, vans and lorries are the largest contributor for PM_{10} (67.78%), NO_2 (63.02%) and SO_2 (60.56%). Contributors for HC are motorcycles by 60.74% and CO contributor are passenger cars (45.35%) followed by vans and lorries (35.37%) [4].

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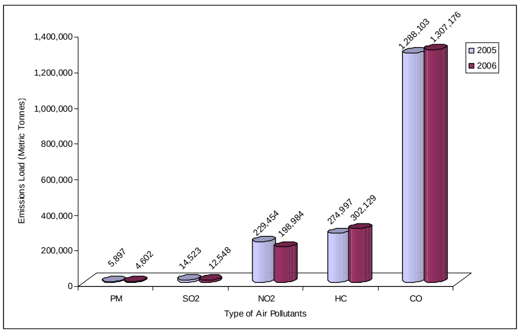


Figure 2: Air pollutant emission load from motor vehicles, 2005-2006 [4]

Increasing concerns on the fuel prices, lowest fuel consumption, higher operating efficiency and low level of CO and HC during cold start have generated noticeable interests on diesel engine as a prime mover. It is classified as powerful, durable and reliable than gasoline engine. Nevertheless, diesel exhaust contain several pollutants that are harmful to public health and can also effect the environment through HC, NO_X, fine PM, CO and combination with other substance [1].

Diesel engine vehicle are not popular in Malaysia as much as gasoline engine vehicle. The usage of diesel engine vehicles only concentrates on vehicles with capacity of 3000cc and above as shown in Figure 3.

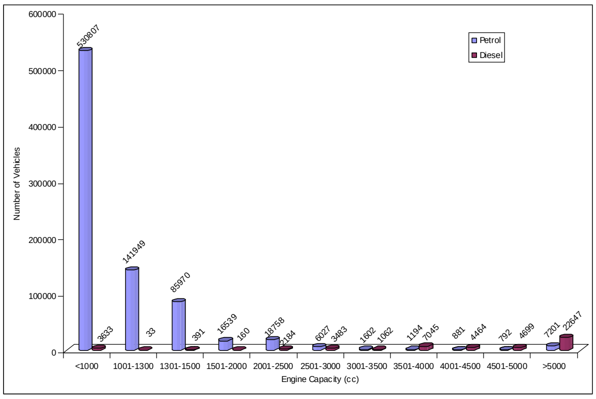


Figure 3: Number of vehicle for new registration for 2006 [4]

Although the number of diesel fuelled vehicle only about 3% of total number of vehicle registered from 2003 until March 2008 the emission issue must be addressed urgently.

In this paper, overviews on the regulations for diesel fuelled vehicle are briefly presented. In addition to that, initial report on the development and performance of new exhaust after treatment for diesel vehicle is also presented.

II. Overview On Emissions Legislation and Enforcement for Diesel Fuelled Vehicles

Emission legislation for diesel fuelled vehicles is included in Environmental Quality Act 1974 (Act 127). Under this legislation, two regulations are specific for diesel fuelled cases. Emissions of smoke and gaseous pollutants from motor vehicle exhausts are controlled under the Environmental Quality (Control of Emission from Diesel Engines) Regulations 1996 and diesel properties under the Environmental Quality (Control Petrol and Diesel Properties) Regulations 2007.

1) Environmental Quality (Control of Emission from Diesel Engines) Regulations 1996

This regulation was enforced beginning 1 September 1996. Part II contains regulations for control of diesel engine on motor vehicle registered after 31 August 1996. For motor vehicle which is already registered but which has a new engine system to replace an existing system they need to obey the standard prescribed in the First Schedule and Second Schedule (refer appendix) for any new model of motor vehicle on or after 1 January 1997. Emission standard of pollutant of motor vehicle for used or new model before and after 1 January 1997 are shown in Table 1 and Table 2. Tests to be conducted by assembler or manufacturer may be determined by the Director General of Road Transport Department, in the presence of an authorised officer, at any approved facility at the cost of the assembler or manufacturer. The test samples of not more than one per centum of the annual projected number of motor vehicles shall be selected at random and they shall submit periodically the results of such tests to the director general of Road Transport Department.

Part III contains regulations for smoke emission control of motor vehicle. This part shall apply to every motor vehicle irrespective of whether it is in use or stationary, or in any bus terminus, taxi stand or private premises or on any private road. For the maximum concentration of smoke shall not exceed Ringelmann No. 2 with the procedure as specified in the Third Schedule and Fourth Schedule (refer appendix). For the maximum density of smoke permitted when tested under the free acceleration test with a smoke meter shall not exceed 50 HSU or other equivalent smoke units or in percentages (%) or other units. The free acceleration test shall be conducted in accordance with the methods specified in the Fifth Schedule (refer appendix).

In Malaysia, the establishment of the inspection centre was awarded to a private company, PUSPAKOM. Its establishment is under policy of the government to provide one integrated inspection which provides services such as initial inspection, routine inspection, re-inspection, special inspection, accident inspection, voluntary inspection and transfer of ownership [5].

Table 1: Emission standard of pollutants of motor vehicles before 1 January 1997 [6]

a) Gross vehicle weight of not exceeding 3.5 tonnes

Reference Mass (rw)	CO	Combined Emission of HC and NO_X
(kg)	g/test	g/test
rw ≤ 1020	58	19.0
1020 < rw ≤ 1250	67	20.5
1250 < rw ≤ 1470	76	22.0
1470 < rw ≤ 1700	84	23.5
1700 < rw ≤ 1930	93	25.0
1930 < rw ≤ 2150	101	26.5
2150 < rw	110	28.0

b) Gross vehicle weight over 3.5 tonnes

Mass of CO	Mass of HC	Mass of NO_X
Grammes per kWh	Grammes per kWh	Grammes per kWh
14	3.5	18

Table 2: Emission standard of pollutants for new models of motor vehicles on or after 1 January 1997 [6]

a) Gross vehicle weight of not exceeding 3.5 tonnes

Reference Mass (rw)	CO	Combined Emission of HC and NO_x	Mass of PM
(kg)	g/test	g/test	g/km
rw ≤ 1250	2.72	0.97	0.14
1250 < rw ≤ 1700	5.17	1.4	0.19
1700 < rw	6.90	1.7	0.25

b) Gross vehicle weight over 3.5 tonnes

Mass of CO	Mass of HC	Mass of NO_x	Mass of PM
Grammes per kWh	Grammes per kWh	Grammes per kWh	Grammes per kWH
4.5	1.1	8.0	0.36

Any offences under these regulations except the offence under regulation 4 which may be compounded accordance with the procedure prescribed in the Environmental Quality (Compounding of Offences) Rules 1978 [P.U. (A) 281/78]. Excessive black smoke emissions from diesel vehicle exhausts are implemented under the AWASI (Area Watch and Sanction Inspection) programme. This programme involves patrols by the Department of Environment mobile squad. Observation and testing of diesel vehicles belching excessive smoke is carried out. On the spot compounds are issued to drivers and owners if their vehicles fail to comply with the stipulated smoke limit of 50 HSU, and a prohibition order (prohibiting vehicle usage) is issued if the smoke limit exceeds 70 HSU. The compound not exceeding RM20,000 and maximum RM100,000 if the cases prosecuted in court or not exceeding 5 years in prison [7].

2) Environmental Quality (Control of Petrol and Diesel Properties) Regulations 2007

This regulation was operated since 1 April 2007 and applies to fuel used in any internal combustion engine (mobile and stationary applications) and in industrial plants. Fuel which is produced, stored, distributed, transported, supplied, sold or offered for sale within Malaysia shall comply with the standard of properties as prescribed in the case of diesel in column (2) of the Second Schedule in the Federal Subsidiary Legislation under this regulation or shown as in the Table 3. This regulations must be followed by the fuel supplier (producer or importer of fuel). It is important because Bernama has reported that Malaysia ranked 78th per 100 country in the list trailing behind the several Asian countries by International Fuel Quality Centre (IFQC) according to the sulphur limits in diesel used by this country.

Table 3: The Malaysian diesel standards (Federal Subsidiary Legislation, Environmental Quality Act 1974 [Act 127]) [8].

(1)	(2)		(3)
PROPERTIES	EURO 2-M		TEST METHOD
	MINIMUM	MAXIMUM	
Density at 15 deg C, kg/l	0.810	0.870	ASTM D 1298/ D 4052
Cetene Number	49	-	ASTM D 613/ D 6890/ IP 498
Or			
Cetene Index	49	-	ASTM D 976 D 4737
Distillation at 95% deg C	-	370	ASTM D 86
Total Sulphur, mg/kg	-	500	ASTM D 4294/ D 2622/ D 5453/ IP 336

III. Current Technologies on The Control Of Diesel Exhaust Emissions

A. Diesel Oxidation Catalyst

Diesel oxidation catalyst (DOC) consists of a stainless steel canister containing a honey comb structure called substrate. The interior surfaces of the substrate are coated with catalytic precious metal such as platinum or palladium. As exhaust flows over the precious metal, a chemical reactant occurs, which removes the soluble organic carbon fraction of the particulate matter (oxidizing it into water vapour and other gases), usually resulting in a PM reduction of 20% to 50%. Since no additional heat or energy sources required to achieve this PM reduction, DOCs are referred to as passive devices [9]

B. Diesel Particulate Filters

Diesel particulate filter (DPF) consists of a porous substrate that permits gases in the exhaust to pass through but traps the PM. DPFs are very efficient in reducing PM emissions. It can typically achieve PM reductions in excess of 90%. Most DPFs employ some means to periodically regenerate the filter (i.e. burn off the accumulated PM). There are three issues of DPF. Firstly issue on active regeneration strategies. Second issue are to remove ash, handling and disposal strategies. The last is alternative substrate construction [10,12].

C. Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is one of the most effective engine control method for reducing NO_X emissions. EGR works by recirculating a portion of an engine exhaust gas back to the engine cylinders (intake system) to lower the concentration and also increase the heat capacity of the air/fuel charge. Cooling the exhaust gas that is to be recirculated can minimize combustion temperatures. This reduced peak combustion temperature and the rate of combustion, thus reducing the NO_X emissions. Typically NO_X reductions are about 50% [10].

D. Selective Catalytic Reduction

Selective catalytic reduction (SCR) systems use a reductant, usually ammonia or urea to convert NO_X to Nitrogen and Oxygen. In this system, the reductant is injected into the exhaust upstream of the catalyst. As the exhaust gases, along with the reductant, pass over a catalyst applied to either a ceramic or metallic substrate, NO_X emissions can be reduced by more than 70%. In addition, PM emissions could be reduced by 25% and HC emissions by 50% - 90% in SCR system. The ammonia created by thermal hydrolysis primarily reacts in the SCR catalytic converter with NO_2 to form nitrogen and water. Modern SCR can incorporate the function of hydrolyzing catalyst so that there is frequently no need to use a hydrolyzing catalyst. The issue is about urea infrastructure and cost, EPA acceptance and ammonia slip [10,11,12].

E. NO_X Adsorbers

NO_X adsobers also called NO_X traps are one of the newest emissions control strategies under development. Catalyst is employed to which NO_X in the exhaust stream adsorbs when the engine runs lean. After the adsorbed has been fully saturated with NO_X, the system is regenerated with released NO_X being catalytically reduced when engine runs rich. NO_X reduce in excess of about 80% - 90%. The issues for NO_X adsobers are $DeNO_X$ and Desulfation strategies and emissions during regenerations [10,12, 13].

IV. Experimental setup

A. Preparation of Novel Diesel Particulate Filter (NDPF)

Preparation of NDPF based on porous ceramic is started by selecting the correct sponge as main structures. A polymeric sponge must be selected with suitable properties. The pore size of the sponge determines the pore size of the final ceramic after firing. It must also be able to recover its original shape and convert into a gas at a temperature below that zeolite is required to fully vaporised fire the ceramic.

After the sponge is selected, the slurry is made by mixing the alumina, zeolite, polivinal alkohol (PVA) and ovalbumin as additive. The ceramic powder consists of particles less than 50 microns in size.

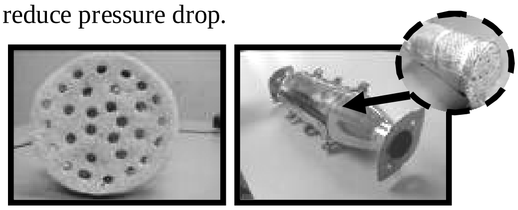
Before immersion, the sponge is usually compressed to remove trapped air, sometimes using a mechanical plunger for several times. Once it is immersed in the slurry, the sponge is allowed to expand and the slurry fills the open cells. The compression/expansion step may be repeated to achieve the desired density.

After infiltration, certain percentage of the slurry must be removed from the sponge. This is done by compressing the sponge between wooden boards, centrifuging, or passing through preset rollers. The gap between rollers determines the amount removed. Sometimes the impregnated foam goes through another shaping step since it is still flexible.

The infiltrated sponge is then dried using one of several methods - air dryer, oven drying, or microwave heating. Air drying takes 8 to 24 hours. Oven drying takes place between 100-700°C and is completed from 15 minutes to six hours.

The ceramic structure must be heated to temperatures between 1,000-1,700°C to densify the material at a controlled rate to avoid damage. The firing cycle depends on the specific ceramic composition and the desired final properties.

Figure 4 shows NDPF after firing process and placed in the elements casing. The holes or channels on NDPF are used to reduce pressure drop.



(a) (b)

Figure 4: (a) DPF after firing (b) DPF placed in the case

B. Exhaust emissions test

Exhaust emission tests were conducted to the vehicle to get the gaseous emission and opacity data. These tests were in steady state condition at 1000, 2000, 3000, 4000 and 5000 rpm with and without the installation of the NDPF in the exhaust pipeline.

C. Preparation of test vehicle

NDPF will be placed in a specially made case which will ease maintenance work. It is placed before silencer as shown in Figure 5.

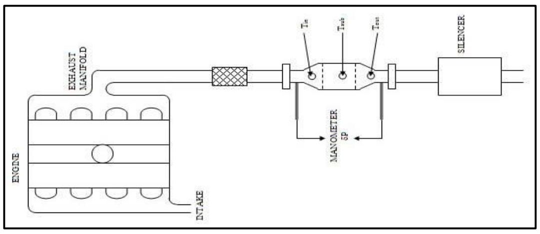


Figure 5: Exhaust pipeline with NDPF

V. RESULTS EMISSION REDUCTION PERFORMANCE

Results of standard exhaust emission test

Standard exhaust emission tests were conducted to get the benchmark data for its gaseous emission and opacity values. The results from this test are shown in Table 4 and Table 5. The results show that NPDF can reduce the value of gaseous and opacity from the vehicle.

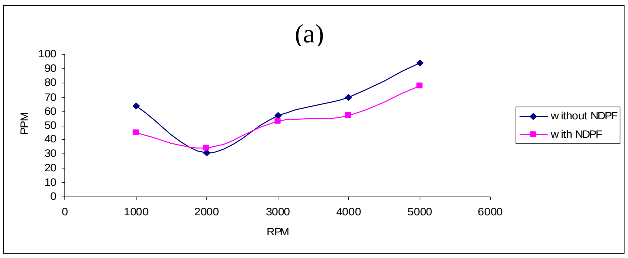
Table 4 : Gaseous emission and opacity data for standard exhaust without NPDF

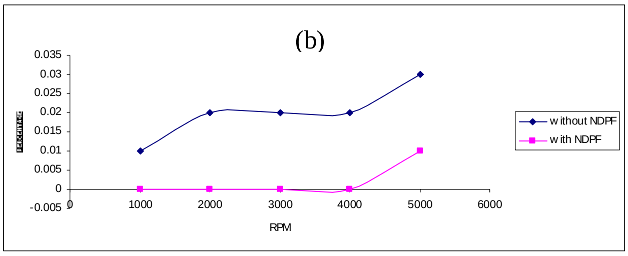
RPM	GASEOUS					OPACITY (%)
	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_X (ppm)	
1000	3.57	0.01	13	16.17	64	4
2000	3.48	0.02	14	16.08	31	2.6
3000	3.86	0.02	13	15.63	57	9.3
4000	5.38	0.02	14	13.19	70	13.6
5000	6.35	0.03	15	11.59	94	19.8

Table 5 : Gaseous emission and opacity data with NDPF

RPM	GASEOUS					OPACITY (%)
	CO_2 (%)	CO (%)	HC (ppm)	O_2 (%)	NO_X (ppm)	
1000	3.48	0	3	16.72	45	0.4
2000	3.38	0	2	16.74	34	1
3000	4.24	0	2	15.45	53	1.5
4000	5.38	0	3	13.84	57	2
5000	6.78	0.01	3	12.03	78	1.6

Figure 6 and Figure 7 show that exhaust with NPDF can reduce the values of NO_X, CO, HC and opacity percentage.





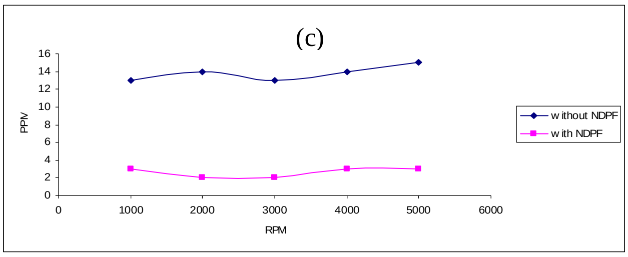


Figure 6: Comparison of gaseous values (a) NO_X, (b) CO, (c) HC

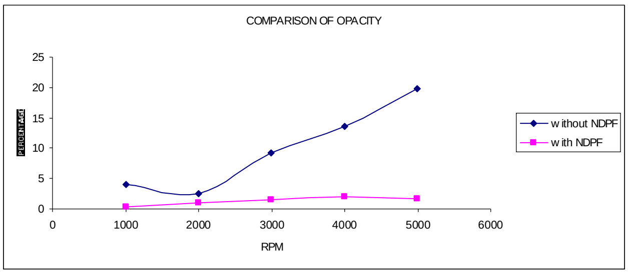


Figure 7: Comparison of opacity data

Initial test have shown that the NPDF capability to reduce the soot emissions. The test will be conduct again to see effect for the engine performance where the vehicle will connect to dynamometer.

VI. SUMMARY

In this paper, the development of a novel diesel particulate filter system is described, which will help vehicle users to control the emission with lower cost and in easy way.

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Appendix

ENVIRONMENTAL QUALITY (CONTROL OF EMISSION FROM DIESEL ENGINES) REGULATIONS 1996

FIRST SCHEDULE [Subregulation 4(1) and regulation 7]

EMISSION STANDARD OF POLLUTANTS

1. The emission standard for a diesel engine tested at a steady speed shall not exceed the following limits of emission of visible pollutants:

Nominal flow G (litres/second)	Absorption Coefficient K (m-1)
42	2.26
45	2.1.9
50	2.08
55	1.985
60	1.90
65	1.84
70	1.775
75	1.72
80	1.665
85	1.62
90	1.575
95	1.535
100	1.495
105	1.465
110	1.425
115	1.395
120	1.37
125	1.345
130	1.32
135	1.30
140	1.27
145	1.25
150	1.225
155	1.205
160	1.19
165	1.17
170	1.155
175	1.14
180	1.125
185	1.11
190	1.095
195	1.08
200	1.065

as measured by the Economic Commission for Europe ("ECE") Regulation No. 24.03 annexed to the United Nations Agreement which was done at Geneva on March 20, 1958 Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts.

2. In addition to paragraph 1, for a heavy-duty diesel engine for a vehicle with a Gross Vehicle Weight ("GVW") of over 3.5 tonnes, the exhaust emission of the gaseous pollutant of Carbon Monoxide ("CO"), Hydrocarbon ("HC") and Nitrogen Oxides ("NOx") shall not exceed the following standard:

Mass of Carbon Monoxide (CO) Grammes per k Wh	Mass of Hydrocarbons (HC) Grammes per kWh	Mass of Nitrogen Oxides (NOx) Grammes per k Wh
14	3.5	18

as measured by the ECE Regulation No. 49. annexed to the United Nations Agreement which was done at Geneva on March 20, 1958 Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts.

3. For a diesel engine with a Gross Vehicle Weight of not exceeding 3.5 tonnes, in addition to paragraph 1, the emission of the gaseous pollutant of Carbon Monoxide and the combination of Hydrocarbons and Nitrogen Oxides shall not exceed the following standard:

Reference Mass (rw) (kg)	Carbon Monoxide g/test	Combined Emission of Hydrocarbons and Nitrogen Oxides in g/test
rw ≤ 1020	58	19.0
1020 < rw ≤ 1250	67	20.5
1250 < rw ≤ 1470	76	22.0
1470 < rw ≤ 1700	84	23.5
1700 < rw ≤ 1930	93	25.0
1930 < rw ≤ 2150	101	26.5
2150 < rw	110	28.0

as measured by the ECE Regulation No. 15 annexed to the United Nations Agreement which was done at Geneva on March 20, 1958 Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts.

SECOND SCHEDULE [Subregulation 4(2)]

EMISSION STANDARD OF POLLUTANTS FOR NEW MODELS OF MOTOR VEHICLES ON OR AFTER 1 JANUARY 1997

1. For a diesel engine having a total mass exceeding 3.5 tonnes, the emission of gaseous pollutants of Carbon Monoxide, Hydrocarbons, Oxides of Nitrogen and Particulates must not exceed the following standard:

Mass of Carbon Monoxide(CO) Grammes per kWH	Mass of Hydrocarbons(HC) Grammes per kWH	Mass of Oxides of Nitrogen (NOx) Grammes per k WH	Mass of Particulates (PT) Grammes per kWH
4.5	1.1	8.0	0.36

as measured by the ECE Regulation No. 49.02 annexed to the United Nations Agreement which was done at Geneva on March 20, 1958 Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts.

2. For a diesel engine having a total mass not exceeding 3.5 tonnes, the emission of gaseous pollutants of Carbon Monoxide, the combination of Hydrocarbons and Oxides of Nitrogen and Particulates shall not exceed the following standard:

Reference Mass rw (kg)	Mass of Carbon Monoxide g/Km	Combined Mass of Hydrocarbons and Oxides of Nitrogen g/km	Mass of Particulates g/km
rw ≤ 1250	2.72	0.97	0.14
1250 < rw ≤ 1700	5.17	1.40	0.19
1700 < rw	6.90	1.70	0.25

as measured by the Council Directive 93/59/EEC of June 28, 1993 amending Directive 70/220/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emission from motor vehicles.

FIFTH SCHEDULE [Regulation 11]
FREE ACCELERATION TEST

1. The free acceleration test shall be carried out with a smoke meter which shall be capable of indicating the full range of smoke density during the accelerating and decelerating cycle.

2. The smoke meter shall have been regularly serviced and maintained in accordance with the manufacturer's instructions. It shall have undergone tests and calibration, not more than 12 months before its use, by a competent authority appointed by the Director General and has been issued a certificate of fitness with a record of the date to indicate that as a result of those tests and calibration, the smoke meter was found to be in good working order.