

SFTP Cycle Contributions to Light-Duty Diesel Exhaust Emissions

**INTERIM REPORT
TFLRF No. 361**

by

Edwin A. Frame

Kevin A. Whitney

U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®)

Southwest Research Institute™

San Antonio, TX

for

U. S. Department of Energy

Office of Transportation Technologies

1000 Independence Avenue, SW

Washington, D. C. 20585

Under Contract to

U.S. Army TARDEC

Petroleum and Water Business Area

Warren, MI 48397-5000

Contract No. DAAE-07-99-C-L053 (WD 12)

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Edwin C. Owens, Director
U.S. Army TARDEC Fuels and Lubricants
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13. ABSTRACT (Maximum 200 words) U.S. light-duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle, and SC03 air conditioning cycle. The objective of this investigation was to determine the relative contribution of each individual test cycle to each measured exhaust emission. Based on the exhaust emissions data from the ligh-duty diesel powered vehicle used in this project, the following conclusions are made: While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total Nox emissions are derived from this cycle. The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NOx is 17% less than when the SC03 is included.			
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EXECUTIVE SUMMARY

U.S. light duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle and SC03 air conditioning cycle. The objective of this investigation was to determine the relative contribution of each individual test cycle to each measured exhaust emission.

Based on the exhaust emissions data from the light-duty diesel powered vehicle used in this project, the following conclusions are made:

- While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total NO_x emissions are derived from this cycle.
- The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NO_x is 17% less than when the SC03 is included.

FOREWORD/ACKNOWLEDGMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute™ (SwRI®), San Antonio, Texas, during the period September 2001 through December 2001 under Contract No. DAAE-07-99-C-L053. The work was funded by the U. S. Department of Energy Office of Transportation Technologies (DOE/OTT). The project was administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. John Garbak (DOE) served as the project technical monitor.

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ACRONYMS & ABBREVIATIONS

CFR	Code of Federal Regulations
DFI	Director Filter Injection
EPA	Environmental Protection Agency
GC	Gas Chromatography
NO _x	Oxides of Nitrogen
PM	Particulate Matter
SFTP	Supplemental Federal Test Procedure
SwRI	Southwest Research Institute™
TARDEC	Tank-Automotive Research Development and Engineering Center
TACOM	Tank-Automotive Armaments Command
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
VOF	Volatile Organic Fraction
VW	Volkswagen

I. BACKGROUND/OBJECTIVE

U.S. light duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle, and SC03 air conditioning cycle.(1)* The objective of this investigation is to determine the relative contribution of each individual test cycle to each measured exhaust emission. This information will be useful in defining appropriate emission control devices to be used for the reduction of exhaust emissions.

II. APPROACH

A 2000 model year VW Jetta passenger vehicle powered by a 1.9L light-duty diesel engine with a manual 5-speed transmission was used for this investigation. Vehicle and engine properties are presented in Table 1. A low sulfur diesel fuel designated ECD-1 was used. The properties of ECD-1 fuel are presented in Table 2. Exhaust emissions and fuel economy were evaluated in triplicate over the Supplemental Federal Test Procedure (SFTP) for light-duty vehicles, which includes the chassis dynamometer portion of the FTP, the US06 aggressive driving cycle, and a modified version of the AC2 option of the SC03 air conditioning cycle. Figures 1, 2, and 3 illustrate the vehicle speed and duration for these three test cycles.(2) As given in the Code of Federal Regulations (CFR), the AC2 option does not include elevated temperatures or solar loading; however, there are stipulations for the control of temperature, humidity, and vehicle frontal airflow.(3) In order to conduct this work in a cost-effective manner, deviations from the AC2 test procedure were as follows:

*Underscored numbers in parentheses indicate references at the end of the document.

- Test cell temperature was targeted at 76 degrees F nominal, but was not necessarily maintained at ± 2 degrees F on average and ± 5 degrees F instantaneous.
- Test cell humidity was targeted at 50 grains of water per pound of dry air, but was not necessarily maintained at ± 5 grains of water per pound of dry air.
- A constant speed-cooling fan with nominal output of 5,000 cfm was used in front of the vehicle rather than a variable-speed fan. The fan discharge area is approximately 3.5 ft².
- It is felt that this modified AC2 cycle would still sufficiently simulate the additional loading an engine experiences with the operation of the AC compressor, thus providing an indication of the additional NO_x production expected during AC operation.

Table 1. 2000 VW Jetta Turbodiesel Specifications	
Vehicle, GLS, TDI	
Curb Weight, lb	3036
Transmission,	5-speed, manual
Air Conditioning	Yes
EPA Fuel Economy (City/Hwy)	42/49 mpg
Engine, Turbodiesel	
Displacement,	1.9L
Horsepower	90 @ 3750 RPM
Torque, lb-ft	155 @ 1900 RPM
Bore X Stroke, in	3.13 x 3.76
Compression ratio	19.5: 1

Table 2. ECD-1 Diesel Fuel Properties		
AL No.:		26847F
Fuel I.D.:		ECD-1
Property	Method	
Density@15 C, kg/L	D-4052	0.8315
Hydrogen, mass %	D-5291	13.490
Carbon, mass %	D-5291	86.220
Distillation by Volume	D-2887	
IBP °C		122.5
10% °C		177.8
50% °C		256.2
90% °C		345.7
95% °C		368.2
End Point		419.2
Distillation by Volume	D-86	
IBP °C		169.8
10% °C		205.7
50% °C		259.7
90% °C		326.1
95% °C		343.3
End Point		353.9
Cetane No.	D-613	52.8
Cetane Index	D-976	51.8
K. Viscosity @ 40 °C, cSt	D-445	2.41
Flash Pt., °C	D-93	66
Oxygen, wt. %	difference	0.290
Nitrogen, µg/g	D-4629	9
Sulfur, ppm	D-5453	11
Hydrocarbon Type, wt. %		
Total Aromatics	D-5186	21.65
Monoaromatic	D-5186	18.50
Polyaromatics	D-5186	3.15
Saturates	D-5186	78.36
Paraffins, wt. %	D-2425	NA
Naphthlenes, wt. %		NA
Total Water , ppm	D-6304	88
Color	D-1500	1.0
Appearance	D-4176	Pass, Brt/Clear
Particulates, mg/L	D-6217	1.54
Cloud Pt., °C	D-5773	-8.0
Pour Pt., °C	D-5949	-12.0
TAN, mg KOH/g	D-664	0.13
Net Heat of Combustion, MJ / kg	D-240	41.67
Gross Heat of Combustion, MJ / kg	D-240	44.53
HFRR Lubricity, µm @ 60C	D-6079	460
BOCLE Scuff, grams	D-6078	3150

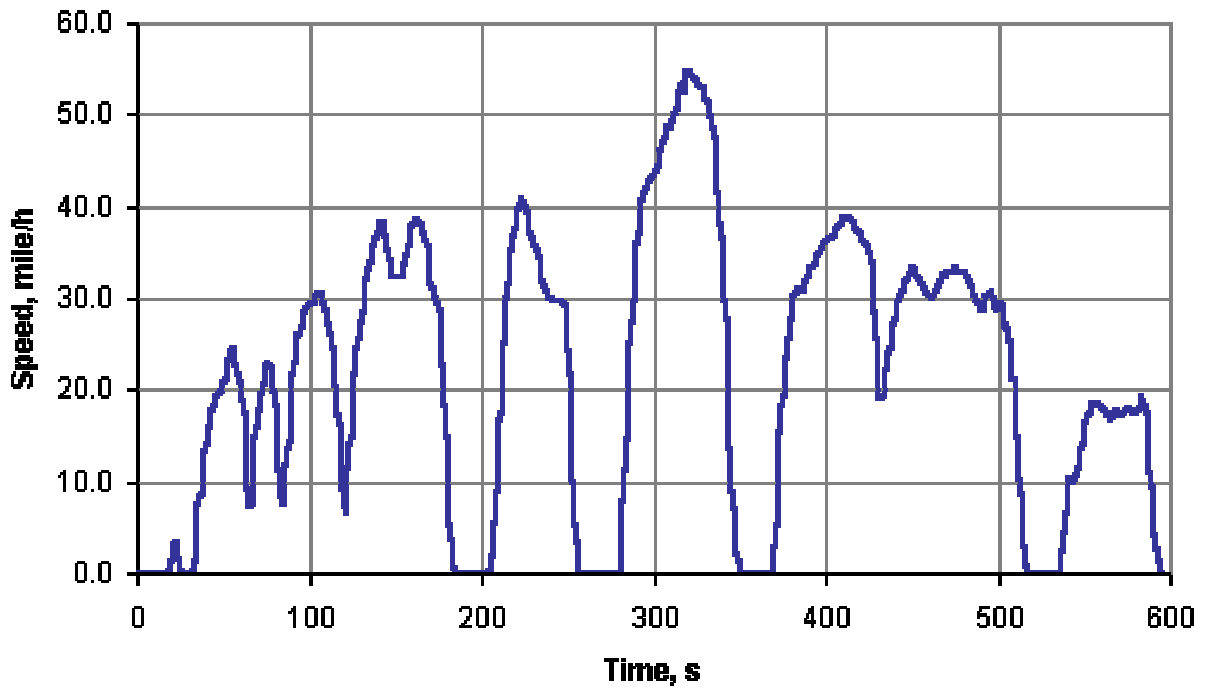


Figure 1. SC03 Test Cycle

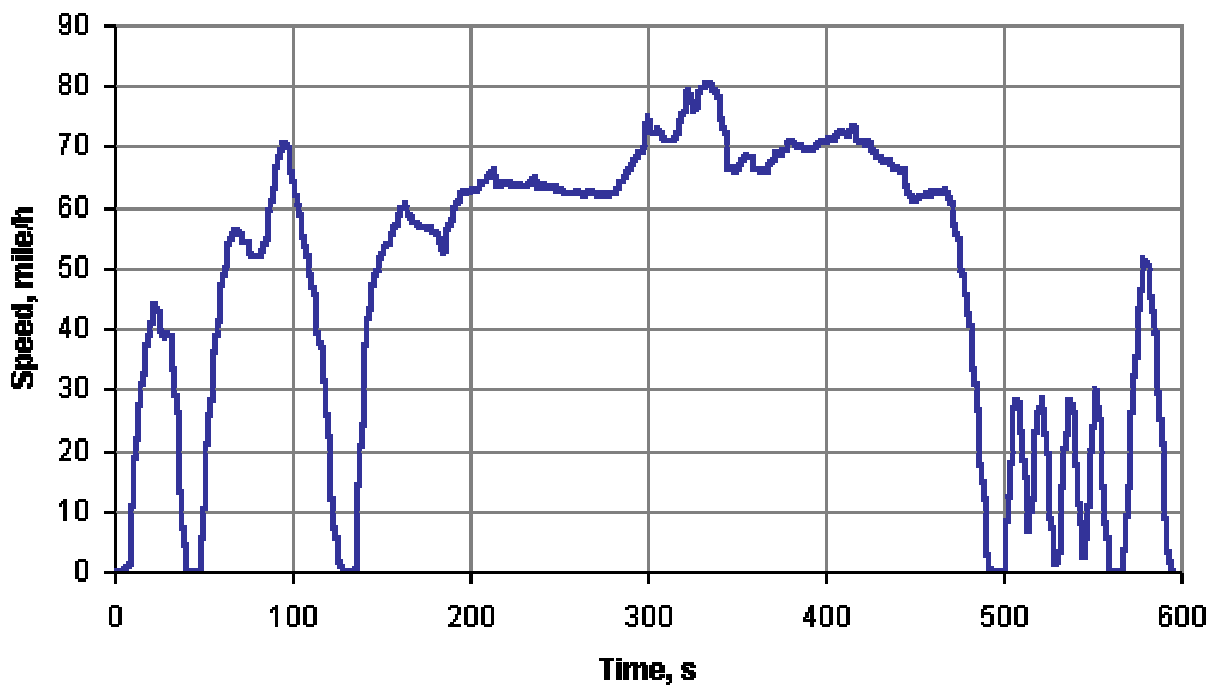


Figure 2. US06 Test Cycle

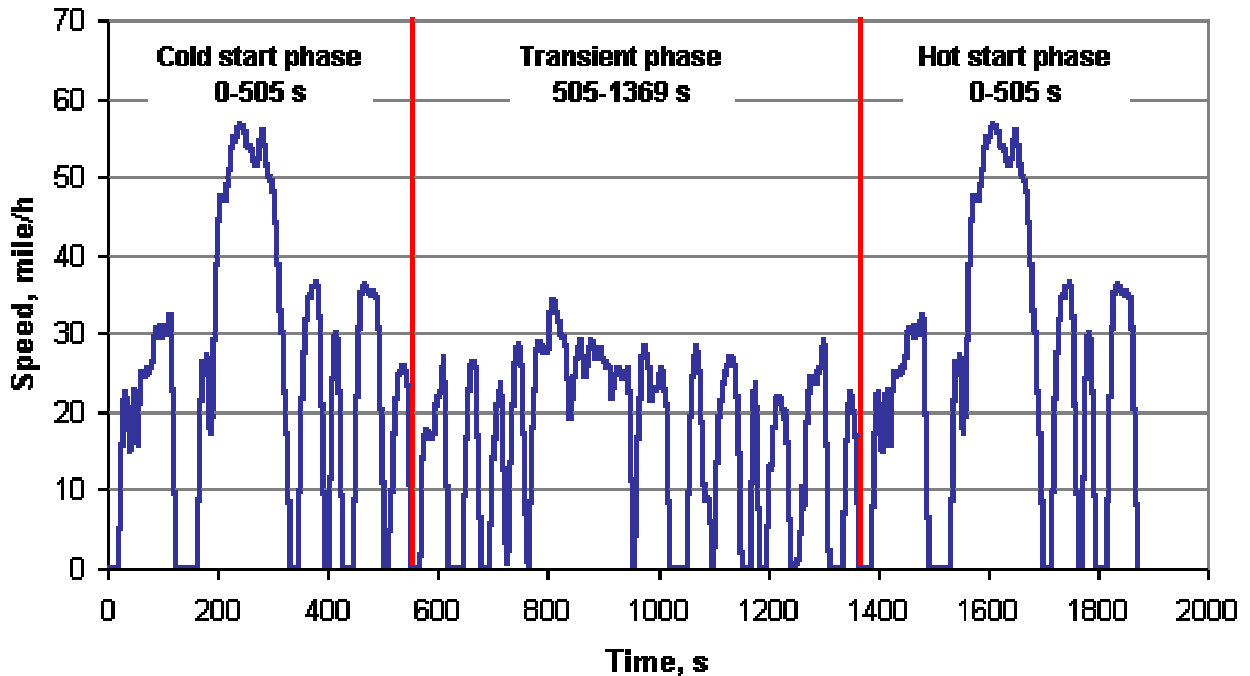


Figure 3. FTP Test Cycle

Regulated exhaust emissions (non-methane hydrocarbons, carbon monoxide, oxides of nitrogen, and particulate matter) and carbon dioxide were determined in a manner consistent with EPA protocols for light-duty emission testing as given in the CFR.(3) Proportional dilute exhaust gas samples were collected in Tedlar bags for analysis of carbon monoxide, carbon dioxide, and methane. Total hydrocarbons and oxides of nitrogen were measured continuously from the dilution tunnel. Concurrently, a proportional sample of the dilute exhaust was drawn through Pallflex T60A20 fluorocarbon-coated glass fiber filters for determination of particulate matter. Filter samples were analyzed by direct filter injection gas chromatography (DFI/GC) to determine the particulate volatile organic fraction (VOF) and lubricating oil contribution to VOF. Ion chromatography was used to determine sulfate fraction of particulate. Exhaust constituents were analyzed as specified below:

Constituent	Analysis Method
Total Hydrocarbon	Heated Flame Ionization Detector
Methane	Gas Chromatography
Carbon Monoxide	Non-Dispersive Infrared Analysis
Carbon Dioxide	Non-Dispersive Infrared Analysis
Oxides of Nitrogen	Chemiluminescent Analysis
Particulate Matter	Gravimetric
Volatile Organic Fraction of PM	Direct Filter Injection Gas Chromatography
Oil Fraction of VOF	Direct Filter Injection Gas Chromatography
Sulfate Fraction of PM	Ion Chromatography

Figures 4 and 5 show the front and rear view of the vehicle test installation, respectively.



Figure 4. Front View of Vehicle Test Installation



Figure 5. Rear View of Vehicle Test Installation

III. TEST RESULTS

The results for the triplicate FTP, US06, and SC03 exhaust emission tests are presented in Table 3. The individual test data sheets are in Appendix A.

Table 3. Test Results									
	THC	CO	NOx	Total PM	Total PM	Wet Sufate*	VOF	Unburned	FE
	g/mi	g/mi	g/mi	g/mi	mg/mi	mg/mi	mg/mi	Oil, %	mi/gal
FTP-1	0.073	0.315	0.708	0.044	44.0	2.18	14.08	22%	41.22
FTP-2	0.057	0.290	0.724	0.055	55.2	2.35	17.14	30%	40.37
FTP-3	0.067	0.285	0.737	0.046	46.1	3.35	15.33	16%	40.16
AVG	0.066	0.297	0.723	0.048	48.4	2.63	15.52	23%	40.58
SC03-1	0.012	0.017	1.124	0.063	63.2	1.79	14.87	15%	34.38
SC03-2	0.000	0.037	1.163	0.059	59.2	1.19	13.11	17%	33.77
SC03-3	0.012	0.046	1.172	0.053	53.2	0.91	16.26	19%	33.80
AVG	0.008	0.033	1.153	0.058	58.6	1.30	14.75	17%	33.98
US06-1	0.002	0.024	1.816	0.276	276.4	89.69	na**	na**	39.48
US06-2	0.000	0.015	1.744	0.216	216.2	80.91	8.82	7%	40.64
US06-3	0.000	0.003	1.701	0.190	190.3	64.49	9.51	5%	40.71
AVG	0.001	0.014	1.754	0.227	227.6	78.36	9.16	6%	40.28
SFTP = 0.35*FTP + 0.37*SC03 + 0.28*US06									
SFTP-1	0.031	0.123	1.172	0.116	116.2	26.54	na**	na**	38.20
SFTP-2	0.020	0.119	1.172	0.102	101.8	23.92	13.32	19%	38.00
SFTP-3	0.028	0.118	1.168	0.089	89.1	19.56	14.04	14%	37.96
AVG	0.026	0.120	1.171	0.102	102.4	23.34	13.68	16%	38.06
* - total includes "dry" sulfate plus associated water of hydration									
** - data not available									

A. PM and NOx Results

Figure 6 shows the weighting factors for the three test cycles that define the SFTP. The contribution of each test cycle to weighted PM exhaust emissions is shown in Figure 7.(1) This illustrates that the majority of weighted PM exhaust emission is attributed to the US06 cycle. The contribution of each test cycle to weighted NOx exhaust emission is shown in Figure 8.

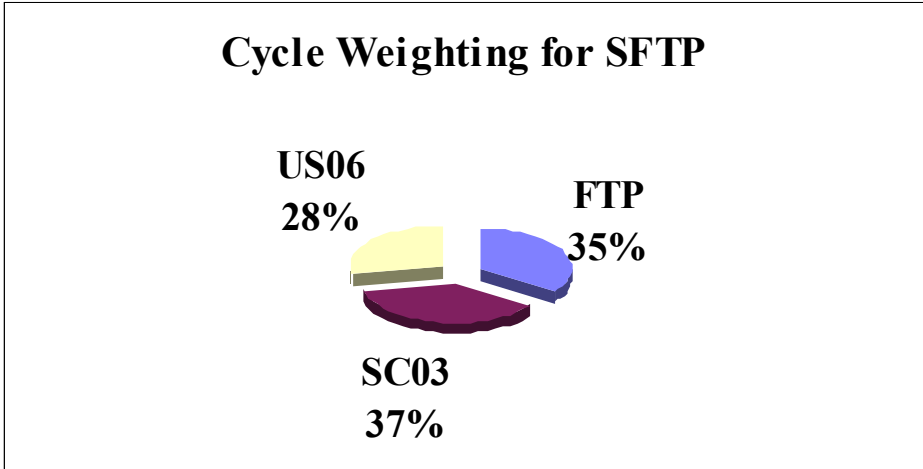


Figure 6. Weighting factors for the three test cycles that define SFTP

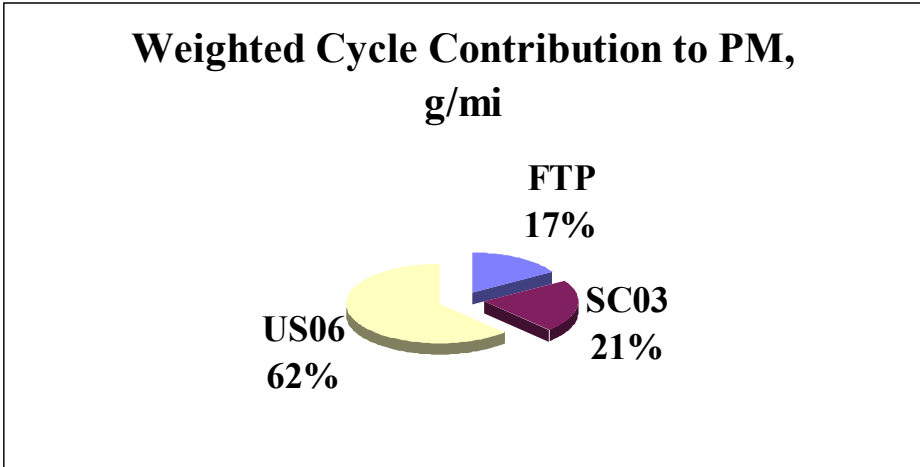


Figure 7. Contribution of each test cycle to weighted PM exhaust emissions

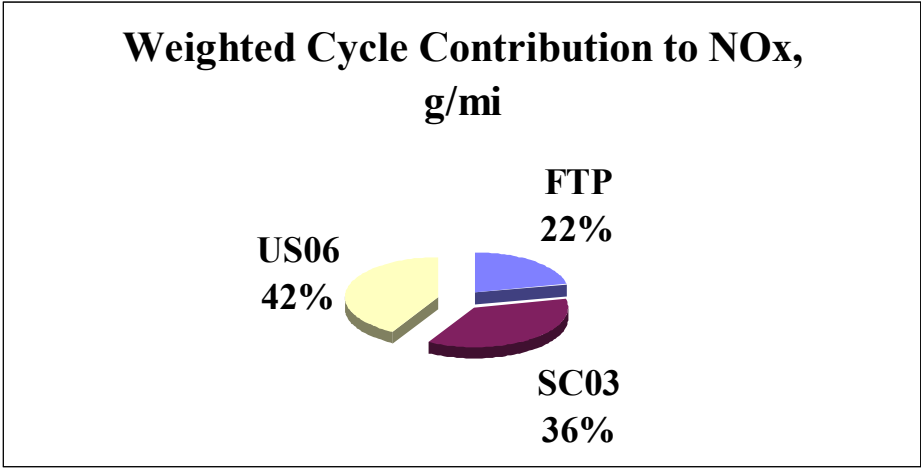


Figure 8. Contribution of each test cycle to weighted NO_x exhaust emission

The formula for calculating weighted exhaust emissions for vehicles without A/C is $SFTP=0.72$ (FTP value) + 0.28 (US06 value). A comparison of SFTP values calculated with and without including the A/C cycle was made for this vehicle. If the A/C cycle is not included in the SFTP calculations, the values are 1.01 g/mi NO_x, and 0.098 g/mi PM. When the A/C cycle is included, the values are 1.17 g/mi NO_x, and 0.102 g/mi PM. The NO_x values for this vehicle are approximately 16% higher when the SC03 cycle is included.

B. Volatile Organic Fraction (VOF) and Wet Sulfate Material Results

The volatile organic fraction (VOF) of particulate matter was similar for the FTP and SC03 cycles, and approximately one third less for the US06 cycle. The unburned oil percentage of the VOF was highest for the FTP, intermediate for the SC03 and lowest for the US06 cycle. The majority of the wet sulfate material was produced during the US06 cycle.

IV. SUMMARY/CONCLUSIONS

Based on the exhaust emissions data from the light-duty diesel powered vehicle used in this project, the following conclusions are made:

1. Because each of the three test cycles produce a unique cycle dependent set of exhaust emissions, the actual contribution of each test cycle is different than its weighting factor.
2. While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total NO_x emissions are derived from this cycle.

3. While the US06 cycle is weighted at only 28%, a full 62% of the total PM emissions and 42% of the total NOx emissions come from US06.
4. The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NOx is 17% less than when the SC03 is included.
5. The vast majority of the wet sulfate material is produced during the US06 test cycle. The lowest VOF of PM and unburned oil portion of VOF were produced during the US06 test cycle.

V. REFERENCES

1. Federal Register, Vol. 61, No. 205, October 22, 1996, Rules & Regulations, p. 54855.
2. <http://www.epa.gov/oms/emisslab/methods>
3. Code of Federal Regulations 40, Part 86, Subpart B, Revised July 2001.