UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

OFFICE OF AIR AND RADIATION

NATIONAL VEHICLE AND FUEL EMISSIONS LABORATORY

2000 TRAVERWOOD DRIVE

ANN ARBOR, MI 48105-2498

05/03/2022

MEMORANDUM

SUBJECT: Test Results from EPA Diesel Engine Demonstration

FROM: James Sanchez, OAR/OTAQ/ASD

TO: Docket EPA-HQ-OAR-2019-0055

The contents of the memo contain the data and details of the diesel engine demonstration study that was led by EPA, which build off of the CARB Stage 3 engine. The memo refers to this as the EPA Stage 3 engine. In this phase of the study, the following improvements were made to the aftertreatment: 1) replacing the zone-coated catalyzed soot filter with a separate diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) that were chemically- and hydrothermally-aged using the Diesel Aftertreatment Accelerated Aging Cycle (DAAAC) to the equivalent of

800,000 miles, and 2) improving the mixing of the DEF with exhaust for the underfloor SCR. A schematic of the aftertreatment is shown in Figure 1.

The results of testing the EPA Stage 3 engine at the equivalent of 435,000, 600,000 and 800,000 miles are shown in Tables 1 through 4.

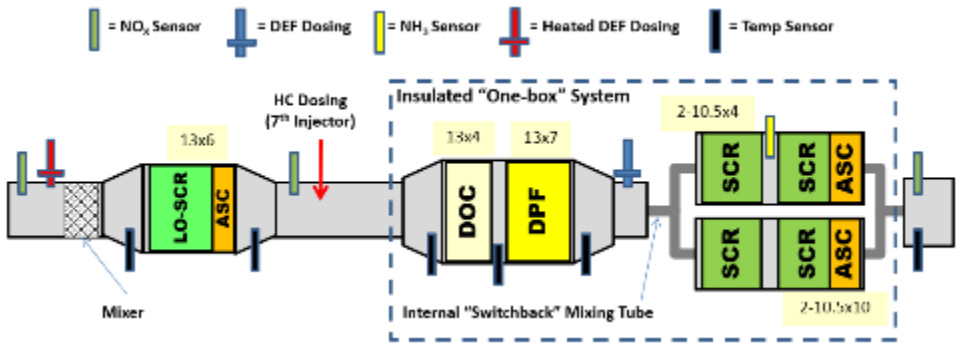

Figure 1: Schematic layout (not to scale) of the dual-SCR selective catalytic reduction (SCR) EAS tested as part of the EPA Stage 3 research at SwRI.

1. EPA Stage 3 Duty Cycle Emissions Performance

Table 1: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **435,000 miles** of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	FTP cold	95% CI	FTP hot	95% CI	FTP composite	95% CI	SET (2021)	95% CI	LLC	95% CI
NO_X (mg/bhp-hr)	55	1	14	1	20	1	17	1	29	11
PM (mg/bhp-hr)	2	1	2	1	2	1	1	1	3	1
NMHC (mg/bhp-hr)	25	7	9	2	12	2	1	1	35	51
CO (mg/bhp-hr)	221	61	128	77	141	75	30	22	245	438
CO_2 (g/bhp-hr)	534	1	511	2	514	2	455	4	617	11
N_2O (mg/bhp-hr)	84	7	74	9	76	9	24	69	132	45

Table 2: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1379 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **600,000 miles** of operation). The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	**FTP cold**	**95% CI**	**FTP hot**	**95% CI**	**FTP composite**	**95% CI**	**SET (2021)**	**95% CI**	**LLC**	**95% CI**
NO_X (mg/bhp-hr)	61	5	21	2	27	2	24	1	33	2
PM (mg/bhp-hr)	2	0	1	2	1	2	1	0	4	1
NMHC (mg/bhp-hr)	23	11	7	4	9	5	1	0	16	6
CO (mg/bhp-hr)	245	31	127	134	144	119	15	0	153	20
CO_2 (g/bhp-hr)	546	3	515	2	519	2	460	1	623	6
N_2O (mg/bhp-hr)	69	9	57	4	58	4	30	6	64	22

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at α=0.05

Table 3: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1839 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **800,000 miles** of operation) before ash cleaning of the DPF. The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	**FTP cold**	**95% CI**	**FTP hot**	**95% CI**	**FTP composite**	**95% CI**	**SET (2021)**	**95% CI**	**LLC**	**95% CI**
NO_X (mg/bhp-hr)	74	3	32	2	38	2	28	1	28	4
PM (mg/bhp-hr)	1	0	1	1	1	1	1	0	3	1
NMHC (mg/bhp-hr)	34	12	14	2	17	3	11	5	49	13
CO (mg/bhp-hr)	259	54	143	25	160	14	18	1	215	71
CO_2 (g/bhp-hr)	540	10	514	7	518	7	457	6	620	19
N_2O (mg/bhp-hr)	118	13	88	5	93	6	34	3	126	8

Table 4: Emissions results for the developmental EPA Stage 3 EAS system with light-off SCR and separate DOC and DPF after 1839 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **800,000 miles** of operation) after ash cleaning of the DPF. The SET (2021) results represent updated 40 CFR §1036.505 SET procedures.

Cycle Results:	**FTP cold**	**95% CI**	**FTP hot**	**95% CI**	**FTP composite**	**95% CI**	**SET (2021)**	**95% CI**	**LLC**	**95% CI**
NO_X (mg/bhp-hr)	73	12	31	3	37	1	30	0	34	8
PM	1	1	1	1	1	1	2	1	1	4

(mg/bhp-hr)										
NMHC (mg/bhp-hr)	32	16	11	6	14	7	1	0	40	20
CO (mg/bhp-hr)	260	68	130	73	149	68	23	7	205	40
CO_2 (g/bhp-hr)	544	2	516	4	520	4	458	0	629	2
N_2O (mg/bhp-hr)	99	59	91	45	92	47	28	4	125	17

For results where the 95% CI is greater than the average, the results are not statistically different from zero based on a 2-sided Student's t-test at α=0.05

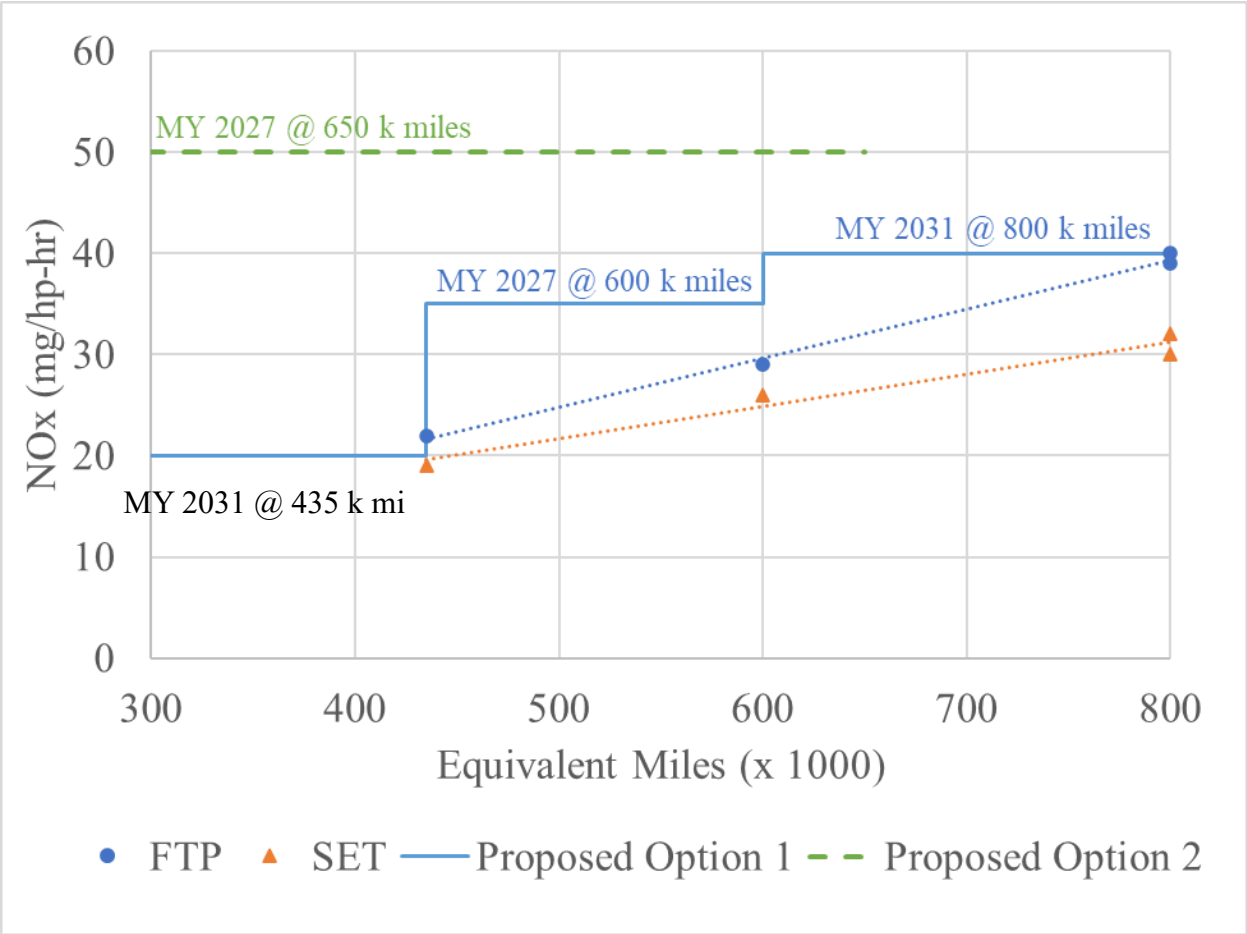

Figure 2: EPA Stage 3 NOx Emissions for FTP and SET duty cycles compared to Proposed Option 1 and 2 NOx Standards for FTP and Set

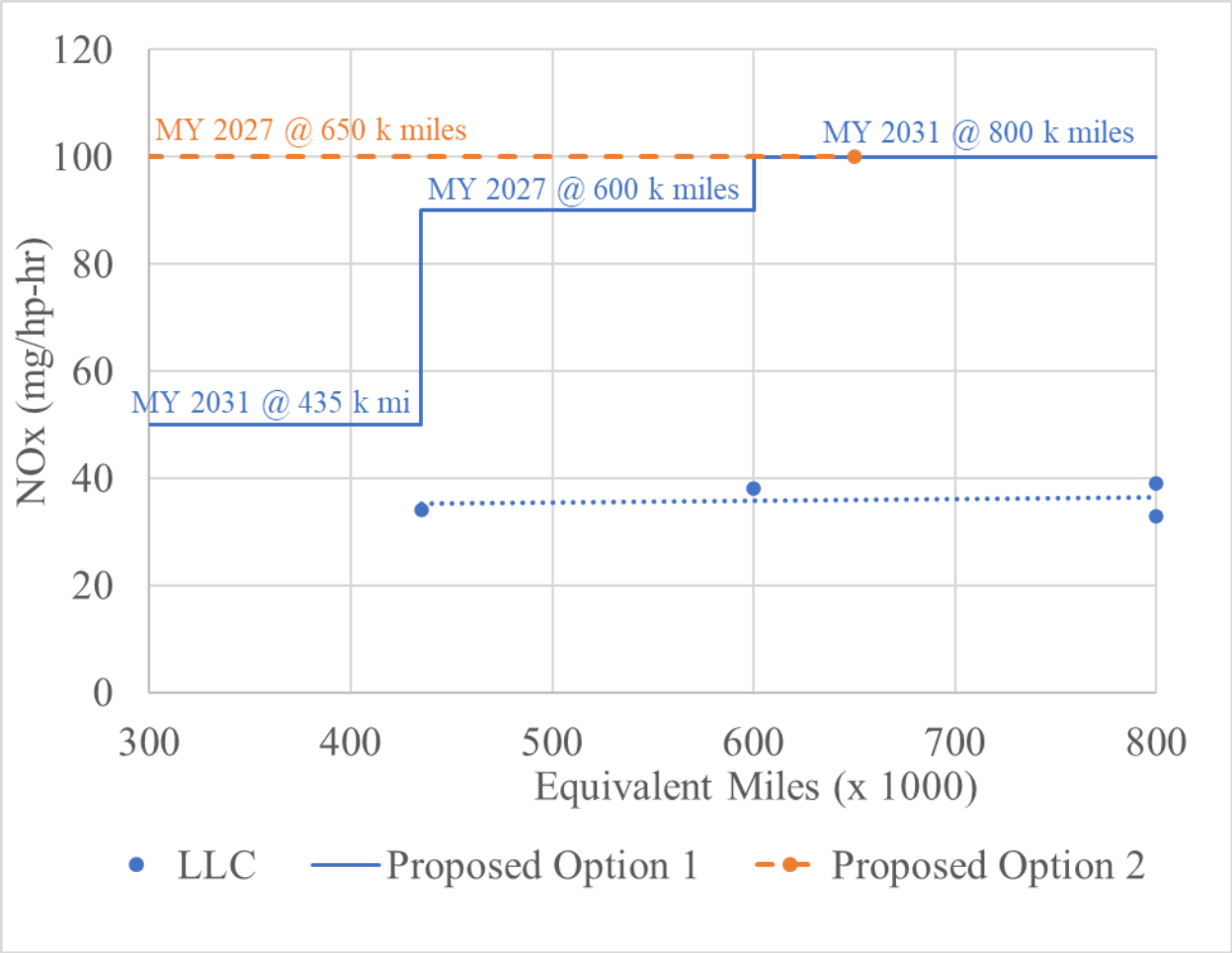

Figure 3: EPA Stage 3 NOx Emissions for LLC duty cycle compared to Proposed Option 1 and 2 NOx Standards

As shown in Table 2 through Table 4 the CO_2 emissions from the engine are higher than with the tests at the equivalent of 435,000 miles. Since the calibration has not been changed in a way that should affect the fueling of the engine, the data suggests that there could be a shift in the efficiency of the base engine. To confirm this, we plan to rerun the engine in its baseline configuration. As more data from the EPA Stage 3 engine and the Team A Emission Aftertreatment System (EAS) become available, the data will be added to the docket (EPA-HQ-OAR-2019-0055).

2. EPA Stage 3 Off-cycle Emissions Performance

In addition to the FTP, SET and LLC, the Stage 3 engine with the DAAAC aged aftertreatment to an equivalent of 435,000 miles was run on five cycles that cover a range of off-cycle operation. These cycles are the CARB Southern Route Cycle, Grocery Delivery Truck Cycle, Drayage Truck Cycle, Euro-VI ISC Cycle and the ACES 4-hour Cycle. The CARB Southern Route Cycle is dominantly highway operation with elevation changes resulting in extended motoring sections followed by high power operation. The Grocery Delivery Truck Cycle represents goods delivery from regional warehouses to downtown and suburban supermarkets and extended engine-off events characteristic of unloading events at supermarkets.

Drayage Truck Cycle includes near-dock and local operation of drayage trucks, with extended idle and creep operation. Euro-VI ISC Cycle is modeled after Euro VI ISC route requirements with a mix of 30% urban, 25% rural and 45% highway operation. ACES 4-hour Cycle includes 5 mode cycle developed as part of ACES program. Figure 4 through Figure 9 show the engine speed, engine torque and vehicle speed of the cycles. The engine speed and torque shown in the plots are specific to the Stage 3 engine.

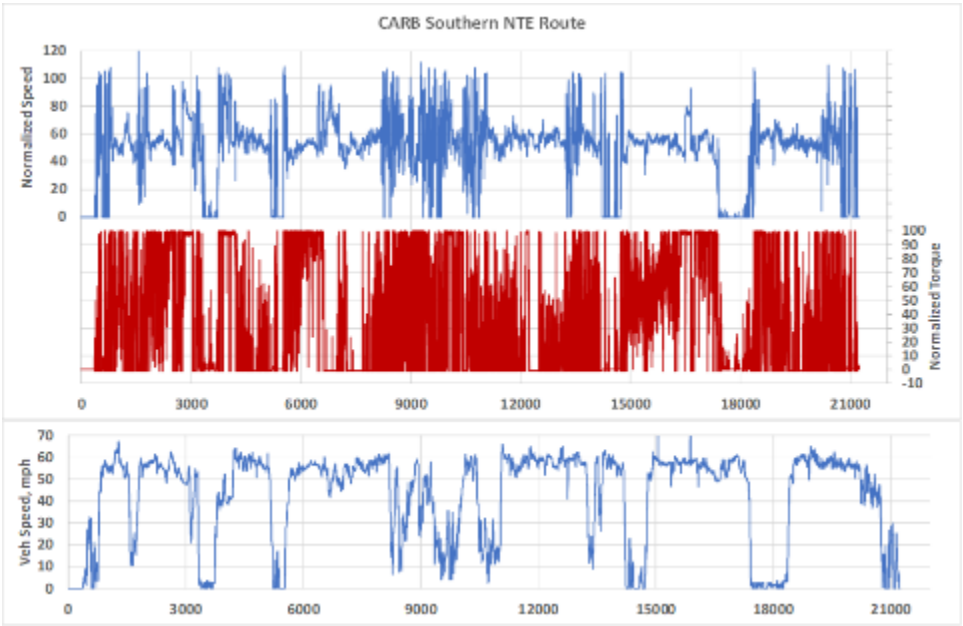

Figure 4: CARB Southern NTE Route Cycle (SNTE)

Figure 5: Grocery Delivery Truck Cycle

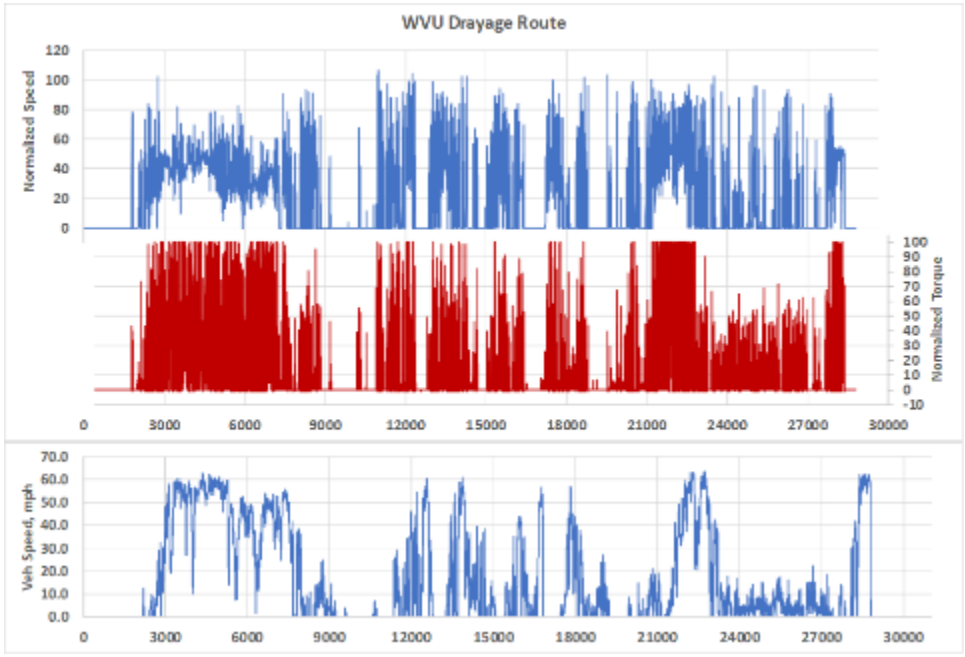

Figure 6: Drayage Truck Cycle

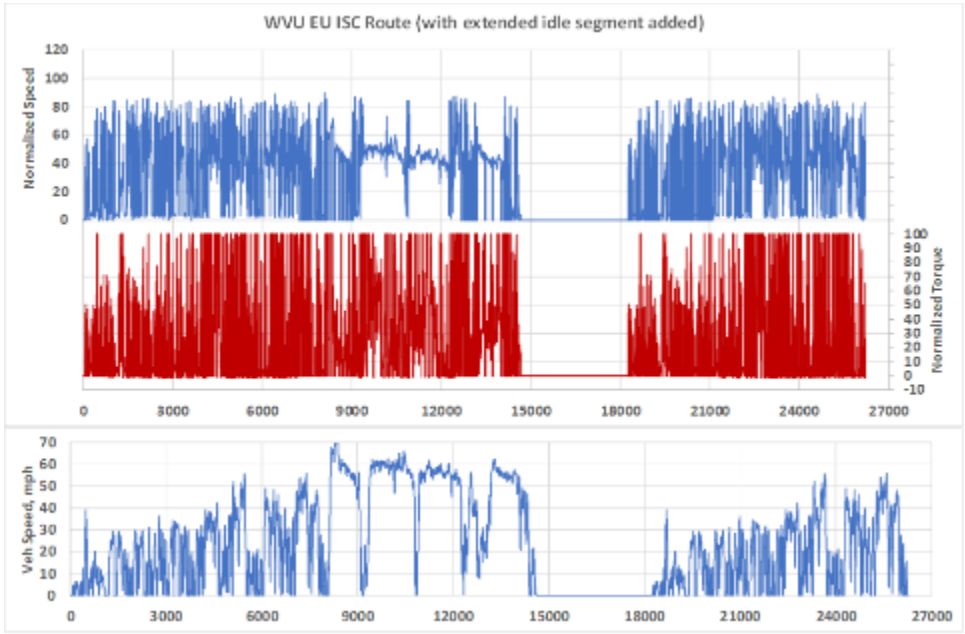

Figure 7: Euro-VI ISC Cycle

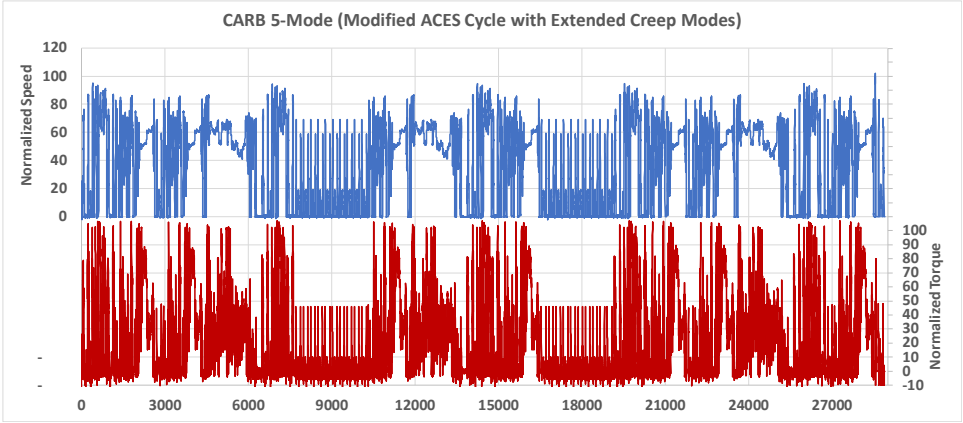

Figure 8: ACES 4-hour Cycle

The NO_X emissions from the EPA Stage 3 engine with aftertreatment aged to the equivalent of 435,000 miles are at or below the proposed Option 1 and 2 off-cycle standards at 435,000 miles except for the EU ISC cycle as shown in Table 5. Table 6 and Table 7 show that the NHMC and CO emissions from this engine are well below the proposed Option 1 and 2 HC an CO standards. With the aftertreatment aged to the equivalent of 800,000 miles, the engine was tested over the same five real world cycles. The NO_X emissions (shown in Table 8) from the EPA Stage 3 engine for each of the cycles are below the MY 2031 proposed Option 1 and 2 full useful life standards, with margin. The margins to the NOx standards are greater than 56%, 68%, and 23% for Bin 1, Bin 2, and Bin 3, respectively.

Table 5: Off-cycle NO_X emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **435,000 miles** of operation)

Bin	SNTE	Grocery Cycle	ACES	EU ISC	Drayage
Idle (g/hr)	0.7	1.0	0.9	0.4	0.3
Low (mg/hp-hr)	41	25	29	25	15
Mid/High (mg/hp-hr)	30	18	16	33	23

Table 6: Off-cycle NMHC emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **435,000 miles** of operation)

Bin	SNTE	Grocery Cycle	ACES	EU ISC	Drayage
Idle (g/hr)	-0.2	-0.6	-0.4	-0.1	0.0
Low (mg/hp-hr)	2	28	1	6	12
Mid/High (mg/hp-hr)	2	4	1	0	7

Table 7: Off-cycle CO emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1000 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **435,000 miles** of operation)

Bin	**SNTE**	**Grocery Cycle**	**ACES**	**EU ISC**	**Drayage**
Idle (g/hr)	0.3	12.7	1.0	1.9	7.6
Low (mg/hp-hr)	40	265	66	90	461
Mid/High (mg/hp-hr)	12	21	18	18	44

Table 8: Off-cycle NOX emissions results for the developmental EAS system with light-off SCR and separate DOC and DPF after 1839 hours of accelerated thermal and chemical aging using the DAAAC (equivalent to approximately **800,000 miles** of operation)

Bin	**SNTE**	**Grocery Cycle**	**ACES**	**EU ISC**	**Drayage**
Idle (g/hr)	0.7	3.3	1.5	0.4	1.1
Low (mg/hp-hr)	48	46	47	35	33
Mid/High (mg/hp-hr)	46	22	29	30	23