NATURAL RESOURCES CANADA - INVENTIVE BY NATURE

Comparing the EPA Non-road Transient Cycle (NRTC) with CanmetMINING LHD test cycles.

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Background

- Volvo-Penta through partners SwRI and CanmetMINING have been carrying out series of diesel engine testing at the SwRI Engine, Emissions and Vehicle Research facility, San Antonio, Texas.
- The current five engine models employ SCR after-treatment technology and will be the first series of Tier 4 final engines certified for use in both American and Canadian U/G mines

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Background

- Most diesel engines imported into North America that are used in the Canadian U/G mining industry require certification following procedures incorporated in the current test standards:

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Test Standards

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- CSA-M424.1-88 for coal mines
- CSA-M424.2-M90 for non-gassy mines

USA - Coal Mines
- 30 CFR Part 7, Subpart E, MSHA approved
- Category engines A for gassy areas
- Category engines B for all other areas

USA – M/NM Mines
- Part 7, Subpart E, MSHA approved engines
- Part 36, MSHA approved engines
- EPA approved Tier 2 or higher engines

U.S. Department of Labor MSHA Mine Safety and Health Administration

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Test Standards
Regulated limits

- EPA provides tiered reductions in regulated emissions based on engine power category and specific emissions
- MSHA and CSA are based on personal exposure limits to raw engine emissions, diluted at the tailpipe by a prescribed ventilation rate

New engine EPA1065 compliance for Tier 4 final

Engine Power	Year	CO	NMHC	$NMHC+NO_x$	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

- DieselNet.com

Diesel Engine Ventilation Canada & USA

- CSA – Canada
  - Ventilation rate is based on individual 18 mode testing
  - Dilution air is calculated at each test mode to reduce EQI to a value of 3.
  - Ventilation rate is the highest dilution air
- MSHA - USA
  - Ventilation is based on individual 8 mode testing
  - Dilution air is calculated at each mode to reduce gaseous emissions: CO_2 to 5000 ppm, CO to 50 ppm, NO to 25 ppm, and NO_2 to 5 ppm
  - Gaseous ventilation rate is the highest dilution air
- Particulate Index (PI) is based on a weighted average of 8 mode testing, and is amount of dilution air to reduce weighted average to 1 mg/m^3

Engine Ventilation – CSA/Canada

Exhaust Quality Index (EQI) =

$$\frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5\left[\frac{SO_2}{3} + \frac{DPM}{2}\right] + 1.2\left[\frac{NO_2}{3} + \frac{DPM}{2}\right]$$

Where, DPM (mg/m^3) and gas concentrations (ppm) are measured in raw exhaust gas

ISO 8178-C1 8-Mode test cycle

Mode #	1	2	3	4	5	6	7	8
Engine Speed, rpm	Rated power speed				Peak torque speed			Idle
Torque, %	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

CanmetMINING LHD transient test cycles

- CanmetMINING has developed LHD transient test cycles which in their present forms have never been evaluated according to the EPA test standard, CFR 1065

CFR 1065 vs ISO 8178 and CFR 30 standard - some differences

- CVS (constant volume sampler) dilute exhaust sampling for gases and PM vs direct raw exhaust sampling.
- CVS engine airflow and fuel vs direct engine airflow and fuel measurement
- Transient test cycle vs steady state test cycle
- Emission sampling during entire transient test cycle versus the last 1 minute for steady state mode, 10 minute test period

NRTC vs CanmetMINING Test Cycles Why compare?

- A comparison test would provide information on whether the EPA NRTC test cycle provides a fair assessment of diesel engines that are slated for use underground

- Could the NRTC or other transient test cycles be adopted as means to carry out diesel engine assessments in future modified Canadian test standards?

Monitoring Peak Emissions
Why?

- CanmetMINING also recognize that diesel engine emission reduction strategies through engine and/or after-treatment design, often can lead to some unexpected emissions increases to the u/g mine.

- A comparison test can also be carried out monitoring both raw gaseous and diesel particulate matter to study peak emissions and to evaluate after-treatment technology, especially, its performance when subject to the transient test cycle.

Purpose

- To conduct a comparison of the EPA Non-road Transient Cycle against CanmetMINING LHD transient test cycles for potential development of new engine test cycles for use in underground mining.

Testing - SwRI

- SwRI are a national and internationally qualified test facility and have agreed to carry out this assessment.
- SwRI have carried out data processing and will participate in writing a final test report comparing the NRTC and CanmetMINING LHD test cycles.

Test Plan

- Engine Set-up
- Test Engine specifications
- CanmetMINING LHD Test Cycle
- NRTC Test Cycle
- Test Calculations

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Test Engine Specifications

Make	Volvo Penta
Model	TAD572VE
Serial number	5-604
Displacement	51318 cm3
Rated power, gross	160 kW@ 2300 rpm
Fuel rate at rated power	34 kg/hr
Peak torque	910 N.m @1450 rpm
Peak torque speed	1200 rpm/ Intermediate Speed at 1260 rpm
Aspiration	Turbocharged, charge air cooled
Fuel system	Denso HP4 / Volvo EMS 2.3
Max exhaust backpressure	18 kPa
Low idle speed	700 rpm
High idle speed	2500 rpm

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SWRi - Engine set-up

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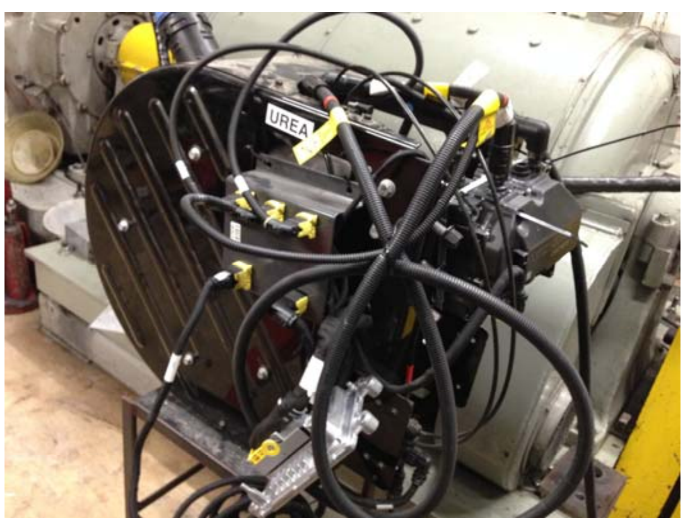
SWRi - Engine set-up

SWRi – Urea dosing pump



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SWRi – Adblue tank

CanmetMINING - List of Engines

Engine Manufacturer: **Volvo Penta**
Engine Model: **TAD570VE, TAD571VE, TAD572VE, Tier 4F**
Governing Standard: **CSA M424.2-90 (Non-Gassy Mines)**

Certificate Number	Engine Rating and Fuel Rate at Sea Level	Sulphur in Fuel - ppm	Ventilation Prescription CFM	Ventilation Prescription m^3/s
1276	TAD570VE, 141 HP (105 kW) @ 2300 RPM, 50.0 lb/h	15	1,600 4,800+	0.76 2.27+
	TAD571VE, 173 HP (129 kW) @ 2300 RPM, 61.0 lb/h	15	1,900 5,800+	0.90 2.74+
	TAD572VE, 215 HP (160 kW) @ 2300 RPM, 75.0 lb/h	15	2,800 7,100+	1.32 3.35+

+ These ventilation rates are recommended by NRCan/CanmetMINING where, some of the gases govern ventilation rates rather than the EQI criterion.

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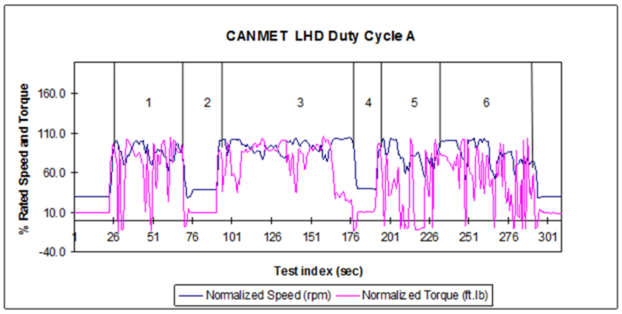
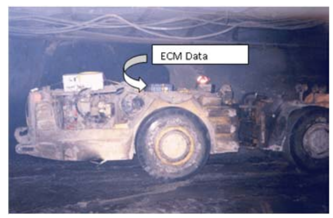
CanmetMINING LHD Cycle



1	Loading
2	Idle
3	Haul Loaded
4	Idle
5	Dumping
6	Return Empty



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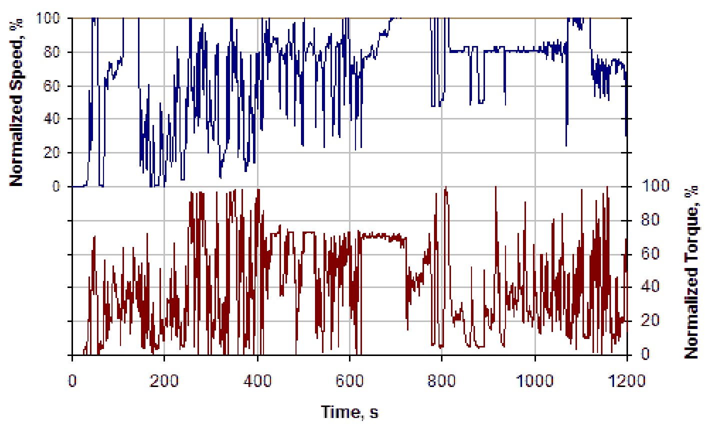
NRTC Test Cycle



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Test Calculations

- Emission calculations were conducted as per the CFR 1065 standard for both the NRTC and CanmetMINING LHD test cycles
- Emission calculations were also performed per a variant of ISO 8178 for both the NRTC and CanmetMINING LHD test cycles.

Test Results

- EPA Emission limits – NRTC vs the CanmetMINING LHD test cycles using CFR 1065 method
- Comparison of emission values following CFR 1065 method and ISO 8178/CFR variant method
- Comparison of steady state and transient cycle emissions – 8 mode maximum versus NRTC and LHD C transient cycles exhaust mass emissions rate
- Ammonia slip for the LHD C transient test cycle

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Legislated non-road transient cycle (NRTC)

EPA Tier 4f Transient NRTC Results		
	Standard	TAD572VE
CO g/kW-hr	3.500	0.101
NOx g/kW-hr	0.400	0.149
HC g/kW-hr	0.190	0.007
PT g/kW-hr	0.020	0.015

- DieselNet.com

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Integrated 8 mode, NRTC and LHD A test cycles - Emissions

Engine Data	Int 8 Mode	NRTC		LHD A1		LHD A2		LHD A3	
	CFR 30	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065
Speed (rpm)	1804	1791	1791	1846	1846	1840	1840	1840	1840
Torque (N.m)	440.6	302.4	302.4	314.7	314.7	314.3	314.3	313.2	313.2
Power (kW)	87.4	57.8	57.8	62.3	62.3	62.4	62.4	62.4	62.4
Fuel (kg/hr)	18.9	13.2	13.1	14.3	14.3	14.0	14.2	14.2	14.0
CO2 g/kW-hr	673.4	713.4	721.4	715.7	719.3	706.8	715.2	705.1	713.2
CO g/kW-hr	0.145	0.103	0.101	0.129	0.125	0.124	0.120	0.115	0.120
NO2 g/kW-hr	0.005	0.016	0.009	0.020	0.015	0.021	0.021	0.024	0.022
NO g/kW-hr	0.078	0.091	0.140	0.100	0.152	0.105	0.158	0.110	0.168
NOx g/kW-hr	0.083	0.107	0.149	0.119	0.167	0.126	0.178	0.134	0.190
HC g/kW-hr	0.000	0.008	0.007	0.009	0.008	0.008	0.008	0.008	0.008
PT g/kW-hr	0.019	n/a	0.015	n/a	0.015	n/a	0.015	n/a	0.012
Fuel g/kW-hr	216	229	227	230	226	228	225	228	224
Cycle Work kW-hr	30.10	19.89	19.89	22.32	22.32	22.32	22.32	22.31	22.31

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Integrated 8 mode, NRTC and LHD B test cycles - Emissions

Engine Data	Int 8 Mode	NRTC		LHD B1		LHD B2		LHD B2	
	CFR 30	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065
Speed (rpm)	1804	1791	1791	1627	1627	1627	1627	1627	1627
Torque (N.m)	440.6	302.4	302.4	372.7	372.7	373.5	373.5	373.9	373.9
Power (kW)	87.4	57.8	57.8	67.1	67.1	67.2	67.2	67.1	67.1
Fuel (kg/hr)	18.9	13.2	13.1	14.5	14.1	14.5	14.1	14.5	14.1
CO2 g/kW-hr	673.4	713.4	721.4	661.0	668.7	662.0	669.6	662.1	669.9
CO g/kW-hr	0.145	0.103	0.101	0.104	0.101	0.102	0.101	0.100	0.103
NO2 g/kW-hr	0.005	0.016	0.009	0.020	0.018	0.020	0.020	0.024	0.022
NO g/kW-hr	0.078	0.091	0.140	0.085	0.129	0.086	0.130	0.087	0.135
NOx g/kW-hr	0.083	0.107	0.149	0.105	0.147	0.106	0.150	0.111	0.157
HC g/kW-hr	0.000	0.008	0.007	0.007	0.006	0.005	0.005	0.005	0.005
PT g/kW-hr	0.019	n/a	0.015	n/a	0.012	n/a	0.011	n/a	0.011
Fuel g/kW-hr	216	229	227	216	210	216	210	216	210
Cycle Work kW-hr	30.10	19.89	19.89	24.66	24.66	24.67	24.67	24.67	24.67

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Integrated 8 mode, NRTC and LHD C test cycles - Emissions

Engine Data	Int 8 Mode	NRTC		LHD C1		LHD C2		LHD C3	
	CFR 30	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065	CMIN	CFR 1065
Speed (rpm)	1804	1791	1791	1873	1873	1873	1873	1873	1873
Torque (N.m)	440.6	302.4	302.4	408.7	408.7	409.3	409.3	408.4	408.4
Power (kW)	87.4	57.8	57.8	82.7	82.7	82.7	82.7	82.7	82.7
Fuel (kg/hr)	18.9	13.2	13.1	17.9	17.6	17.9	17.6	17.9	17.6
CO2 g/kW-hr	673.4	713.4	721.4	670.1	678.4	671.5	678.9	670.1	678.4
CO g/kW-hr	0.145	0.103	0.101	0.124	0.121	0.114	0.115	0.115	0.113
NO2 g/kW-hr	0.005	0.016	0.009	0.014	0.012	0.013	0.012	0.016	0.013
NO g/kW-hr	0.078	0.091	0.140	0.071	0.110	0.074	0.112	0.072	0.112
NOx g/kW-hr	0.083	0.107	0.149	0.085	0.122	0.087	0.124	0.088	0.125
HC g/kW-hr	0.000	0.008	0.007	0.007	0.007	0.006	0.006	0.006	0.005
PT g/kW-hr	0.019	n/a	0.015	n/a	0.010	n/a	0.010	n/a	0.010
Fuel g/kW-hr	216	229	227	217	213	217	213	217	213
Cycle Work kW-hr	30.10	19.89	19.89	30.40	30.40	30.38	30.38	30.39	30.39

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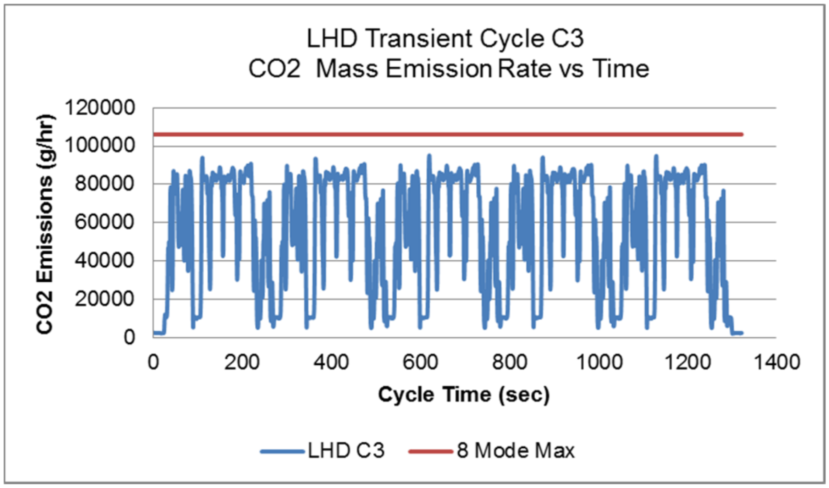
Legislated non-road transient cycle (NRTC)

- Testing at SwRI showed that the engine complied with the legislated non-road transient cycle (NRTC) limits.
- EPA Tier 4f limits are not exceeded on any of the CANMET LHD cycle tests either.

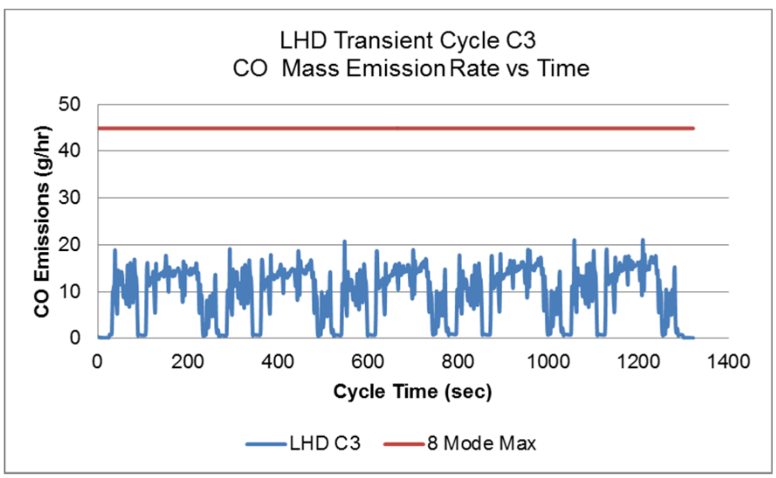
CMIN vs. EPA1065 Analysis Methods

- This work shows that both analysis methods are comparable and give similar results.
- In addition the specific emission calculation methods for each method give similar results when applied to transient cycle data.

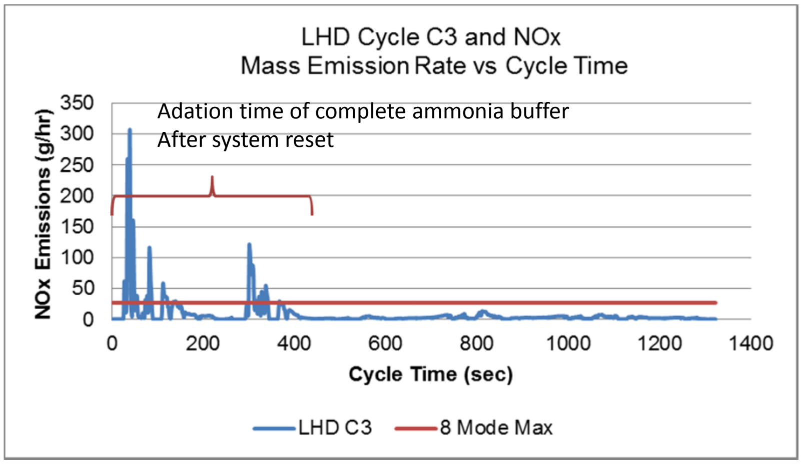
Steady state versus transient cycle emissions



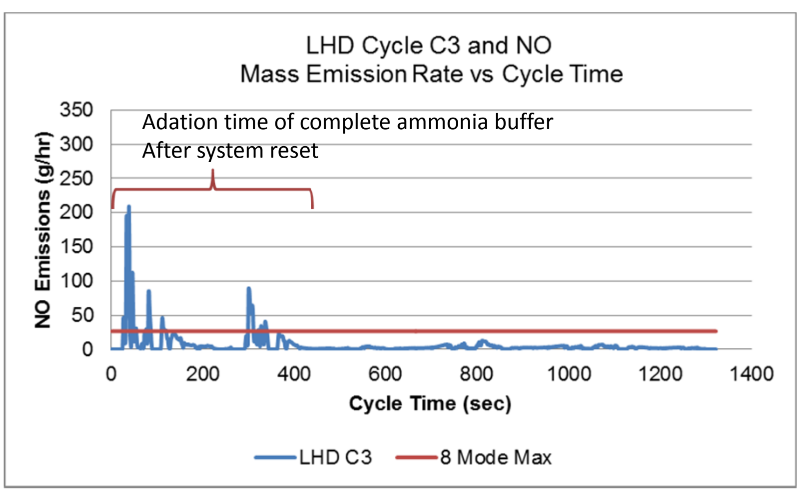
Steady state versus transient cycle emissions



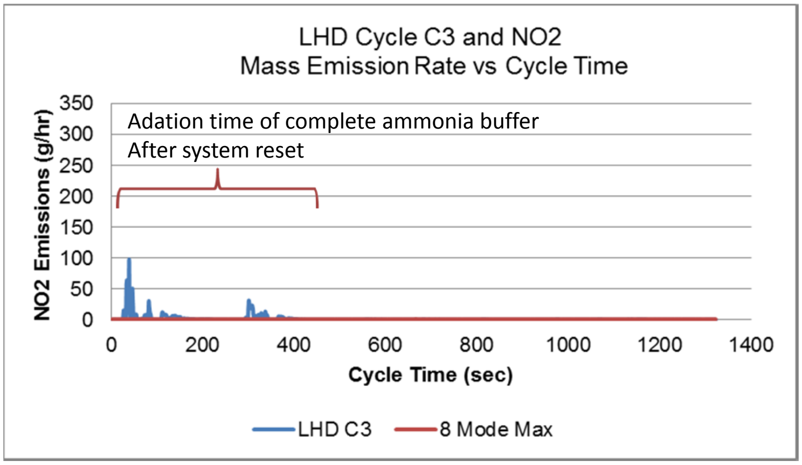
Steady state versus transient cycle emissions



Steady state versus transient cycle emissions



Steady state versus transient cycle emissions



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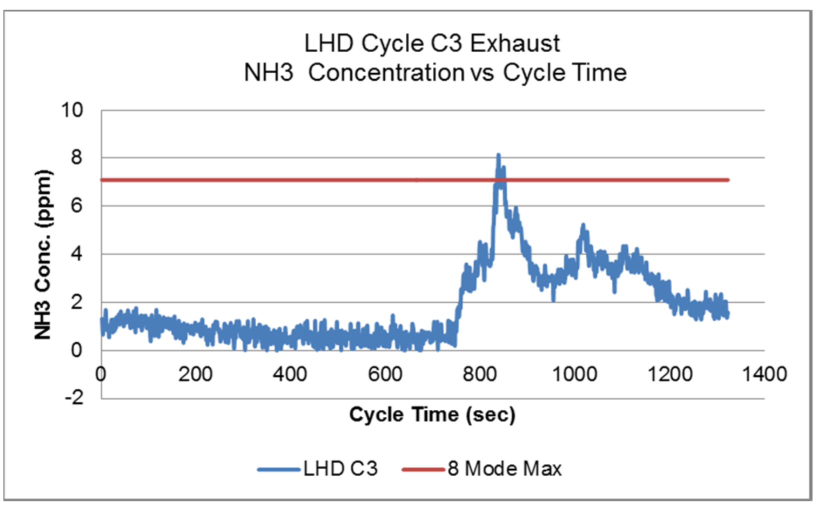
Steady state versus transient cycle exhaust NH3 concentrations



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Conclusions: NRTC / CANMET LHD

- TAD572VE complies as expected with the EPA T4f standards over the NRTC cycle.
- The T4f limits are also never exceeded during the CANMET LHD cycle tests.

Conclusions: ISO8178 vs EPA1065

- Analysis of specific emissions data is compatible with either data treatment method and gives comparable results.

Conclusions: Transient vs Steady S.

- Large archive of current and historical CSA ventilation rates on steady-state test.
- LHD Test Cycle
  - LHD cycle "C" is within 5% of the steady-state cycle work (kW-h).
  - LHD cycle "A" is within 10% of the NRTC cycle work.

Discussion: Round-table Session

- Revision of the CSA standard is planned.
- Should the new standard include a transient test?
- What should that test be? NRTC/LHD?
- Is in necessary to maintain backward compatibility with the CSA list?
- Are additional test methods for after-treatment required?

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