Heavy-Duty Certification Standards and Test Procedures Workgroup Meeting

Mobile Source Control Division
California Air Resources Board

March 6, 2017

California Environmental Protection Agency
Air Resources Board

Outline

- Rulemaking Timeline
- Purpose of the Workgroup
- CARB Optional NOx Standards
- CARB HD Low NOx Research Activities
- Low Load Test Cycle
- Outside the Box Ideas
- Open Discussion/Questions

Heavy-Duty Truck Rulemakings
Scheduled Board Dates

Rulemaking	Scheduled Board Hearing Date
Revisions to Periodic Smoke Inspection Program	September 2017
California Phase 2 GHG Standards	October 2017
Revisions to the Warranty Period and Recall Authority Requirements	December 2017
Revisions to the - NOx Standard and Test Procedures, - In-Use Compliance Program, and - Durability/Useful Life Requirements	2019
Heavy-duty Inspection and Maintenance	2020

Purpose of Heavy-Duty Cert. Standards and Test Procedures Workgroup

- Provide stakeholders the opportunity to provide suggestions and comments
- Exchange data and ideas between CARB staff and stakeholders to make informed decisions
- Considerations
  - Potential supplemental test cycle
  - Low NOx technology
  - Emission measurement issues
  - Durability demonstration and useful life requirements
  - OBD implications
  - Other outside the box ideas

CARB Optional NOx Standards

- Adopted in 2013
- Optional NOx standards – three levels
  - 90%, 75%, and 50% below 2010 NOx standards
  - 0.02 g/bhp-hr, 0.05 g/bhp-hr, and 0.10 g/bhp-hr
- CARB Certified Engines:
  - 8.9L ISL G – CNG certified to 0.02 g/bhp-hr (90% below)
  - 6.7L ISB6.7 G – CNG certified to 0.1 g/bhp-hr (50% below)
- 8.9L ISL G Testing by UCR, CE-CERT
  - Meets the optional 0.02 g/bhp-hr NOx standard for both certification <u>and</u> non-certification cycles (Refuse, Neardock, Local, Regional, Bus)
    - (http://www.cert.ucr.edu/news/2017/2017-02-01.html)
  - Incentives being provided for deployment

CARB HD Low NOx Research Activities

- Stage 1 – Low NOx feasibility demonstration
  - CARB Funding: $1.6M
  - Contractor: SwRI
  - Additional support: MECA, Volvo, SwRI
- Stage 2 – Low load cycle (LLC) development/ LLC optimization
  - CARB funding: 1.05M
  - Contractor: SwRI
- Stage 3 – Low NOx Demonstration on an Alternative Non-Turbocompound (TC) Engine
  - Funding: CARB, AQMD, and others (total of $1.3M)
  - Contractor: SwRI
  - Additional support: MECA

Stage 1: Low NOx Program

- Started October 2013/ completed December 2016
- Optimization on FTP, RMC, WHTC, and CARB Idle
  - Target NOx on aged parts: 0.02 g/bhp-hr on the FTP and RMC
- Additional testing on 3 vocational cycles: NYBC, Cruise Creep, and OCTA bus cycle
- Two Engines:
  - CNG: 2012 Cummins ISX12 G (Stoichiometric), and
  - Diesel: 2014 Volvo MD13TC (Euro VI, with TC)

More information:
https://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm

Stage 1: Natural Gas Engine

Engine and Aftertreatment (AT) Options

- Engine: 2012 Cummins ISX12 G, 11.9L, 320hp
- Engine upgraded to improve AFR control
  - Aftermarket prototype ECU from EControls
  - Proprietary injection and mixing hardware
  - Closed crankcase ventilation system
- AT Options: 4 packages of three way catalyst (TWC)
- Final downselected:
  - Close coupled TWC (9L) and underfloor TWC (20L)
  - Thermally aged to full useful life (FUL) – acceleration based on EPA Standard Bench Cycle for TWC

Stage 1: Natural Gas Engine

Final Aged Results – FTP, RMC, WHTC

Engine	Pollutant	Unit	FTP	RMC-SET	WHTC
Baseline	**NOx**	g/bhp-hr	**0.115**	**0.012**	**0.308**
	CH_4		0.96	1.20	1.54
	CO2		542	454	510
	NH_3	ppm	76	162	100
Low NO_X	**NOx**	g/bhp-hr	**0.01 (91%)***	**0.001 (92%)**	**0.011 (96%)**
	CH_4		0.15 (84%)	0.93 (23%)	0.10 (94%)
	CO_2		547 (-0.9%)	445 (2.0%)	513 (-0.6%)
	NH_3	ppm	52 (32%)	37 (77%)	44 (56%)

Note: *(%) Percent reduction from baseline
CARB Idle NOx is essentially zero.

Stage 1: Natural Gas Engine

Final Aged Results – Vocational Cycles

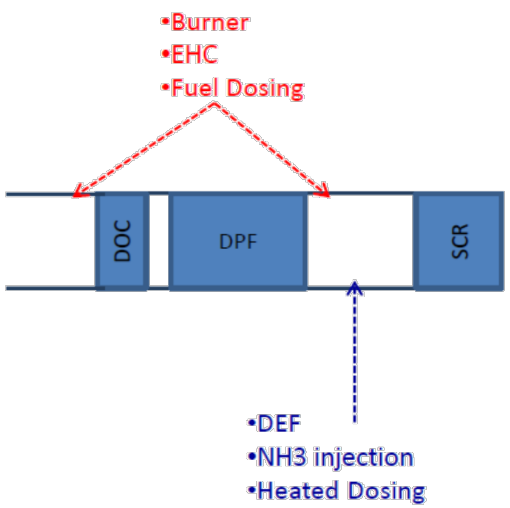
Engine	Pollutant	Unit	NYBC	Cruise Creep	OCTA
Baseline	**NO_X**	g/hp-hr	**0.9**	**0.1**	**0.1**
	CH_4		1.9	1.6	1.1
	CO2		672	612	553
	NH_3	ppm	12	124	92
Low NO_X	**NO_X**	g/hp-hr	**0.002**	**0.002**	**0.000**
	CH_4		0.5	1.0	0.04
	CO2		661	897	550
	NH_3	ppm	25	85	47

Stage 1: Diesel – AT System

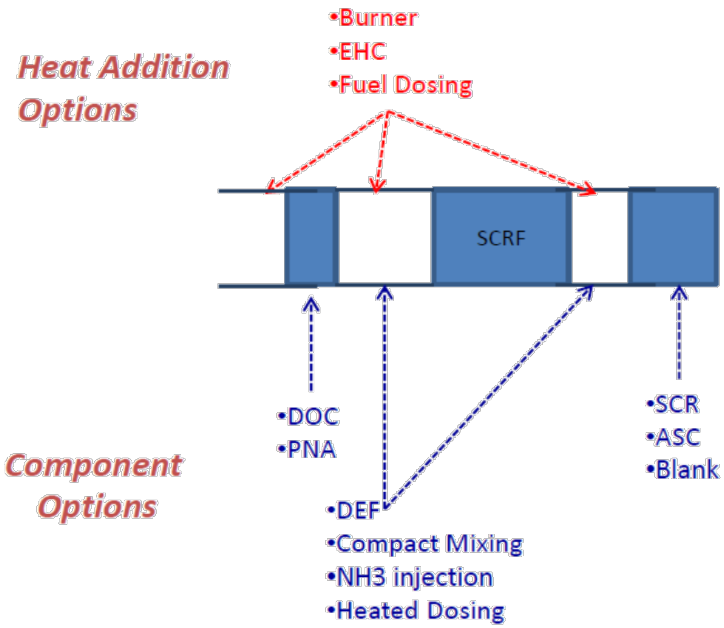
AT Options

- Engine: 2014 Volvo MD13TC (Euro VI, with TC)

Traditional Approach



Advanced Approach

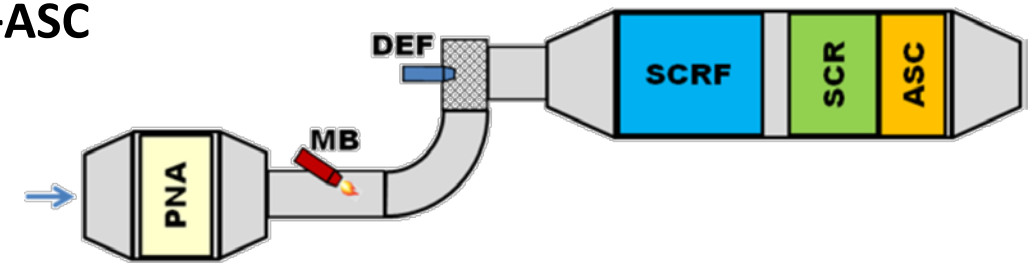


Stage 1: Diesel – AT System

Final Low NOx Configuration

- Screened approximately 33 technology packages
- Ranked them based on fuel penalty, cost, durability, and complexity
- Top four ranking packages tested on engine dynamometer with development aged parts

- **Demonstrated well below 0.02 g/bhp-hr NOx**
  - **PNA+MB+DEF+SCRF+SCR+ASC**
  - 0.012 g/bhp-hr NOx



- Impact on GHG from baseline including engine calibration
  - 2% on FTP – (0.5% engine cal, 0.5% SCRF regen, 1% mini-burner)
  - < 0.5% on RMC-SET – due to increased frequency of SCRF regen only

Stage 1: Diesel – AT System

Aging

- Final parts aged on engine thermally and chemically
- Issues during aging
  - PNA canning failure (detected @710 hours)
  - Mat material in front of SCRF (and some in channels)
  - Large buildup of coke/soot on PNA front
- PNA and SCRF were cleaned and recovered in a manner that did not further disturb aging

Stage 1: Diesel – AT System

Final Aged Parts – FTP and RMC

NOx (g/bhp-hr)		FTP			RMC
		Cold	Hot	Composite	
Baseline	Tail Pipe	0.71	0.047	0.140	0.084
	NOx Conv.(%)	75.0	98.4	95.2	96.7
Development Aged Parts	Tail Pipe	0.027	0.010	0.012	0.015
	NOx Conv.(%)	97.8	99.7	99.4	99.5
Final "Engine" Aged	Tail Pipe	0.114	0.021	**0.034**	**0.038**
	NOx Conv. (%)	95.8	99.3	**98.8**	**98.2**

- WHTC results were similar to the FTP results

Stage 1: Diesel – AT System

GHG Impacts

	BSCO2, g/hp-hr			
	Cold	**Hot**	**Composite**	**RMC**
Baseline Engine	574.2	542.6	547.4	457.7
Final ULN Config	604.4	548.8	558.2	463.6
% change	5.3%	1.1%	**2.0%**	**1.3%**
Mini-burner air	0.4%	0.2%	**0.2%**	
Increased SCRF Regeneration			**0.3%**	**0.3%**
Total FTP CO2 Impact			**2.5%**	**1.6%**

- Tailpipe NH3 < 2 ppm cycle average
- Tailpipe N2O = 0.10 g/hp-hr

Stage 1: Diesel – AT System

Final Aged Parts – CARB Idle and Cruise Creep

Carb Idle								
	Low Idle (550 rpm)				PTO Idle (1100 rpm)			
	EO NOx (g/hr)	TP NOx (g/hr)	% Conv.	Fuel Rate kg/hr	EO NOx (g/hr)	TP NOx (g/hr)	% Conv.	Fuel Rate kg/hr
Baseline	46.1	11.7	75	1.18	66.2	52.7	20	3.16
with relight	10.6	0.2	98	1.00	42.4	14.6	66	3.21
without relight	7.0	0.1	99	0.99	30.5	33.7	-10	2.93

Cruise Creep x 10				
	EO NOx (g/hr)	TP NOx (g/hr)	% Conv.	Fuel Rate kg/hr
Baseline	71.8	13.3	81.0	2.75
with relight	41.3	7.45	82.0	2.76
without relight	41.1	12.8	69.0	2.63

- Tests run both with and without burner re-light to show impact of thermal management on NOx and fuel consumption

Stage 1: Diesel – AT System

Final Aged Parts - NYBC and OCTA

NYBCx4				
	EO NOx (g/bhp-hr)	TP NOx (g/bhp-hr)	% Conv.	Fuel Rate kg/hr
Baseline	6.10	2.30	62.0	5.29
with relight	3.90	0.38	90.0	5.30
without relight	3.60	0.78	78.0	5.18

OCTA				
	TP NOx (g/bhr-hr)	TP NOx (g/bhr-hr)	% Conv.	CO2 (g/bhp-hr)
Baseline	3.8	0.023	99.4	529
with relight	2.7	0.006	99.8	534
without relight	2.7	0.011	99.6	543

- Tests run both with and without burner re-light to show impact of thermal management on NOx and fuel consumption

Stage 2: LLC Development/ Optimization on Low Load Profiles

- Follow-on project to Stage 1
  - Initiated in January 2017,
  - Completion by June 2018
  - ARB funding: $1 M
  - Contractor: SwRI
    - NREL as subcontractor for LLC development

- Engine/AT system from Stage 1
  - **Stage 1b** contract being considered–aging of **new** AT parts for use in Stage 2

- Program tasks/objectives:
  - Develop low load duty cycle profiles and LLC
  - Optimize emission control over these low load profiles and the LLC and determine impacts on GHG
  - Evaluate accuracy of broadcast torque at low loads
  - Evaluate other testing metrics for determining in-use emissions at low loads

Stage 2: LLC Development

Tasks

- Define Low load profiles:
  - Average power at 10% or less, with max ~ 15%
- Typical types of low load profiles:
  - Operation where SCR is “cooled off” below operating temperature and then need to warm up to operating temperature
  - Operation where SCR is initially warm but cooled below effective operating temperature
  - Operation that is in thermal equilibrium with a light load profile (i.e., sustained light load control)
- Develop a single cycle (LLC) representing low load operations

Stage 3: Low NOx Demonstration
Alternative Engine Platform (Non-TC)

- Follow-on project to Stages 1 and 2
  - Contract currently under processing
  - Kick off in summer of 2017
  - Co-funded by ARB, AQMD, and others: $1.325M Total
  - MECA support: AT system and final aging
  - Engine platform without TC (likely 2017 model year)
  - AT system can be different than that demonstrated in Stages 1 and 2

- Optimization on
  - FTP, RMC, and CARB Idle
    - Target NOx emission rate: 0.02 g/bhp-hr on FTP and RMC
  - Low load profiles from Stage 2 development

Low Load Test Cycle Development

- **Activity Data**
  - NREL Fleet DNA Database
    - 500 vehicles
    - 20 vocations
  - CARB program with UCR
    - 90 – 2010 and newer model heavy-duty vehicles
    - 19 vocational/regional groups
    - Includes ECU broadcast data
- Industry data?
- Industry thoughts on approach, need for low load cycle?

Other Outside the Box Ideas

- Geofencing
  - One low NOx national standard, and
  - Secondary calibration that is switched on when vehicle operates under extended low load operations within a geofenced area
  - Pros: minimizes overall penalty in GHG emissions
  - Cons: In-use enforcement issues – determining compliance, tampering, etc.

- Crediting vehicle technologies that provide NOx reductions? (e.g., stop-start, improved transmissions, hybrids, etc.)
  - Power train testing
  - Modeling (GEM)

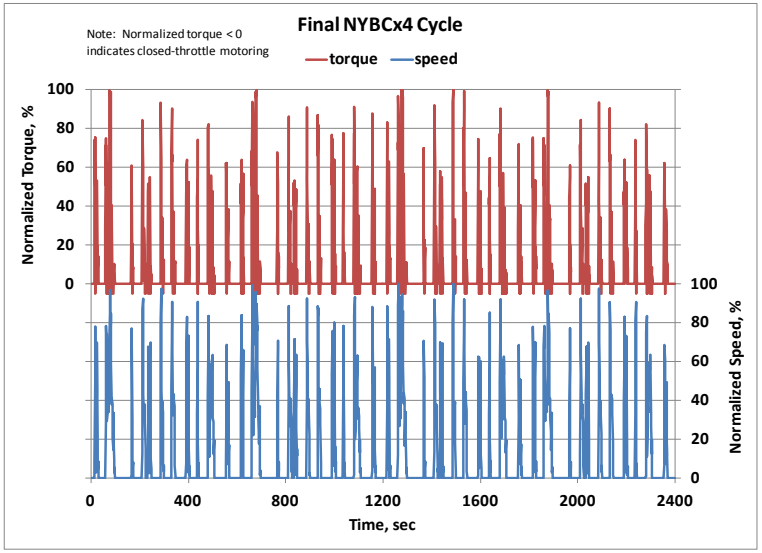
- Other Concepts?

Questions? Comments?

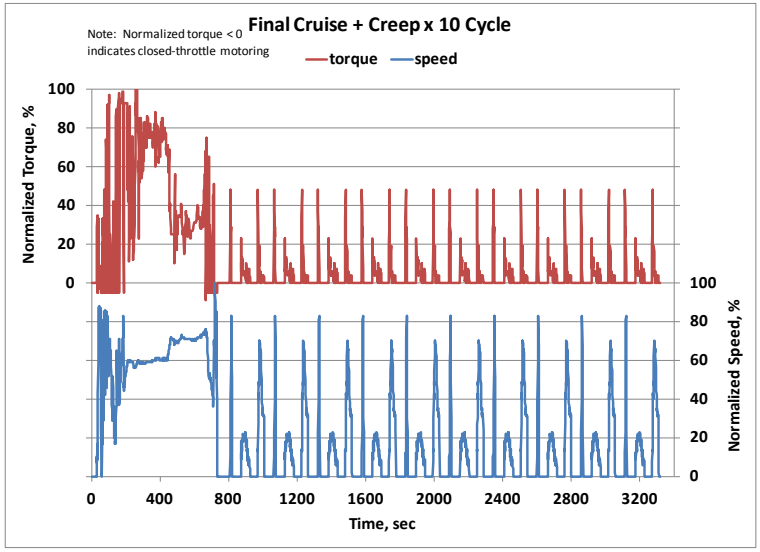
Backup slides

Vocational Cycles

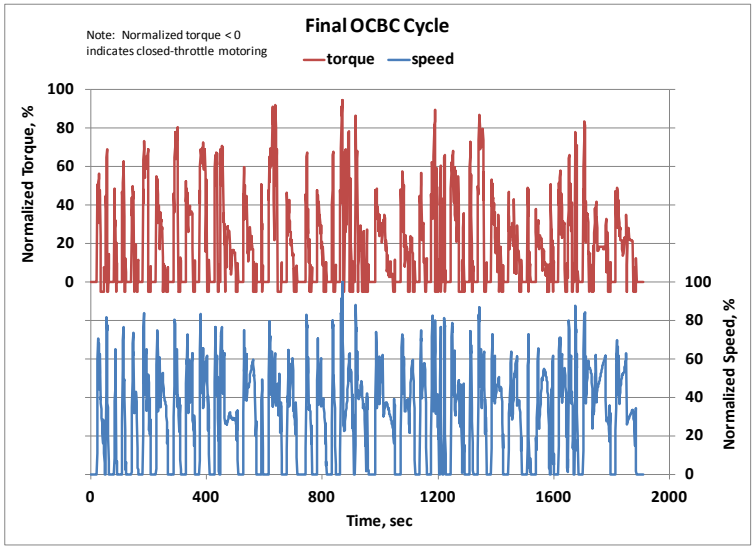
New York Bus Cycle (NYBC) x 4 Cycle



Cruise Creep x 10 Cycle

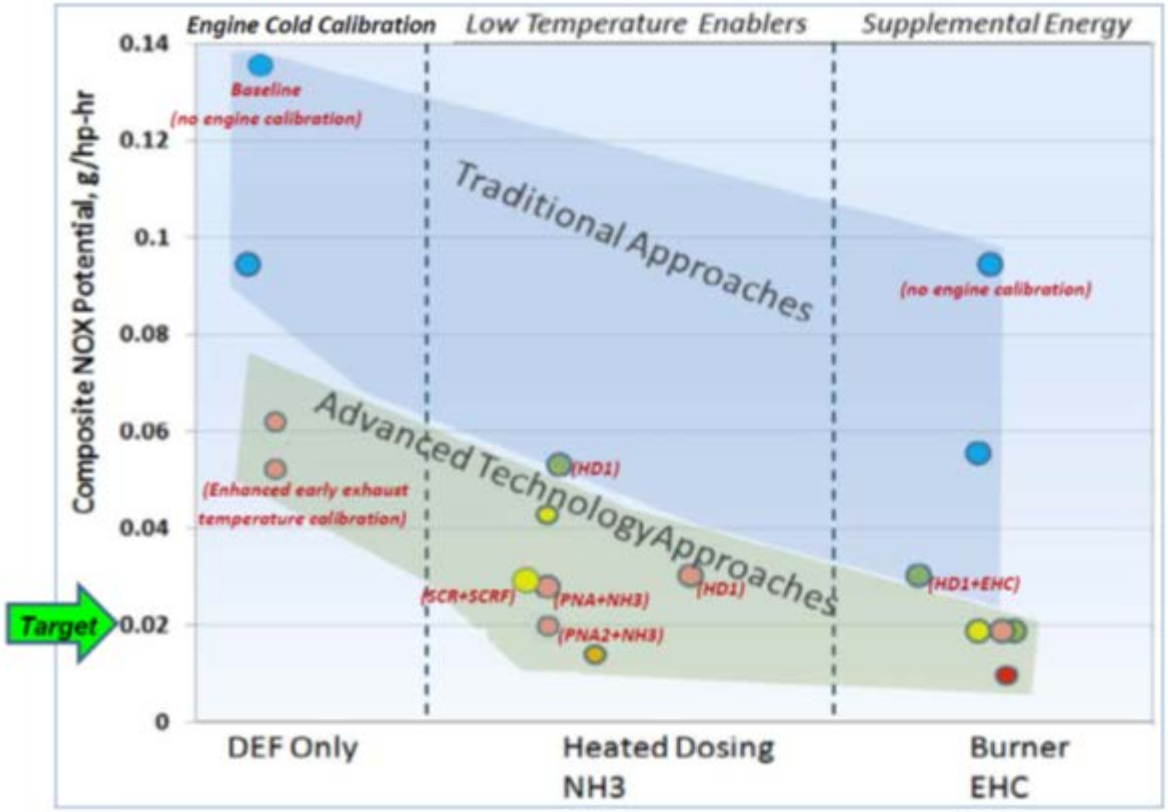


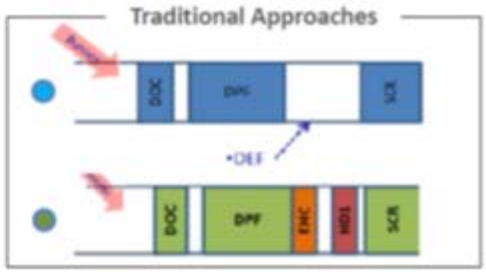
Orange County Transit Authority Bus Cycle (OCTA)

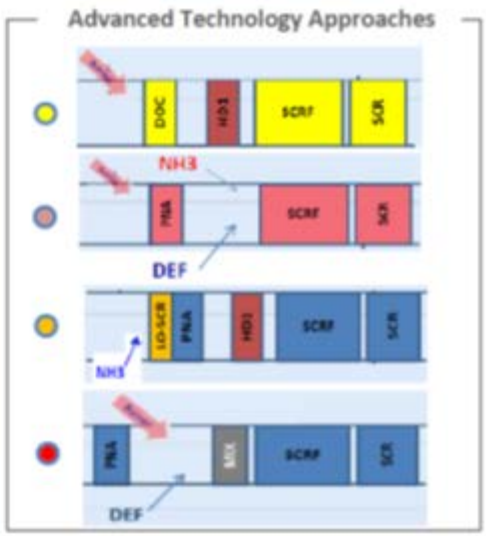


Stage 1: Diesel – AT System

Screening Test Results







Acronyms

DOC: diesel oxidation catalyst; ***DPF***: diesel particulate filter; ***SCR***: selective catalyst reduction; ***Burner***: 10kw mini-burner; ***EHC***: electrically heated catalyst; ***HD1***: heated DEF dosing; ***SCRF***: SCR catalyst coated DPF; ***PNA***: passive NOx adsorber; ***PNA2***: PNA with altered catalyst formulation; ***NH3***: gaseous ammonia injection; ***LO-SCR***: close-coupled light-off SCR

Multiple potential pathways to achieve NOx emissions below 0.02 g/bhp-hr

Stage 1: Diesel – AT System

Final Technology Rankings from Screening

System	Composite NO_x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + HD1 + SCRF + SCR/ASC	0.02	0.9	8/ 13.3	10/10	4/9.8
NH3 + LO SCR + PNA + HDI + SCRF + SCR/ASC (HD1)	0.016	0.95	12/20.7	11/56	11/12.5
EHC/DOC + DEF + SCRF + SCR + SCR/ASC - *(under evaluation)*	///	1.05	7/9.4	7/9	4/6.2
PNA + MB + DEF + SCRF + SCR/ASC	0.01	1.04	13 /16.2	10/13.1	9/12.5
MB + DOC + DEF + SCR + SCRF + SCR/ASC	0.019	1.04	9/10.7	8//10	8/7.7
MB + DOC + DEF + SCRF + SCR + SCR/ASC	0.018	1.04	9/10.7	8//10	8/7.7
DOC + MB + SCRF + SCR + SCR/ASC - *(not evaluated)*	//////////////////	1.04	9/10.7	8/10	7/7.7
MB + DOC + DPF + SCR + SCR/ASC	0.025	0.62	6/6.4	6/7	7/6.3
EHC/DOC + DPF + HD1+ SCR + SCR/ASC - *(not evaluated)*	//////////////////	0.98	5/8.6	6/9	5/8.4
PNA + HD1 + SCRF + SCR/ASC	0.029	0.9	8/13.3	5/13	4/9.8
PNA + NH3 + DEF + SCRF + SCR/ASC	0.031	0.72	8/13.4	8/13	7/12.3
NH3 + LO SCR + DOC + DPF + HD1 + SCR+SCRF + SCR/ASC *(not evaluated)*	//////////////////	0.65	4/15.2	9/16	10/12.4
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033	1.2	2/7.2	2/7	6/7.7
Base engine, stock calibration 4852 g					
Base engine, CC1: 4973 g					

- Scoring Based on Program Advisory Group forum