Environment Canada Environnement Canada

Canada

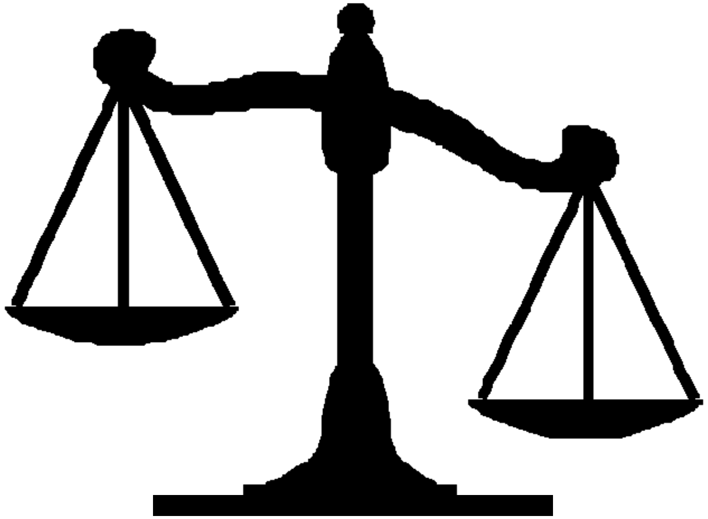
Working Paper No. **HDH-11-08e**
(11th HDH meeting, 10 to 12 October 2012)

Heavy Duty Hybrid Powertrain Testing

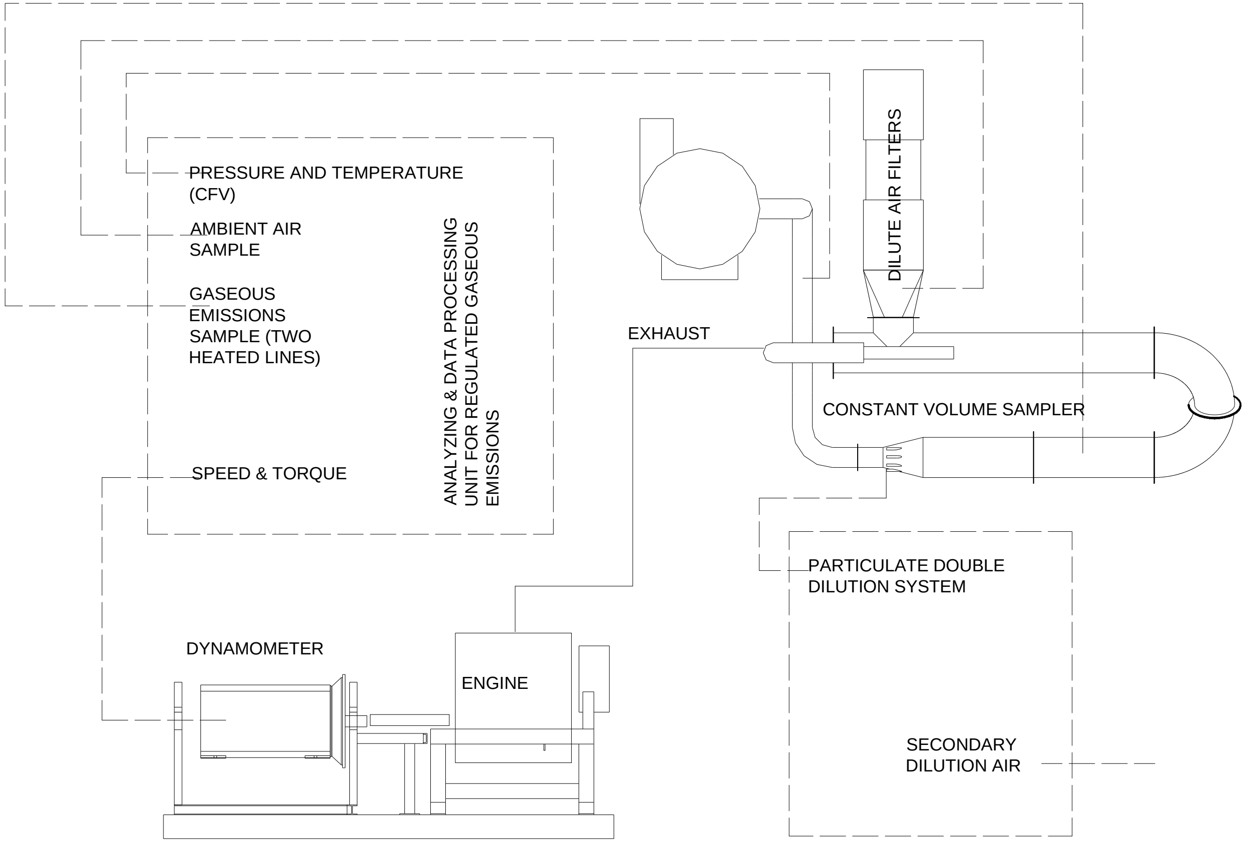
EPA United States Environmental Protection Agency

Objectives

- Compare Hybrid vs. Non-hybrid emission results
- Compare Chassis to Engine dynamometer testing
- Contribute to knowledge base for regulatory development



Heavy-Duty Test Cell #1 Schematic



The instruments

COMPOUND	Analysis Method	Instrument	Sample Collection
Carbon Monoxide (CO)	Non-Dispersive Infrared Detection (NDIR)	HORIBA Model AIA-210 LE	Continuous Collection
Carbon Dioxide (CO_2)	Non-Dispersive Infrared Detection (NDIR)	HORIBA Model OPE-115	Continuous Collection
Oxides of Nitrogen (NO_x)	Heated Chemiluminescence Detection	California Analytical Instruments Model 400-HCLD	Continuous Collection
Nitric Oxide (NO)	Heated Chemiluminescence Detection	California Analytical Instruments Model 400-HCLD	Continuous Collection
Total Hydrocarbons (THC)	Heated Flame Ionization Detection (FID)	California Analytical Instruments Model 300M-HFID	Continuous Collection
Particulate Matter (PM)	Gravimetric Procedure	Sartorius M5P-00V001	70mm Emfab Filters
Particulate Matter (PM)	Gravimetric Procedure	1065-CFR Standard Sampling Cabinet	47 mm Teflon ® Filters

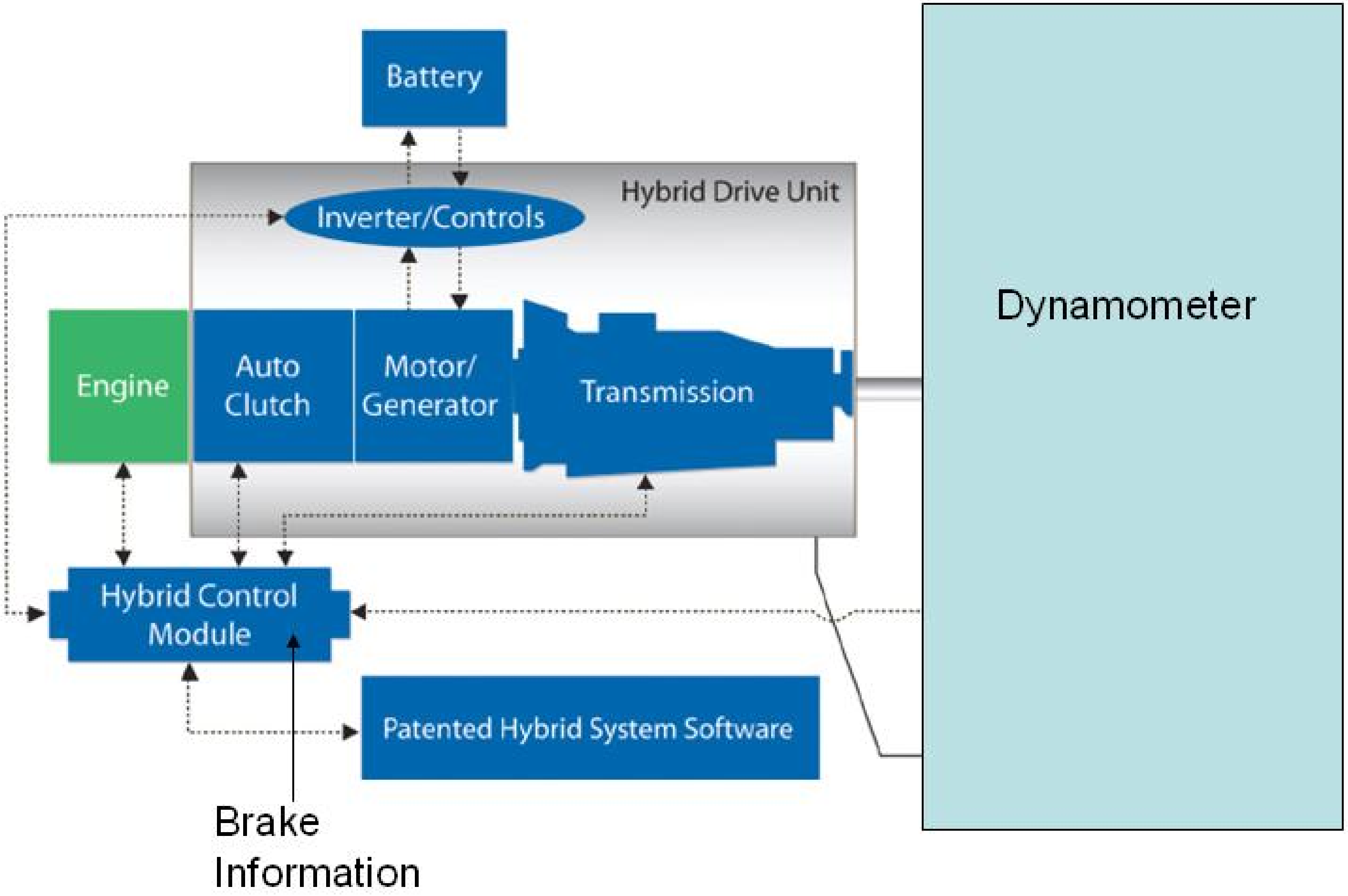
The dynamometer

- 500HP DC motor **2200rpm max speed**
- Trunnion mounted
- Load cell torque measurement.
- 5000 pulses per revolution rpm measurement
- Regenerative drive

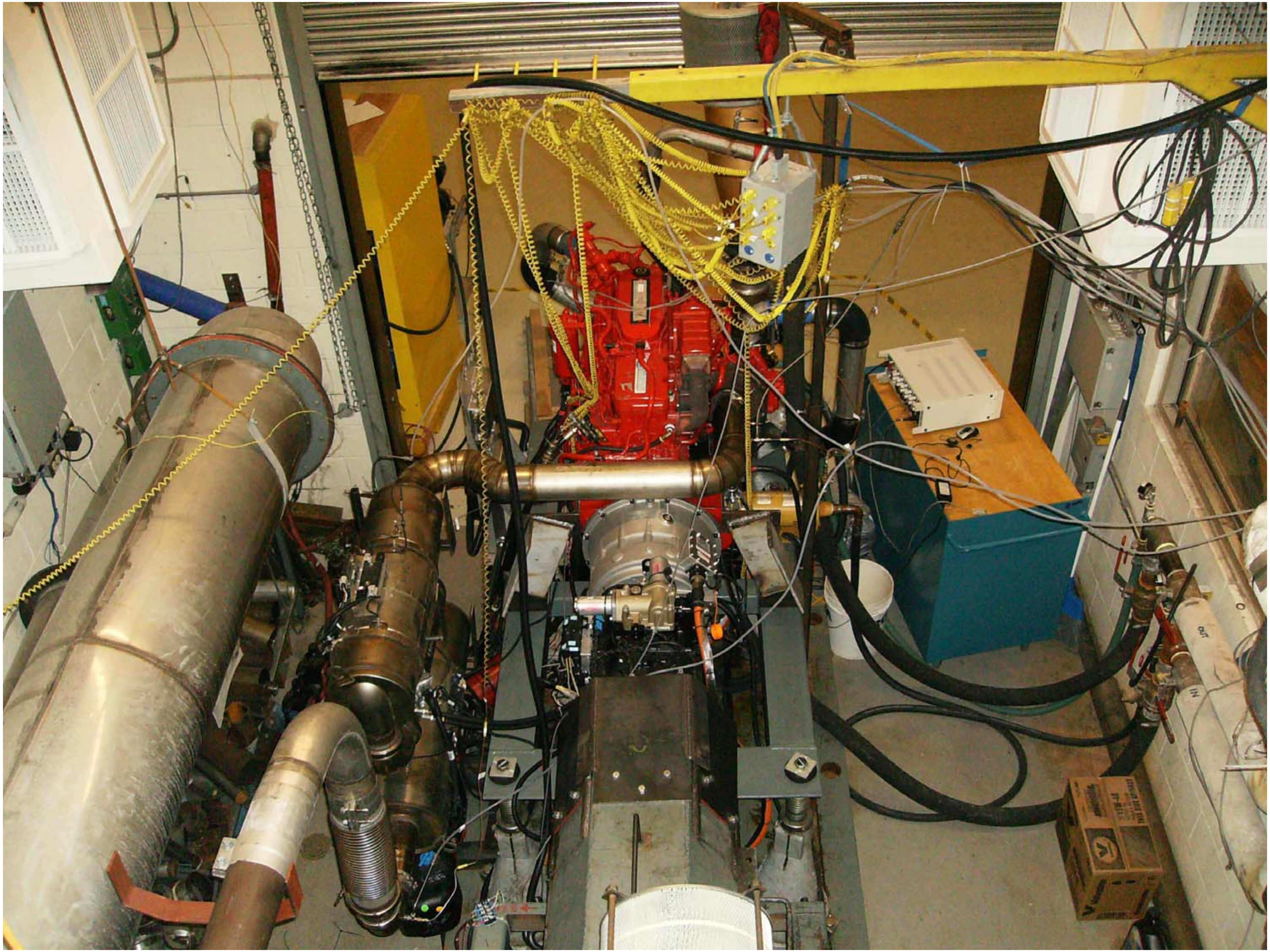
Testing Parameters

	Hybrid Active Vehicle	Hybrid Inactive Vehicle	Hybrid Active Vehicle for Just the HD GHG transient with peak speed truncated to dyno speed limit
m (kg)	6450	5883	6450
A (N)	506.1	506.1	506.1
B (N/(m/s))	7.345	7.345	7.345
C (N/(m/s)^2)	1.960	1.960	1.960
Tire Radius	0.498	0.498	0.498
Final Drive	4.57	4.57	5.57

The setup


Battery
Hybrid Drive Unit
Inverter/Controls
Engine
Auto Clutch
Motor/ Generator
Transmission
Dynamometer
Hybrid Control Module
Patented Hybrid System Software
Brake Information


DANGER
HIGH VOLTAGE


OUT
IN

Connection to Dynamometer

- Typical EC Engine testing: Dyno connected to engine, controlling engine speed and torque
- Hybrid Power Pack Testing: Dyno connected to transmission output
- Testing Engine, Electric motor and Automated Manual Transmission configured as a Hybrid Vehicle
- Simulating road speed: differential gear ratio and tire size simulated to get correct transmission output speed
- Given: tire radius, diff gear ratio, vehicle mass and $A+Bv+Cv^2$ Road Load, cycle as time vs. speed
- Clutch and automated manual transmission allowed to operate by Eaton controller

Change in Dyno Control

- Typical Engine testing Dyno controls torque (or speed), engine controls opposite, speed (or torque), cycle is speed and torque vs. time
- EPA determined shifting was harsh using this type of control due to disconnection of load while transmission shifts, so Dyno controller set up similar to EPA system
- Change Engine Dyno Software to behave like a chassis dyno and use speed vs. time cycle
- Use throttle to control Hybrid, speed following cycle
- Reacted to changes in torque to determine what dyno speed should be

Dyno Cycle Control Modes

- 4 modes of operation, modeled from EPA's experience:

  -Stopped: zero torque

  -Launch: accelerating from a stop; must exceed static RL Force before moving, dyno speed set at zero

  -Braking: throttle at minimum; brakes not simulated, regeneration cannot cause braking too fast, dyno speed setpoint is cycle speed, torque cannot build to unrealistic levels (modulate braking on/off)

  -Accelerating/Cruising: remaining simulation; dyno speed set according to measured force and vehicle parameters

Additional Setup Considerations

- Torque determined from accelerated system inertia and measured dyno torque: $T_{shaft} = \alpha I_{dyno} + T_{dyno}$
- Dyno controller provided brake signal to ECM (Engine Control Module) input, ECM generated CANBus signal for Hybrid Regenerative braking, OK to put into Drive, etc.
- Eaton provide firmware change so that “I’m alive” CANBus signal from ABS module did not need to be generated
- Speed sensor installed on input side of transmission for dyno controller to monitor and ensure clutch and AC motor speed would not exceed max limit

Speed Set Point Formula

- For Engine Speed Control, the speed set point was calculated:

  $\text{CycleSpeed}_{m/s} = \text{fn}(\text{time, cycle})$

  $\text{Rpm} = 60 \text{ x } \text{Ratio}_{axle} \text{ x } \text{CycleSpeed}_{m/s} \text{ x } / (2\pi \text{ x } \text{Radius}_{tire})$
- Did not use force control: $F_{setpoint} = ma + A + Bv + Cv^2$
- For Dyno Speed Control, measured force determines the speed at 100 Hz rate:

  $\text{Force}_{simulated} = \text{Torque}_{shaft} * \text{Ratio}_{axle} / \text{Radius}_{tire}$

  $\text{Force}_{acceleration} = \text{Force}_{simulated} - (A + Bv + Cv^2)_{roadload}$

  $\text{Accel}_{setpoint} = \text{Force}_{acceleration} / \text{Mass}$

  $\text{NewSpeed}_{setpoint} = \text{PreviousSpeed}_{setpoint} + dt * \text{Accel}_{setpoint}$

Target Loading and Cycle Verification

- For cycle verification the measured test speed was compared to the cycle target speed

- Test force was compared to calculated cycle target force:

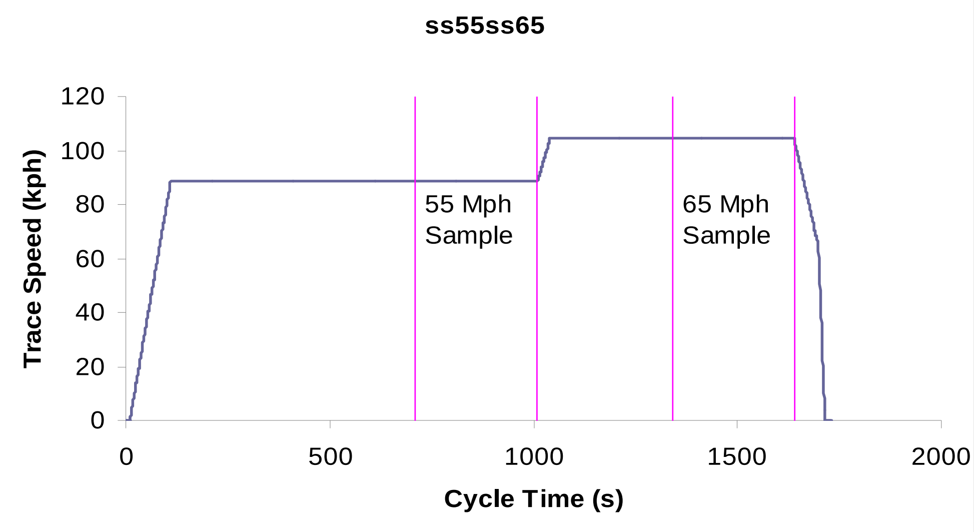
$$a_{taget} = (v_{cycle,i} - v_{cycle,i-1}) / dt$$

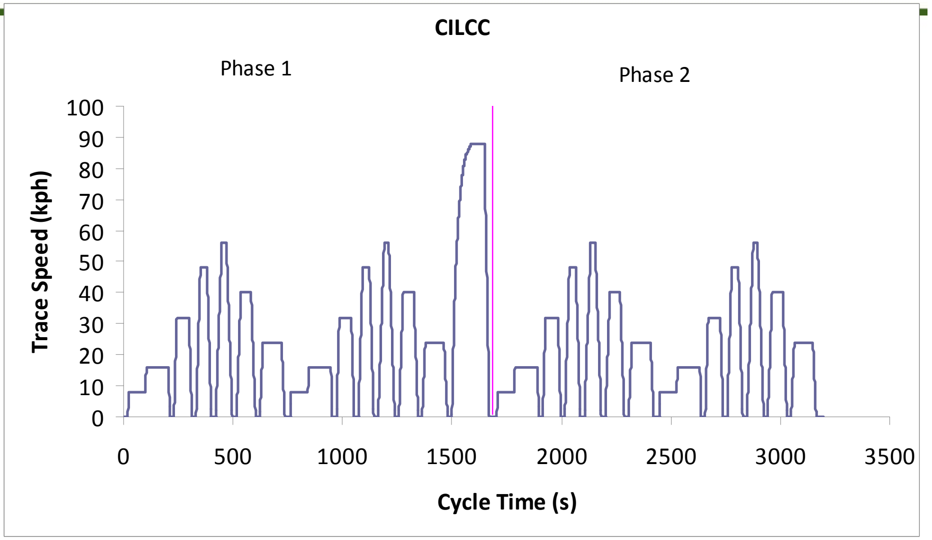
$F_{target} = ma_{target} + A + Bv + Cv^2$, v is the cycle speed

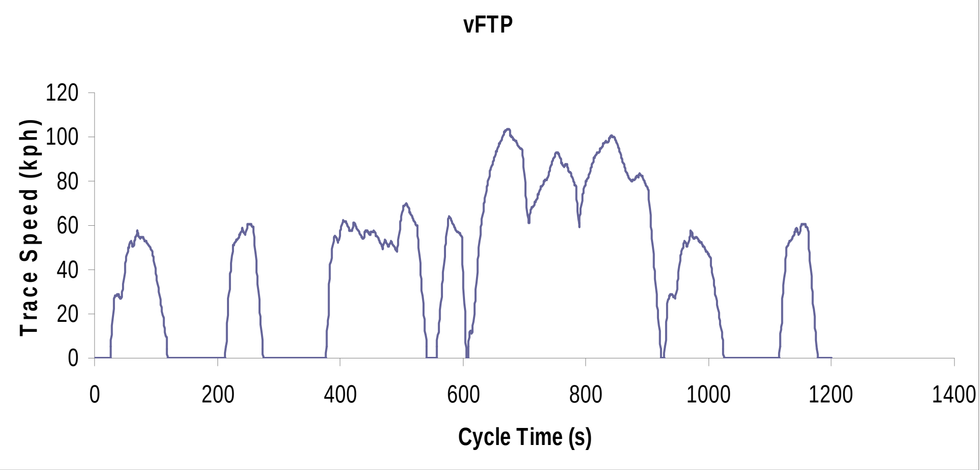
Dyno System Considerations

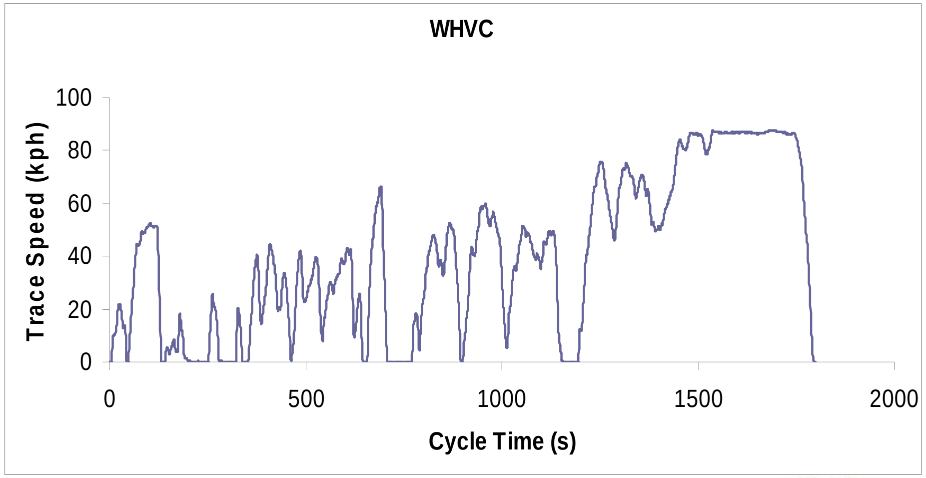
- Max Dyno speed limited choice of differential ratios; could not simulate lower ratios, so higher engine speeds used; use our higher speed dyno in the future
- Assistance from Eaton was invaluable, always willing to work through a problem, provided parts and equipment to keep the project moving ahead
- Several months of active software changes and trials required before able to run tests

Cycles

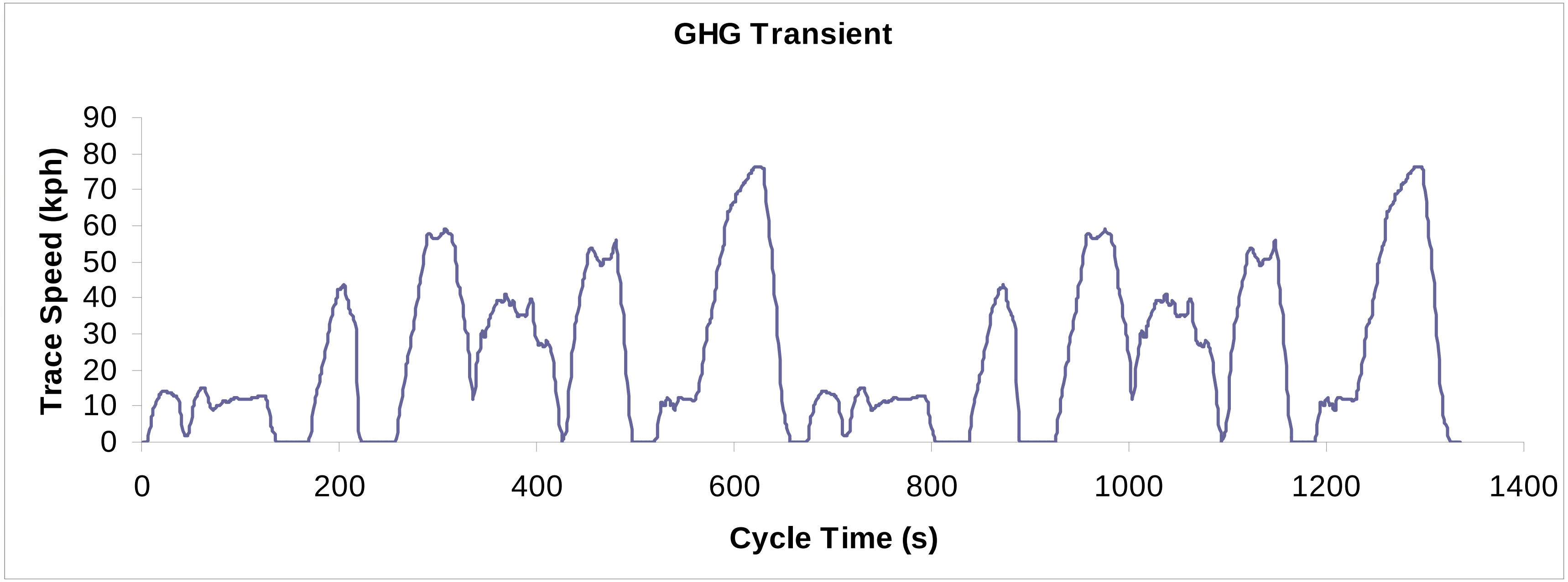

ss55ss65


CILCC

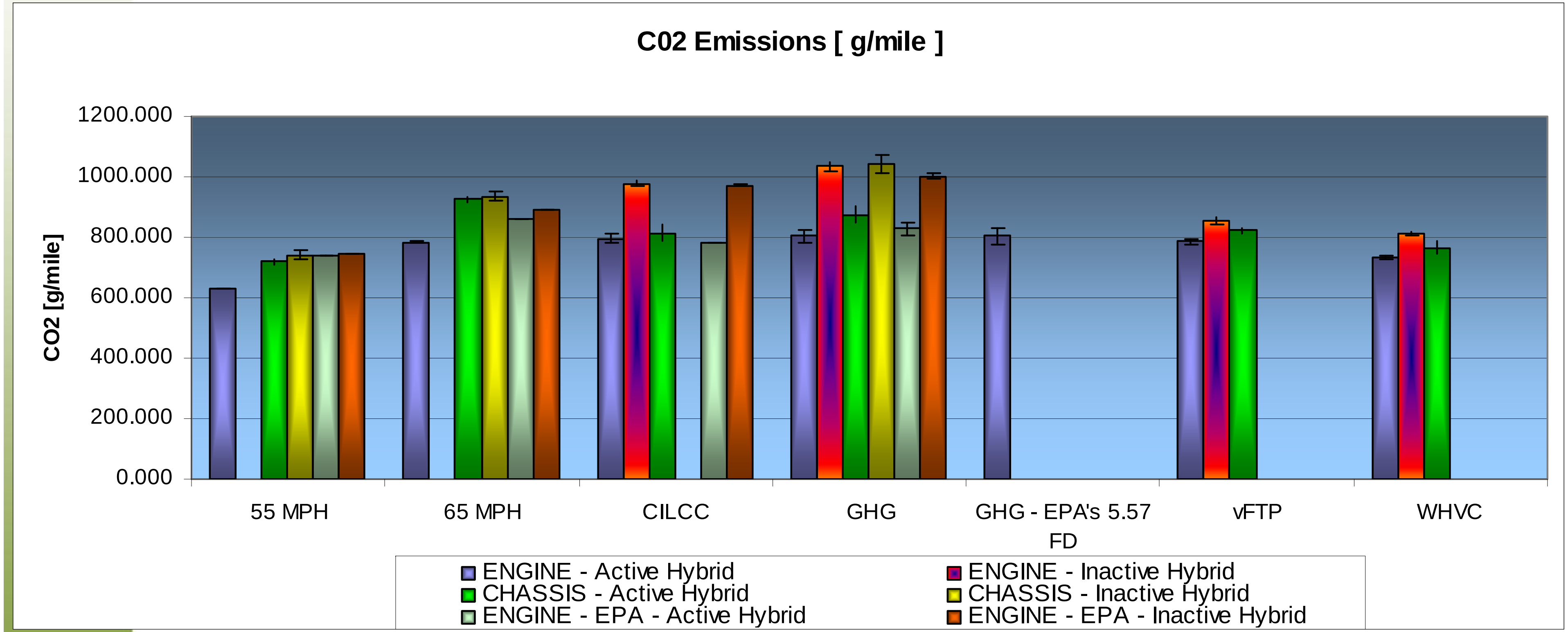

vFTP


WHVC

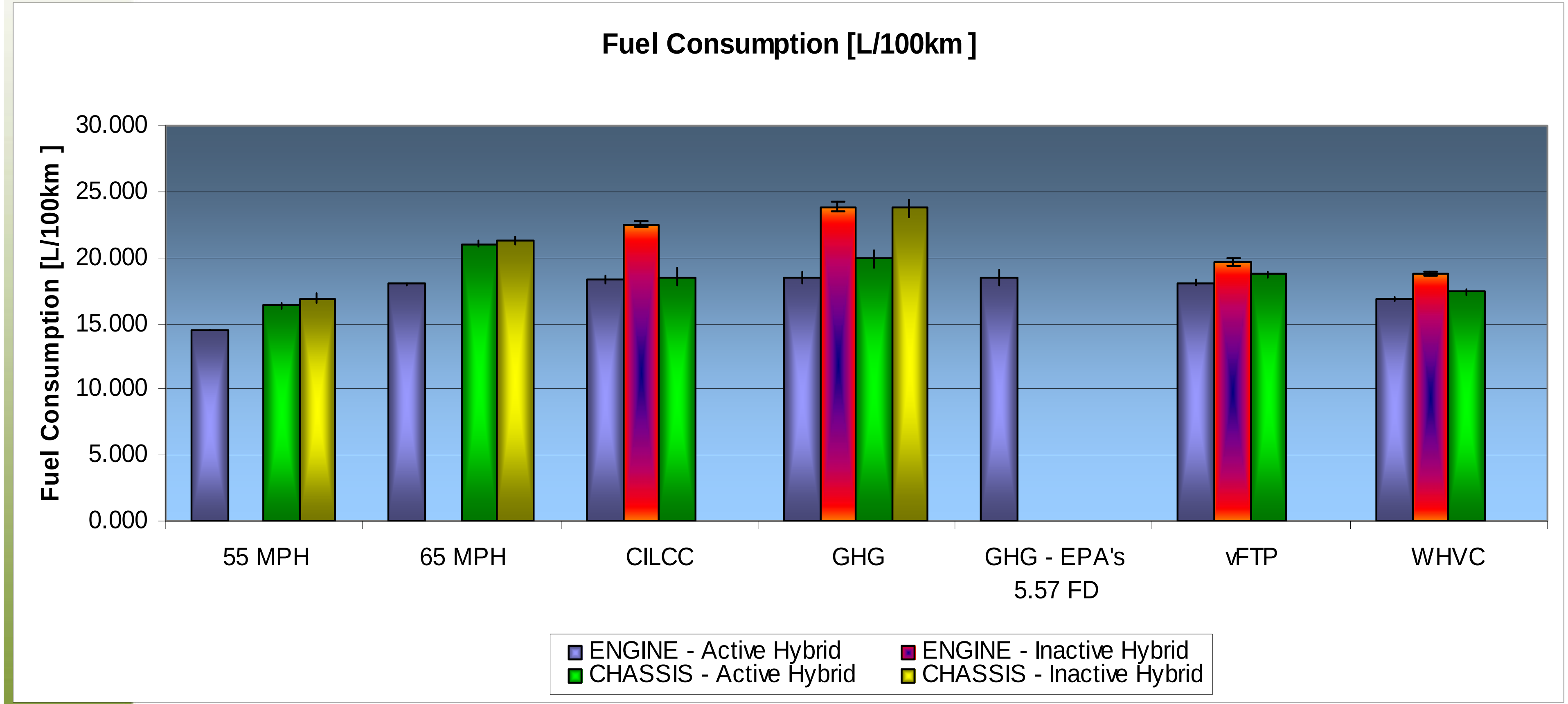
Cycles


GHG Transient
Trace Speed (kph)
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
Cycle Time (s)

Results

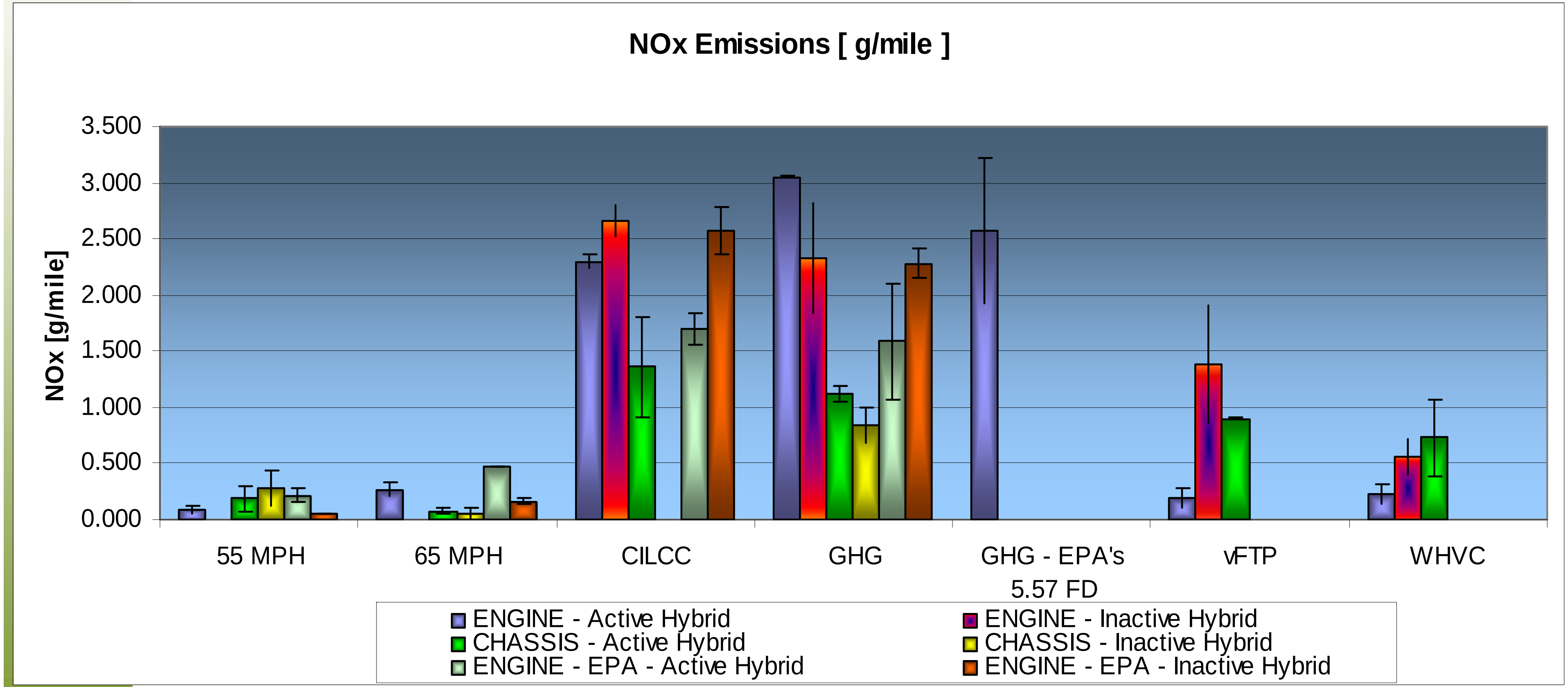

C02 Emissions [g/mile]
CO2 [g/mile]
1200.000
1000.000
800.000
600.000
400.000
200.000
0.000
55 MPH
65 MPH
CILCC
GHG
GHG - EPA's 5.57 FD
vFTP
WHVC
ENGINE - Active Hybrid
ENGINE - Inactive Hybrid
CHASSIS - Active Hybrid
CHASSIS - Inactive Hybrid
ENGINE - EPA - Active Hybrid
ENGINE - EPA - Inactive Hybrid

Results

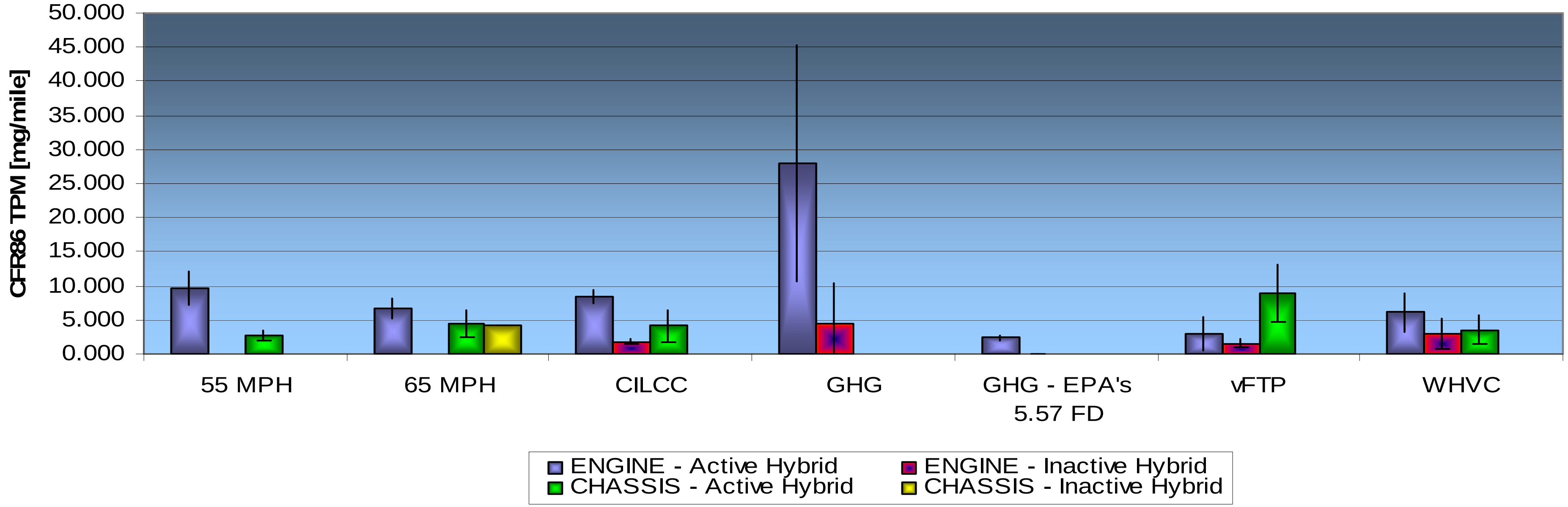


Fuel Consumption [L/100km]
Fuel Consumption [L/100km]
30.000
25.000
20.000
15.000
10.000
5.000
0.000
55 MPH
65 MPH
CILCC
GHG
GHG - EPA's 5.57 FD
vFTP
WHVC
ENGINE - Active Hybrid
ENGINE - Inactive Hybrid
CHASSIS - Active Hybrid
CHASSIS - Inactive Hybrid

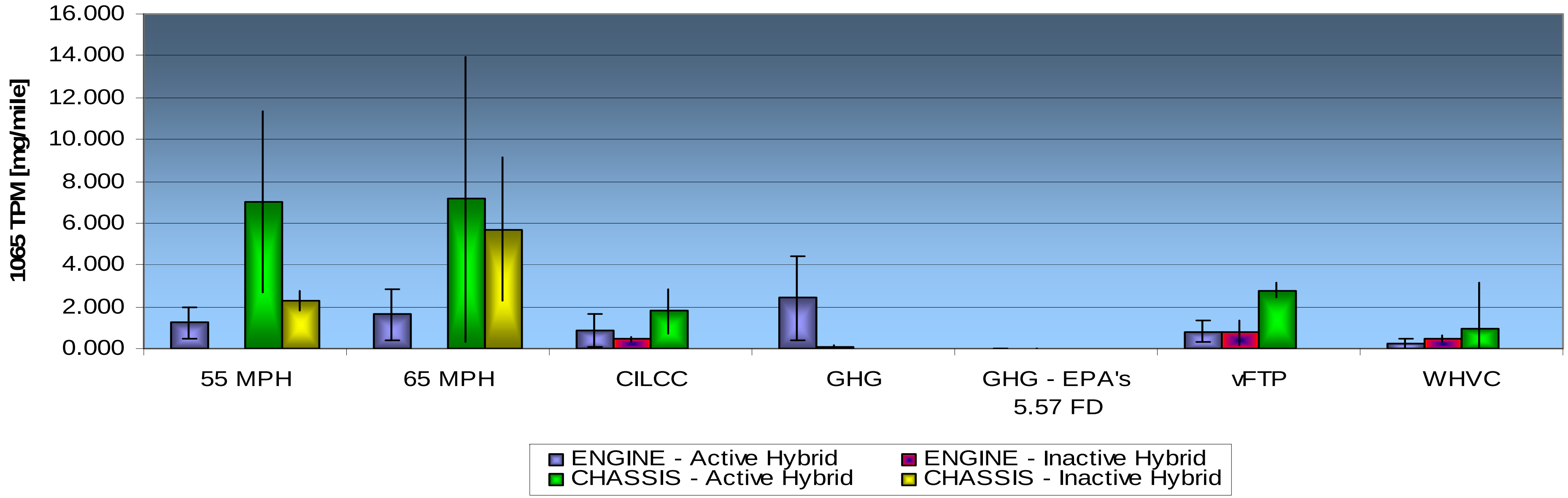
Results

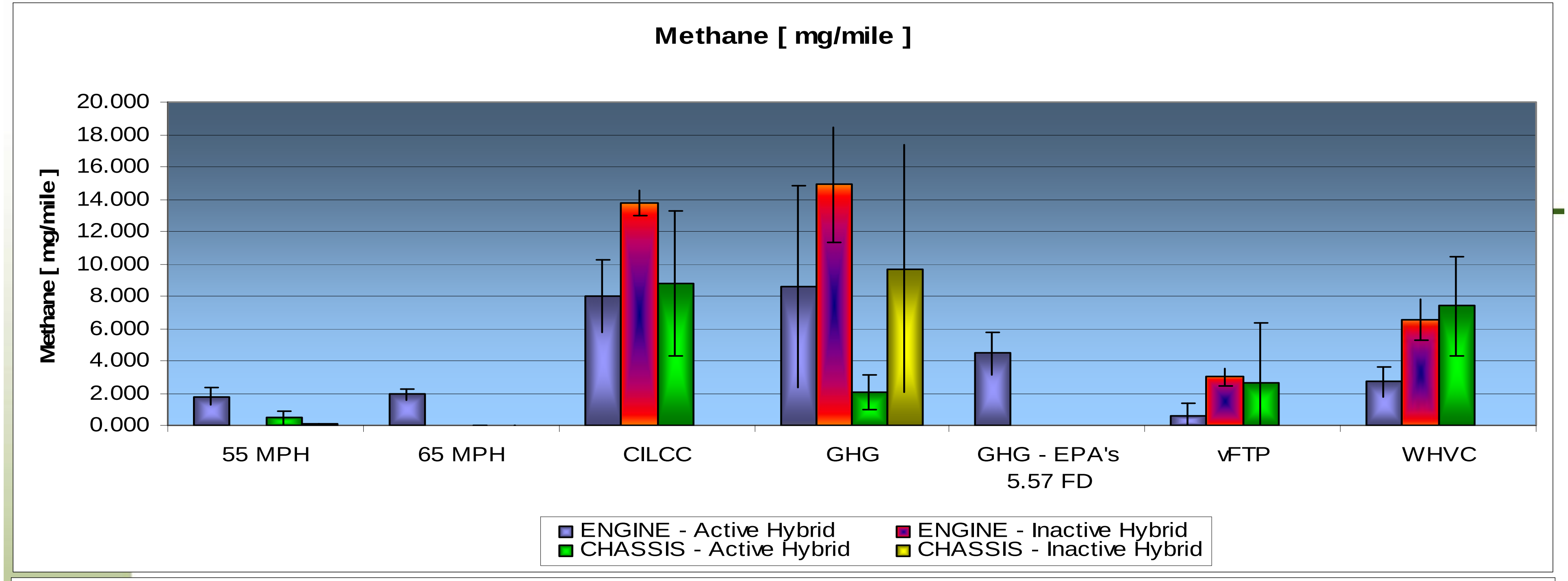

NOx Emissions [g/mile]
NOx [g/mile]
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
55 MPH
65 MPH
CILCC
GHG
GHG - EPA's 5.57 FD
vFTP
WHVC
ENGINE - Active Hybrid
ENGINE - Inactive Hybrid
CHASSIS - Active Hybrid
CHASSIS - Inactive Hybrid
ENGINE - EPA - Active Hybrid
ENGINE - EPA - Inactive Hybrid

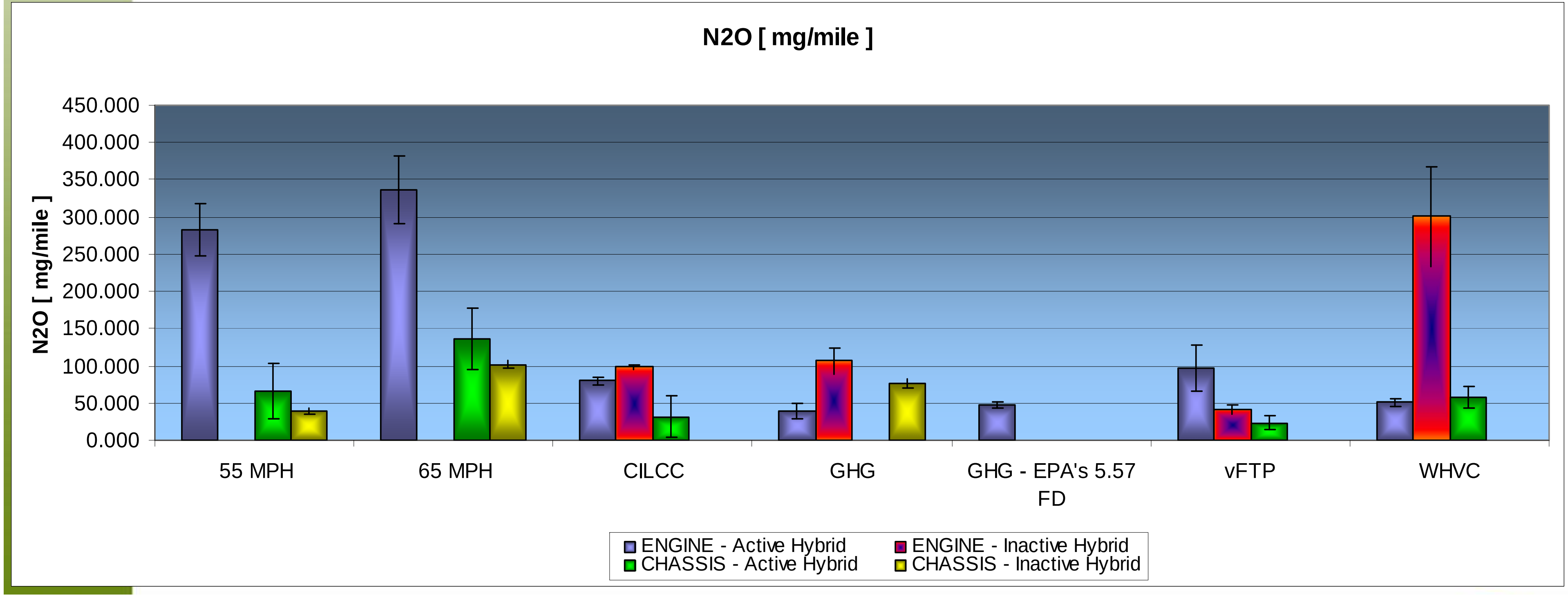
CFR86 TPM Emissions [mg/mile]

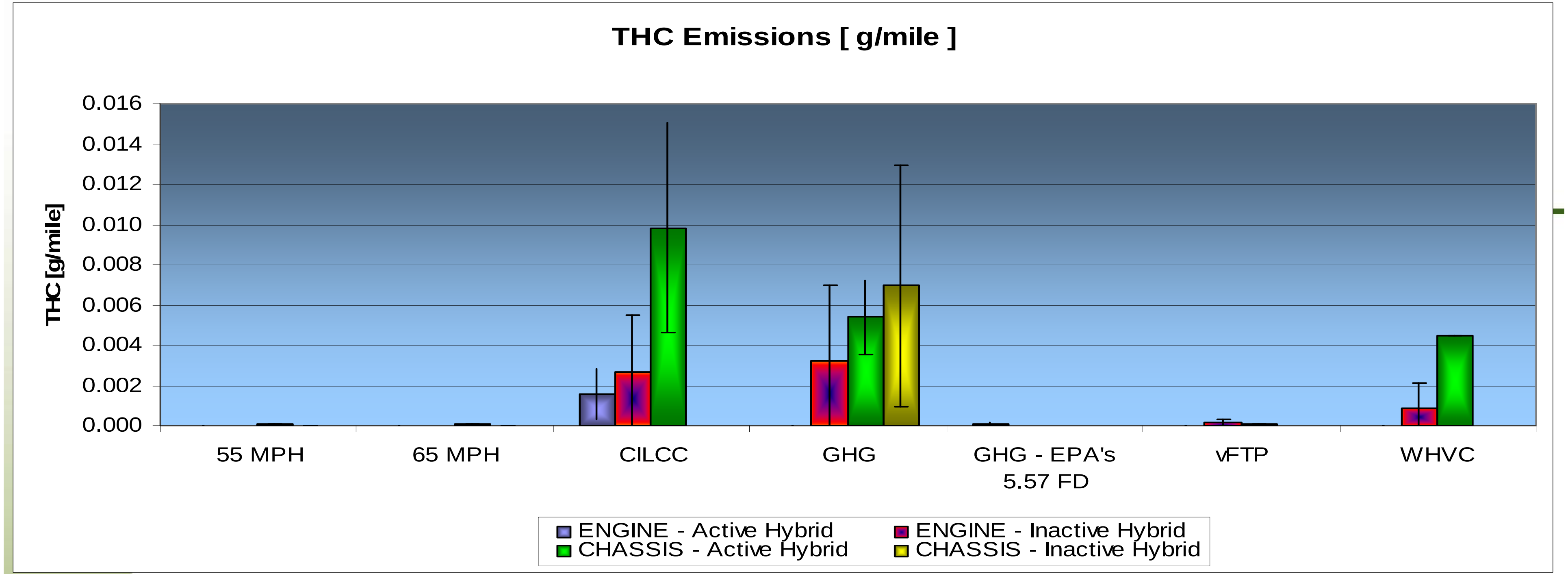


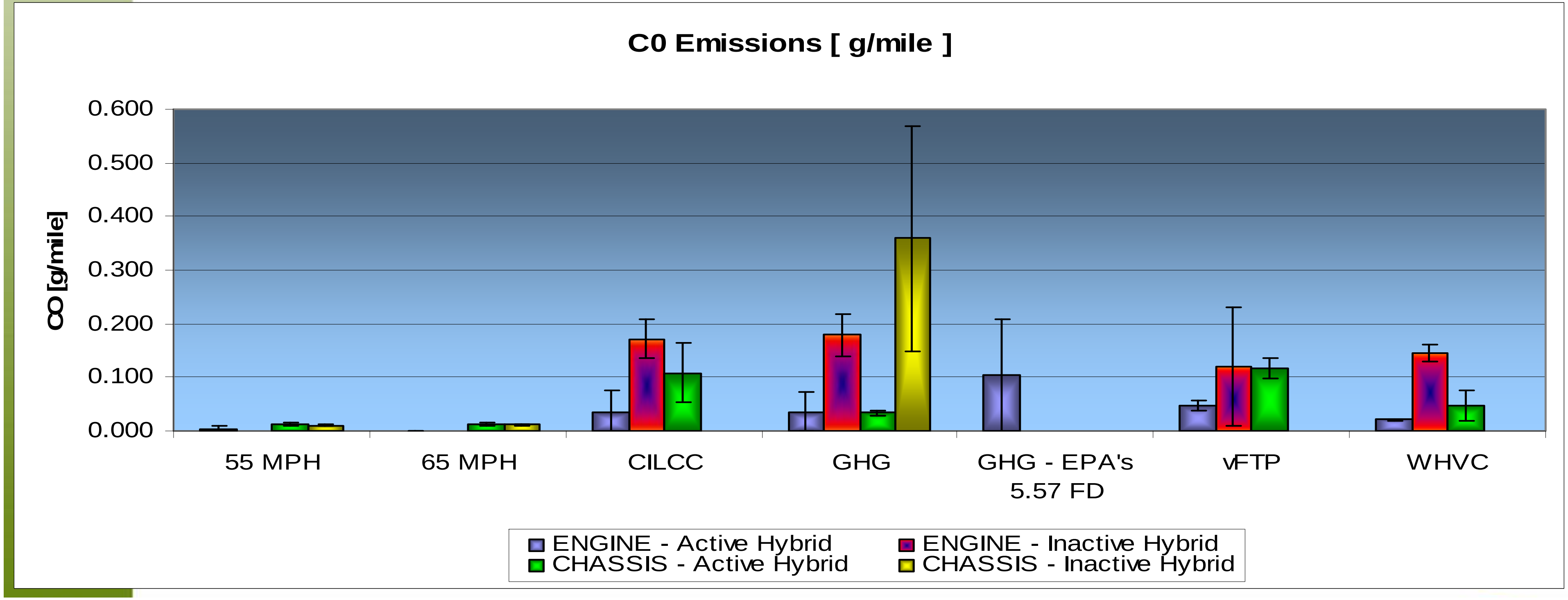
1065 TPM Emissions [mg/mile]



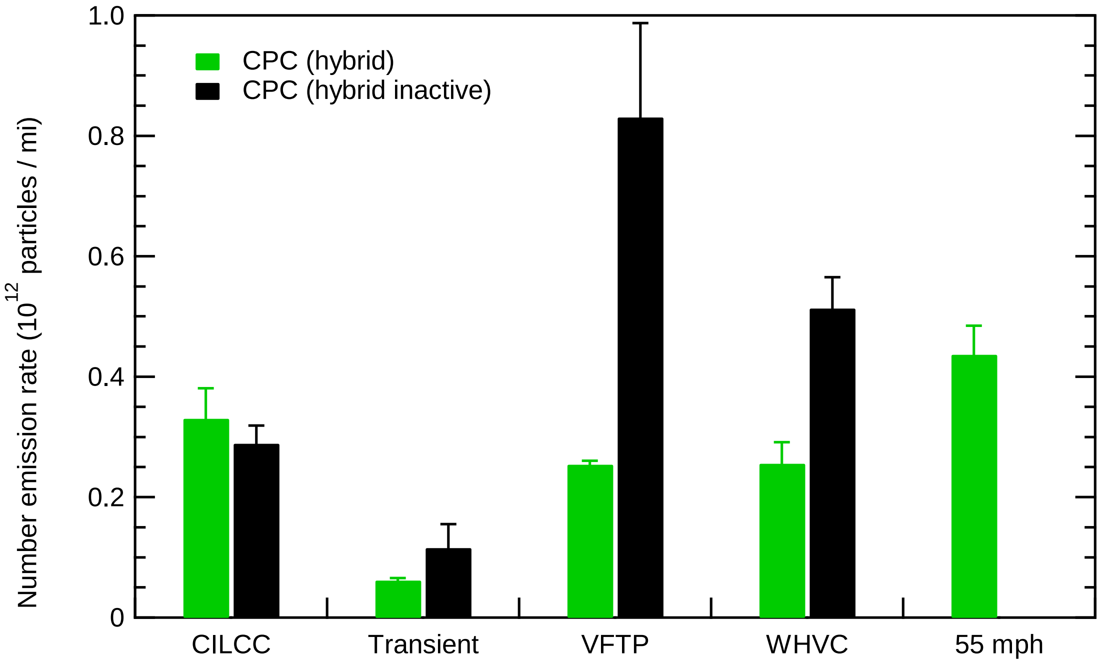

Methane [mg/mile]
Methane [mg/mile]
20.000
18.000
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
55 MPH
65 MPH
CILCC
GHG
GHG - EPA's 5.57 FD
vFTP
WHVC
ENGINE - Active Hybrid
ENGINE - Inactive Hybrid
CHASSIS - Active Hybrid
CHASSIS - Inactive Hybrid

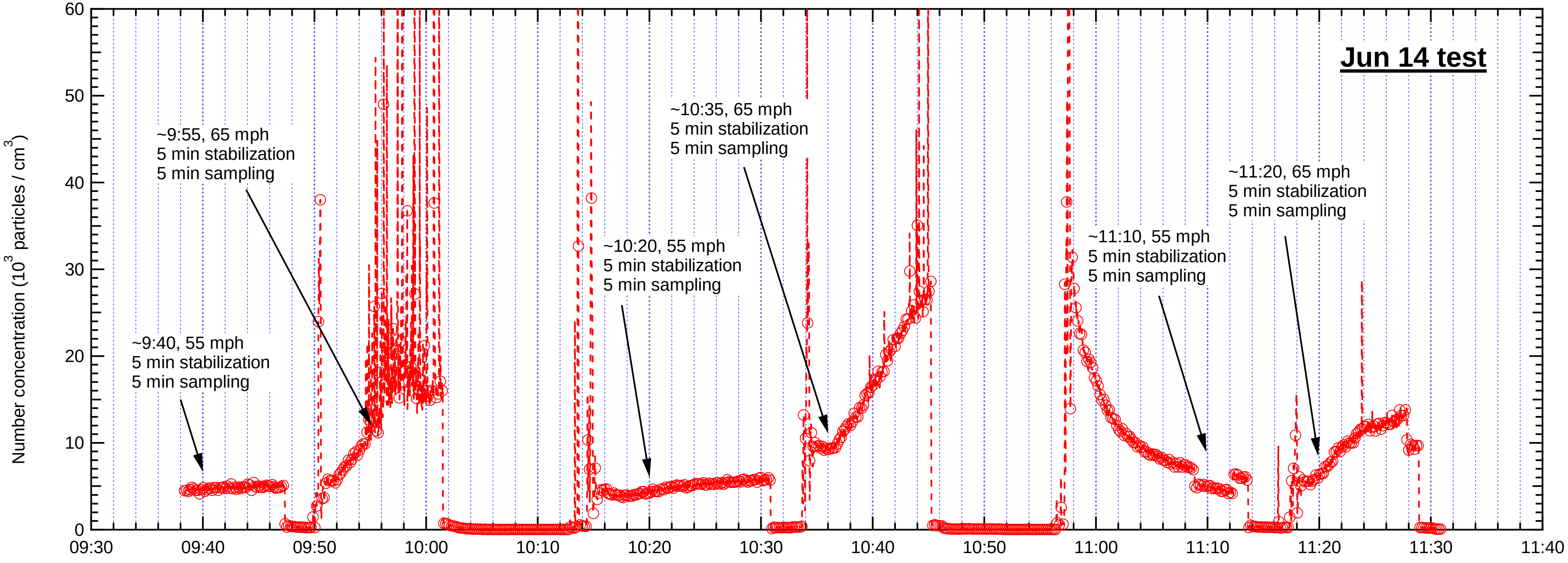

N2O [mg/mile]
N2O [mg/mile]
450.000
400.000
350.000
300.000
250.000
200.000
150.000
100.000
50.000
0.000
55 MPH
65 MPH
CILCC
GHG
GHG - EPA's 5.57 FD
vFTP
WHVC
ENGINE - Active Hybrid
ENGINE - Inactive Hybrid
CHASSIS - Active Hybrid
CHASSIS - Inactive Hybrid

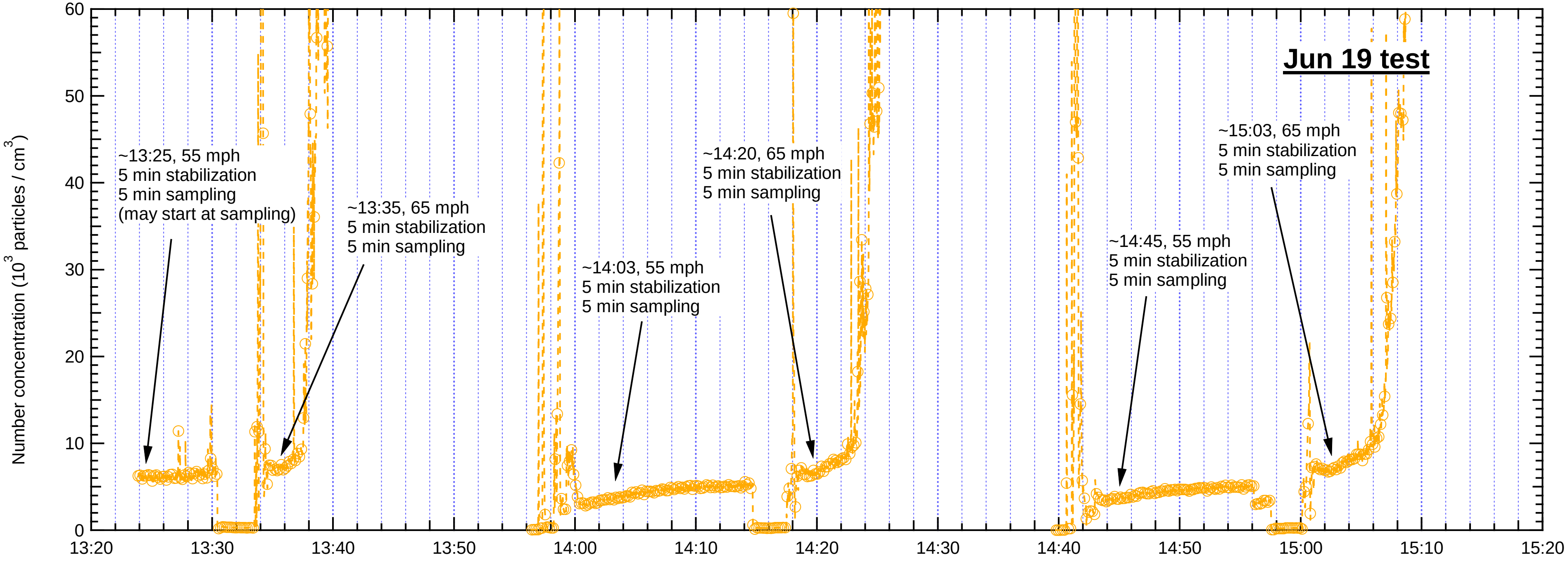

THC Emissions [g/mile]


C0 Emissions [g/mile]

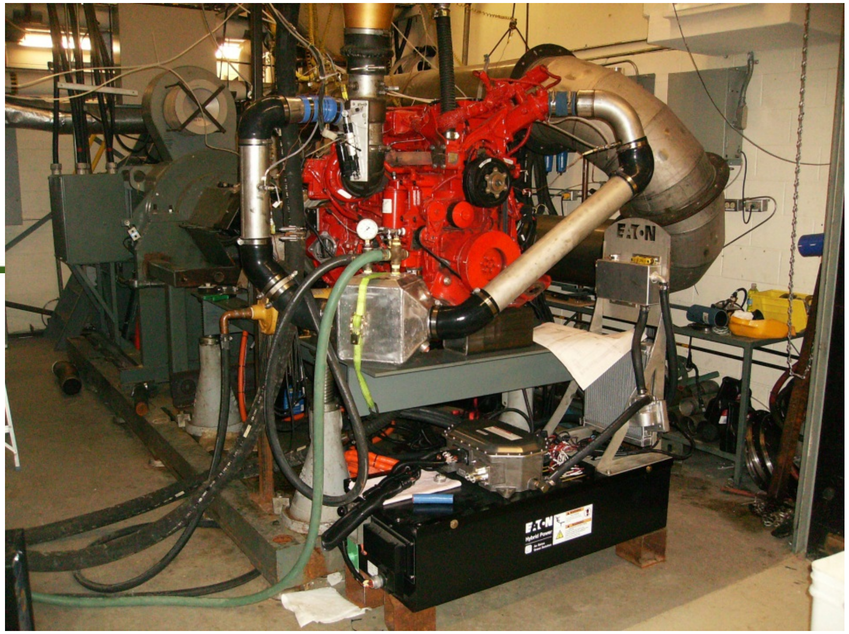
Particulates




Jun 14 test
Number concentration (10^3 particles / cm^3)
0
10
20
30
40
50
60
09:30
09:40
09:50
10:00
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20
11:30
11:40
~9:40, 55 mph
5 min stabilization
5 min sampling
~9:55, 65 mph
5 min stabilization
5 min sampling
~10:20, 55 mph
5 min stabilization
5 min sampling
~10:35, 65 mph
5 min stabilization
5 min sampling
~11:10, 55 mph
5 min stabilization
5 min sampling
~11:20, 65 mph
5 min stabilization
5 min sampling


Jun 19 test
Number concentration (10^3 particles / cm^3)
0
10
20
30
40
50
60
13:20
13:30
13:40
13:50
14:00
14:10
14:20
14:30
14:40
14:50
15:00
15:10
15:20
~13:25, 55 mph
5 min stabilization
5 min sampling
(may start at sampling)
~13:35, 65 mph
5 min stabilization
5 min sampling
~14:03, 55 mph
5 min stabilization
5 min sampling
~14:20, 65 mph
5 min stabilization
5 min sampling
~14:45, 55 mph
5 min stabilization
5 min sampling
~15:03, 65 mph
5 min stabilization
5 min sampling

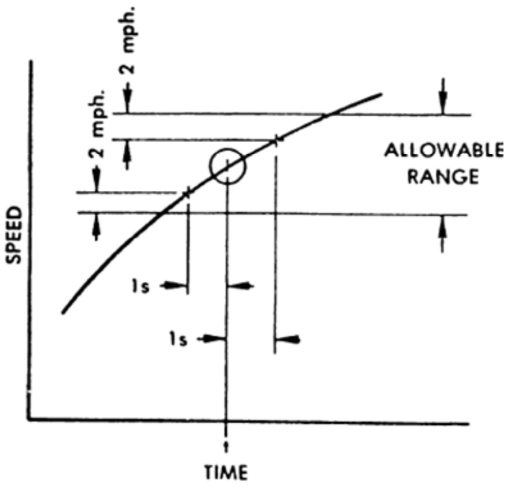
Challenges

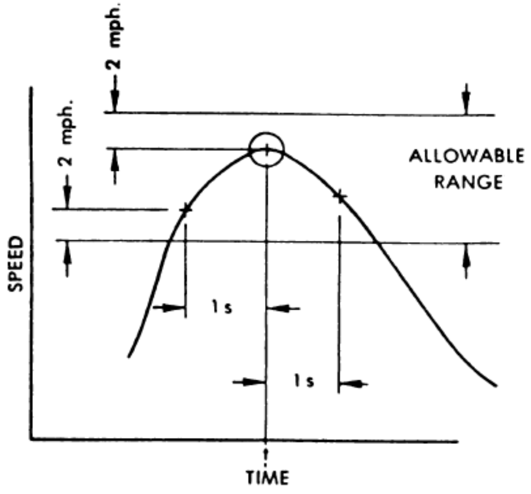


- Physical & system limitations
- Control system
- Complexity of the system:
  - Wiring
  - Additional Sensor (speed)
  - J1939 signals
  - Hybrid control Module required software update to bypass J1939 ABS signals & chassis signal in order to provide regenerative braking
- Simulating chassis testing on an engine dynamometer (simulating driver AND vehicle)
- Signal Simulation (parking brake, braking, etc)
- Required involvement of the manufacturer
- Active Regeneration
- Additional software requirements (J1939, Eaton's Service Ranger)

Suggestions

- Establishing a standard for active regeneration
- If this testing method is to become standard:
  - Manufacturer’s involvement will be required (high voltage, wiring information, J1939 signals, etc)
  - Due to the increased set-up time, a cost/benefit ratio will have to be evaluated vs chassis testing
  - Equipment upgrade may be needed due to higher speed testing due to the inclusion of the transmission
  - The acceptance criteria 2mph/speed regression is challenging to meet





Special Thanks

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  - Greg Nowel
- EPA
  - James Sanchez
- Cummins
  - Morgan Andrea
  - John O’Brien

Summary CO_2 Results

	Cycles	EPA vs EC Powertrain	EPA Powertrain vs Chassis	EC Powertrain vs Chassis
Hybrid Active	55 mph	14.7%	-2.6%	12.4%
	65 mph	9.3%	6.7%	15.4%
	EPA GHG	**2.8%**	6.5%	9.0%
	CILCC	**-1.8%**	3.9%	2.2%
Hybrid Inactive	55 mph	15.5%	-0.6%	15.0%
	65 mph	12.1%	4.9%	16.3%
	EPA GHG	**-3.4%**	4.6%	1.4%
	CILCC	**-0.6%**		

Improvements to Vehicle Model

- Added brake force.
  - Allows the vehicle model not to have additional states to handle vehicle braking
  - Allows for simulation of foundation brakes

$$v_{i,ref} = \left(FR_{meas,i-1} - \left(A + B \cdot v_{i,ref-1} + C \cdot v_{i,ref-1}{}^{2} \right) - F_{brake,i-1} \right) \frac{t_{i} - t_{i-1}}{M} + v_{i,ref-1}$$

- Putting models into Matlab and Simulink to easily:
  - add details to the vehicle model like component inertia and efficiency
  - add components to simulate vehicle accessories

Improvements to Driver Model

- Moving to a feed forward driver model that uses vehicle parameters to predict required wheel torque to follow cycle
- Now includes brake pedal position rather than just on/off
- Cycle speed look ahead

Conclusion

- CO_2 powertrain results for the transient cycles compare very well between labs
- The difference in CO_2 emissions for the steady-state cycles can be explained by the final drive ratio being different between the two labs
- Offset between powertrain and chassis dyno results are likely due to the lack of accessory loads, cooling system and wheel slip
- Differences in NO_x emissions could be due to difference in preconditioning and soak time. Since CO_2 was the main emission of interest, these parameters were not closely controlled