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CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Optimization and Demonstration of a Near-Zero, Heavy-Duty, Hybrid Electric Truck

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Optimization and Demonstration of a Near-Zero, Heavy-Duty, Hybrid-Electric Truck is the final report for the Optimization and Demonstration of a Near-Zero, Heavy-Duty, Hybrid-Electric Truck project (PIR-17-009) conducted by GTI Energy. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Heavy-duty trucks rely on diesel engines because they are powerful, durable, and more fuel efficient than gasoline engines. However, with more stringent emissions standards and the greater availability of low-cost, compressed natural gas (CNG), the market opened for trucks powered by engines fueled with CNG. Compressed natural gas combustion engines have been commercially demonstrated and deployed with their supporting fueling infrastructures. These CNG-fueled engines are available today with NOx emissions certifications 90 percent lower than the mandatory diesel engine standard. When fueled with renewable natural gas, these vehicles can also provide substantial greenhouse gas (GHG) emission reductions.

This project designed, developed, and demonstrated a prototype control system integrated into a CNG hybrid electric Class 8 truck, optimized to achieve both near-zero NOx emissions and significantly reduced GHG emissions. The truck used a 239 kW 8.9-liter near-zero CNG engine, a 222 kW electric motor, 31 kWh Lithium-ion battery pack, and electric accessories to provide equivalent performance to a larger 15-liter diesel engine while adding a 20-mile zero-emission range.

By comparing the emissions test results with similar engines' emissions on other projects, the research team found that a hybridized near-zero power train can offer fuel economy benefits of 40 percent and NOx emissions 22 times lower than the current 0.02 g/bhp-hr standard. Moreover, the team found that 90 percent of NOx emissions can be attributed to cold start operations. The CNG hybrid electric vehicle technology can provide range, reliability, and refueling convenience for certain fleet operations. Further research, optimization of the system, and support from the component manufacturers could yield additional improvements.

Keywords: Hybrid, Natural Gas, Optimization, Near Zero NOx

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Background

The continued development and demonstration of advanced transportation technologies (zero-emission and near zero-emission) are necessary to meet California's long-term greenhouse gas (GHG) emission reduction goals, protect public health, and reach attainment with increasingly stringent federal air quality standards.

Project Purpose

This project addresses California's transportation sector as a major contributor of harmful air emissions, particularly NOx and particulate matter, in alignment with the state's clean transportation policies. The project explores the use of near zero-emission CNG engines and hybrid electric vehicle technology to simultaneously reduce both criteria and GHG emissions. By integrating CNG vehicles with battery power, the project further reduces NOx and CO_2 emissions in urban settings and improves competitiveness with incumbent heavy-duty diesel vehicles.

Project Approach

The technology deployed and demonstrated in this project was US Hybrid's advanced parallel hybrid drive system with advanced system controls. The vehicle control system was optimized and applied to US Hybrid's existing plug-in hybrid Class 8 truck platform with an electric drive system, a 31 kWh Lithium-ion battery, 222 kW electric drive motor. It was retrofitted with a Cummins L9N engine (a state-of-the-art 8.9-liter CNG engine, certified at 0.02 g/bhp-hr NOx). This configuration allowed the electric motor to supplement the engine power, providing superior acceleration and enabling energy recovery during regenerative braking. The hybrid control system optimization logic was based on prior hybrid electric vehicle work developed over numerous iterations with bench testing and low speed operation. The technology testing and demonstration were finalized on a chassis dynamometer at the University of California, Riverside (UCR), where exhaust emissions were both measured and analyzed.

Project Results

The key findings and outcomes of this project were:

- 500+ HP performance in hybrid mode (equivalent to 15-liter diesel engine).
- Emissions analysis applied to four in-use test routes (grocery store route, port-drayage route, goods movement with elevation change route, and highway goods movement route) developed by UCR and were simulated to be at 0.002 g/bhp-hr, which is 90 percent below future standards for each route analyzed, including one cold start.
- Fuel economy and CO_2 emissions improvement of 40 percent over conventional CNG engine performance.

Urban dynamometer driving schedule (UDDS) NOx emissions averaged 0.006 g/bhp-hr for the hot-start tests and 0.028 g/bhp-hr for the cold-start tests. When the results from this study were applied to simulations based on real world driving, the UDDS cold start, warm start, and hot running emissions averaged about 2.3 mg/bhp-hr (0.002 g/bhp-hr). This very low NOx emission rate meets the expectations of a hybrid CNG engine optimized for minimizing rapid torque loads, as found during previous studies of conventional CNG trucks. Future hybrid optimizations should include management of the cold-start and hot-start strategies. These optimizations may further reduce NOx emissions by another order of magnitude (0.2 mg/bhp-hr). In addition, a solution for hot- and cold-start emissions would also allow engine shutdowns, reducing CO_2 emissions estimated at an additional 14 percent savings.

Technology/Knowledge Transfer

The team disseminated findings in the following forums.

- Natural Gas Vehicle Technology Forum led by the National Renewable Energy Laboratory in partnership with the United States Department of Energy and the California Energy Commission (CEC)
- Utilization Technology Development Technology Project Committee, which is a not-for-profit scientific research organization comprised of 20 gas distribution company members who direct a program of near-term applied research to develop, test, and demonstrate safe, energy-efficient, environmentally friendly, and cost-effective end-use technologies. These technologies could benefit more than 37 million gas customers in North America, in collaboration with many partners.
- Natural Gas Vehicle America Annual Conference. The Natural Gas Vehicle conference is the only dedicated natural gas in transportation alternative fuels conference focused on the North American market. On road, off road and everything in between will be featured, from traditional freight, refuse, and transit applications to growing marine, rail, and construction use.
- Coordinating Research Council (CRC), Inc., Real World Emissions Workshop

Future knowledge transfer opportunities including findings at Clean Cities Coalitions forums and events related to alternative fuels.

Benefits to California

The California Energy Commission's Gas Research and Development Program has advanced environmental initiatives through past projects focused on developing low NOx CNG engines certified to the stringent 0.02 g/bhp-hr standard. Building upon these achievements, the project explored integration of hybrid-electric power trains to further reduce in-use emissions, bettering the 0.02 g/bhp-hr threshold. This innovation not only holds the potential to improve public health by contributing to reduced ozone concentrations, but also achieves impressive fuel economy gains of over 40 percent, resulting in a substantial 40 percent reduction in CO_2 emissions.

CHAPTER 1: Introduction

Mobile sources account for over 80 percent of NOx emissions in the San Joaquin Valley and South Coast air basins.[1,2] Heavy-duty diesel trucks, off-road vehicles, marine vessels, and locomotives are among the largest contributors of NOx emissions. Extensive deployment of zero- and near-zero emission technologies is needed to meet current and future mandated clean-air standards. With the commercialization of heavy-duty natural gas engines certified at the optional 0.02 g/bhp-hr NOx on-road emission standard, and the current availability of renewable natural gas, natural gas vehicles represent a near-term solution to reduce greenhouse gas emissions (GHG), improve local air quality, and advance other state energy goals. Continued research and development are needed to address barriers to wider adoption of near-zero-emission heavy-duty CNG vehicles.

While hybrid transit buses and heavy-duty trucks with diesel engines were demonstrated in the 1990s, data on hybrid electric systems with CNG engines were lacking. It was expected that CNG hybrid electric vehicles (HEVs), with today's hybrid technology, would require less fuel storage to achieve an acceptable driving range per fill-up. This combination helped resolve two of the market barriers to CNG vehicles: reduced range and loss of load space. With battery power to minimize idle and low-load engine operation, NOx emissions can also be significantly reduced in stop-and-go urban service.

The continued development and demonstration of advanced technologies (zero-emission and near zero-emission) are necessary to meet California's long-term GHG emission reduction goals, protect public health, and reach attainment with increasingly more stringent federal air-quality standards.

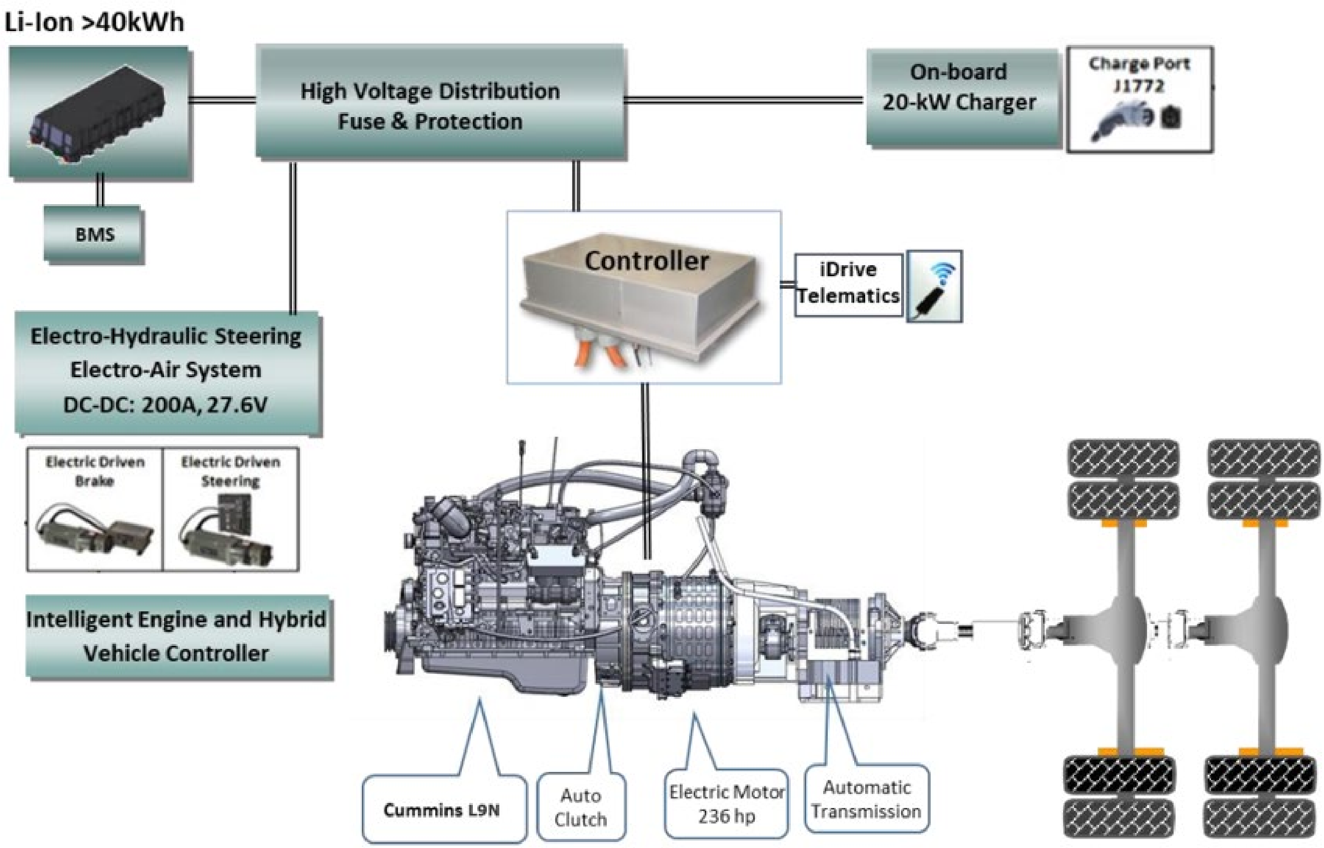
1 San Joaquin Valley Unified Air Pollution Control District. Guidance for Assessing and Mitigating Air Quality Impacts. March 2015. http://www.valleyair.org/transportation/GAMAQI.pdf

2 California Air Resources Board. Revised Draft 2020 Mobile Source Strategy. https://ww2.arb.ca.gov/sites/default/files/2021-04/Revised_Draft_2020_Mobile_Source_Strategy.pdf

CHAPTER 2: Project Approach

With growing demand for new vehicles with lower emissions and fuel consumption, a promising approach is by electrification of traditional power trains, only partially realized by hybrid electric vehicles (HEV). To meet these requirements, this project used a P2 hybrid configuration that utilizes an engine, motor, battery, and transmission to deliver power to the driven wheels, as seen in Figure 1. The P2 module combines a 48 V electric traction motor, engine disconnect clutch, launch device, and dual-mass flywheel into a compact package, nested inside the motor. This configuration uses a separation clutch (P2) to split the power between the motor and the engine.

Figure 1: System Architecture



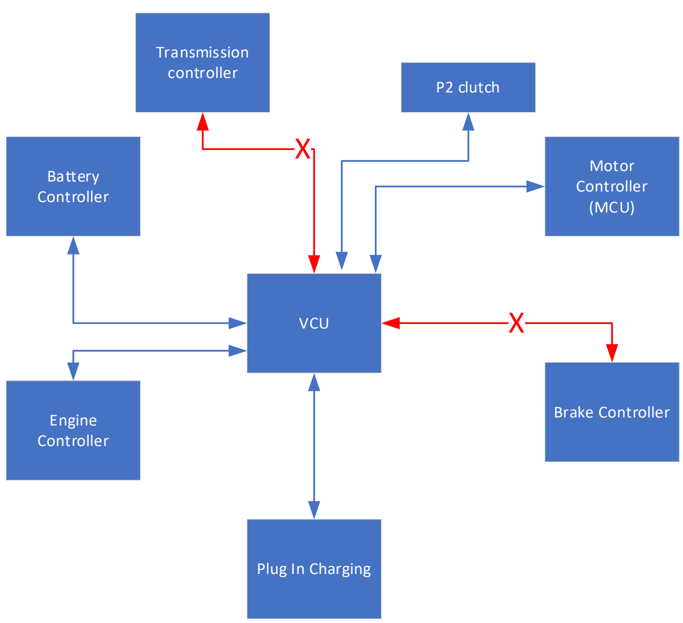
Source: US Hybrid

The automotive and energy consulting company FEV developed a supervisory controller for a vehicle propulsion and energy storage system. The control technique controls the combustion engine and high-voltage (HV) components in parallel to meet the vehicle's power requirements. The vehicle control unit (VCU) of the truck receives driver demand signals from the accelerator and brake pedals. This determines the amount of torque demanded by the driver, which is bounded by the limits of the system (such as motor capacity and transmission capacity). The system limitations are communicated through the engine, motor, battery, transmission, and controller. Based on the calculated torque demand, the supervisory control determines the amount of torque split between the engine and motor. The split between the motor and the engine is achieved through an optimization technique developed by FEV.

Based on the power command and the charge and discharge power of the battery, there is a shift between the electric drive (E-drive) and hybrid drive modes of operation. There are different operating modes within the E-drive and the hybrid drive modes, which are actuated based on certain conditions. These modes determine how the propulsion system works to meet power requirements effectively while decreasing harmful gas emissions and increasing overall fuel economy. This commanded power distribution between the motor and the engine is also split optimally. Motor control and engine control have their own supervisory controls that manage the power based on the real time optimal state of charge (SOC_{opt}) curve generated with various optimization factors, which the system then tries to follow. The power split optimization control algorithm additionally makes use of a brake specific fuel consumption (BSFC) map to calculate the torque requested from the engine while the rest of the torque is requested from the motor within the charge/discharge power limits of both the motor and the HV battery. The motor also compensates for any power command that is not satisfied by the engine because the engine torque is prioritized and dictated by an optimal BSFC map. The engine start-stop strategy and the cold-start strategy were developed for this engine to further reduce NO_x emissions.

Figure 2 shows the VCU software, which consists of two main layers: basic software (BSW) and application software (AppSW). The VCU control strategy within the application software is designed to satisfy driver power demand while maintaining safe and efficient operation of the vehicle.

Figure 2: VCU Interfaces



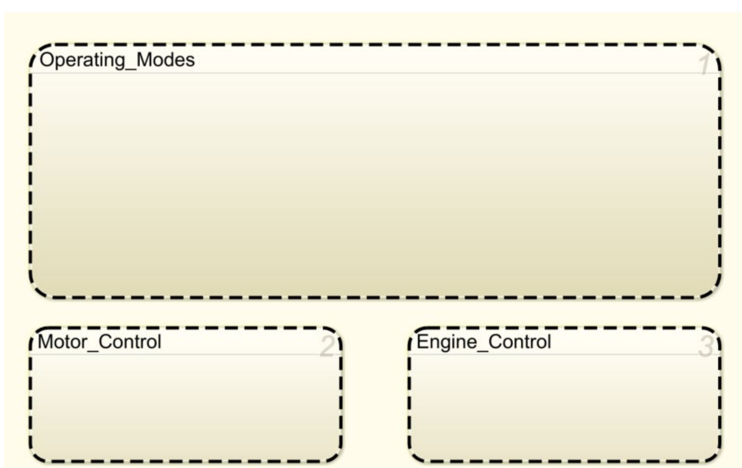
Source: FEV

The system evaluation and demonstration process involved calibration optimization on a chassis dynamometer and emissions testing. For the calibration optimization, portable emissions measurement systems (PEMS) were utilized as screening tools to understand benefit scenarios with each calibration step. Final emissions testing was performed with the University of California, Riverside's, (UCR) mobile emission laboratory (MEL) and PEMS for final quantification of emission results. During previous studies with low NOx engines, it was found that the NOx measurement method required improvements.[1,2] These improvements included various raw and dilute gaseous NOx methods to help quantify NOx emissions at around 0.006 g/bhp-hr (70 percent lower than the 0.02 g/bhp-hr NOx certification level). NOx emissions at 0.006 g/bhp-hr are approaching the detection limit of dilute constant volume sampling (CVS) systems. During previous studies, UCR upgraded its laboratory with various measures to quantify NOx emissions at 0.006 g/bhp-hr. Those systems were replaced by a new low NOx raw and dilute bench manufactured by Horiba. The MEL upgrade (completed in 2020) included a new Horiba state-of-the-art measurement bench for both raw and dilute measurements, with a special emphasis on low-NOx measurements at and below 0.02 g/bhp-hr. The new design was targeted at measuring NOx emissions below 0.002 g/bhp-hr (90 percent below the 0.02 standard). The final emissions results provided in this report are based on these new low NOx measurements, made with the upgraded MEL.

Control System Overview

First, torque demanded at the wheel is calculated based on the pedal request from the driver. Pedal maps were developed using the calibrated combined torque maps from the engine and motor; the raw demanded torque is then calculated as a function of the accelerator pedal percentage. The raw demanded torque is then limited by maximum capabilities of the engine, transmission, and motor. Once the torque/speed calculation is done, the torque request is sent to the supervisory control. The supervisory control consists of three states (Figure 3) that run in parallel: operating mode, motor control, and engine control. The motor control and engine control states describe the actions needed to meet the power command during driving in the operating mode state. The action taken depends on the operating mode actuation.

Figure 3: Supervisory Control States



Source: FEV

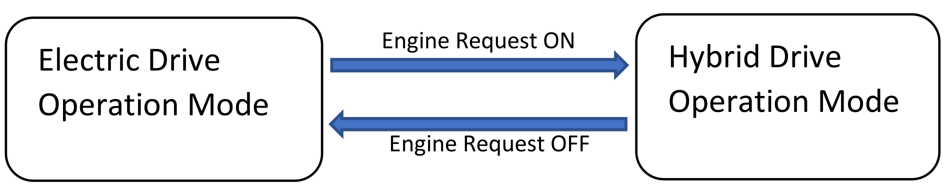
Operating Modes

In general, the supervisory control of the operating modes of the whole propulsion architecture can be broken down into several categories.

- Driving
    - Electric Drive (OpMode=1)
    - Hybrid Drive
        - Engine Start (OpMode=2)
        - Engine Idle (OpMode=3)
        - Engine Sync (OpMode=4)
        - Hybrid Drive
            - P2 Closed (OpMode=5)
            - Torque Converter Closed (OpMode=6)
        - Engine Off (OpMode=8)
- Stationary Charging
    - Off (OpMode=9)

The operating mode state determines which mode the vehicle requires for operation: electric drive mode or hybrid drive mode, as shown in Figure 4.

Figure 4: Operating Mode State



Source: FEV

In the operating mode there is a driving super state. In the driving super state, there are two substates: electric drive operation mode and hybrid drive operation. The vehicle starts in the electric drive mode and stays in E-drive until a request to shift into hybrid mode is received based on the implemented controls logic, which is part of the optimization strategy to determine whether the engine needs to be turned on. The next section explains the various conditions and factors that can prompt a shift to hybrid mode.

E-Drive to Hybrid Drive Transition

In certain conditions, the engine must be turned on before the vehicle will transition to hybrid drive operation mode. In the control logic there exists two conditions which, when one of them is satisfied, signify the need to transition to the hybrid drive mode. The transition depends on two separate conditions: EngOnReq and ImmediateEngOnReq.

EngOnReq

For the EngOnReq to be true, one of the following two conditions needs to be true. First, if the difference between the power command and charge/discharge power becomes greater than a threshold value (battery power cannot meet the power command from the driver), or second, the battery power exceeds the discharge limit, (if more power is extracted from the battery than the rate of discharge allows), then the P2 clutch needs to be closed to allow driving in hybrid mode and transmit engine power to the driven wheels. In other words, EngOnReq is true if one of the following two conditions is true:

$(Power\ Command\ -\ Charge\ Power)\ >\ Threshold\ Value$ -------- (I)

$Battery\ Power\ >\ Discharge\ Limit$ --- (II)

In future implementations, this signal will be modified to reflect that the engine needs to be turned on to meet the deficient power from the motor. The EngOnReq and ImmediateEngOnReq signals are a function of the following list of variables:

- Power Command – PwrCmd
- Charge Power – ChrgPwr
- Battery Power – BattPwr
- Battery Power Discharge Limit – BattPwrDischrgLmt
- Battery Power Charge Limit – BattPwrChrgLmt
- Vehicle Speed – VehSpd
- Battery High Voltage Fault Check- bHVFault
- Vehicle Transmission Gear Engaged – vtm_rGearEngAct
- Vehicle Motor Control Maximum Torque Limit – vmc_tqMotMax
- Vehicle Motor Control Minimum Torque Limit – vmc_tqMotMin
- Battery State of Charge – vbm_rBattSoc
- Hybrid Control Unit Wheel Torque Limit – hcu_tqWhlLimReq
- Vehicle Speed and Motor Speed- vvm_vVehAct,MotSpd
- Vehicle Engine Control – vec_bEngRun

The above variables are inputs to the main supervisory control strategy and the first two variables: PwrCmd and ChrgPwr are calculated as follows:

$$PwrCmd\ =\ TrqCmd\ \times MotSpd$$

$$SOCopt\ = \max\left(\left(\left(\frac{SOCTrgt}{100}\right) - \ 0.5\ \times\ VehMass \times VehSpd \times VehSpd \times \frac{CSChrgFctr}{BattEnrgy}\right), \frac{SOCmin}{100}\right)$$

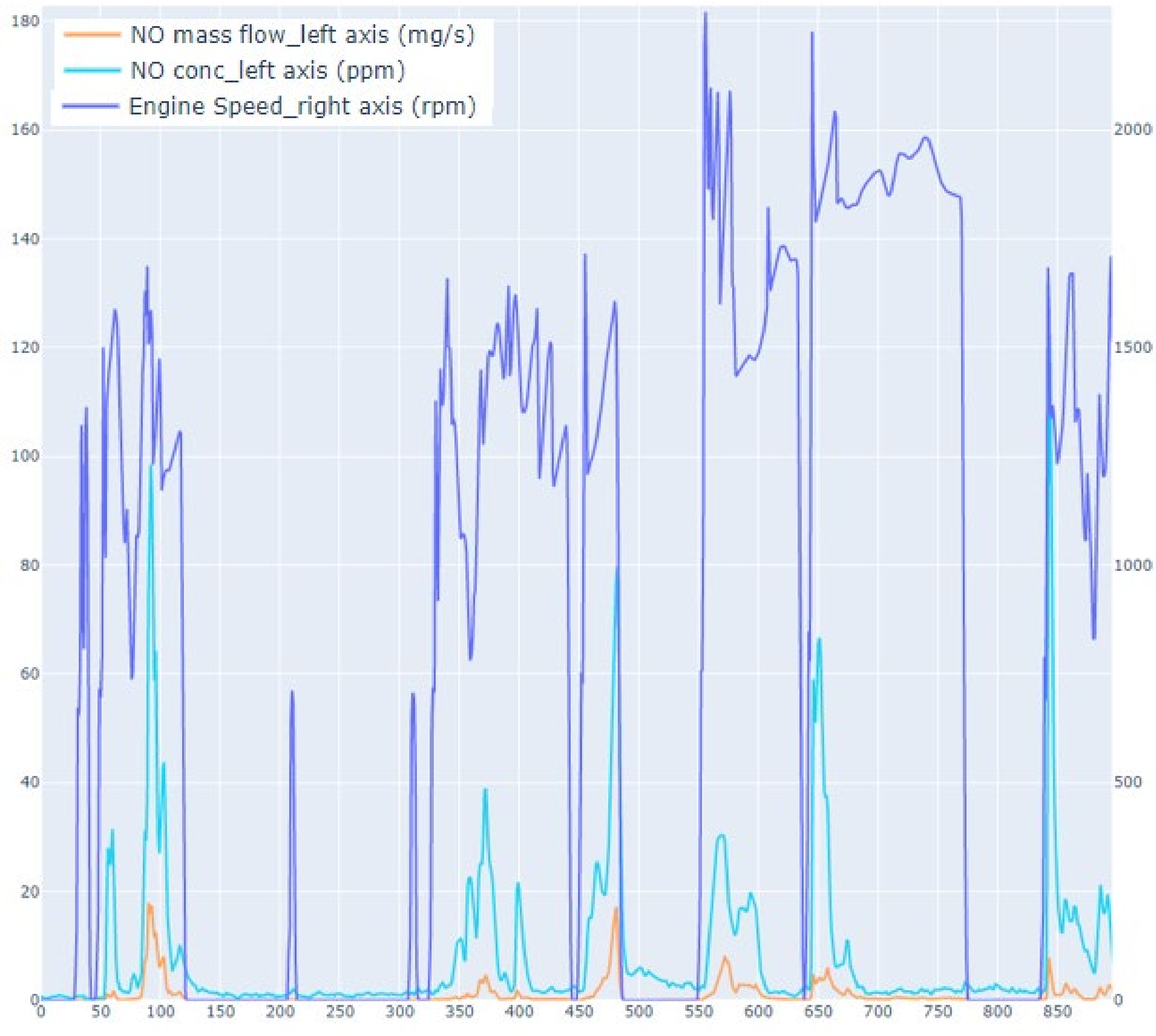
$$ChrgPwr\ =\ -SOCChrgFctr\ \times\left(SOCopt\ - \frac{SOC}{100}\right) \times (VehSpd \geq 5)$$

If the charge power is negative, it signifies the need for charging the batteries because in that case the SOC for batteries becomes less than the optimal SOC. To charge the batteries the engine needs to produce more power and provide negative torque to the motor to generate current, which in turn charges the batteries. In such a scenario, the engine needs to produce higher power to drive the wheels to compensate for the discharge of the batteries.

ImmediateEngOnReq

ImmediateEngOnReq is intended to be true when EngOnReq, which is based on the power demand, is calculated to be false, and the current state of the engine is "off." In the current implementation of controls, once the engine is on it is always kept on during the entire vehicle operation cycle to reduce the overall NOx emissions impacted by the engine start-stop approach. It was observed during the emission testing that every time the engine is turned off and then turned on to meet the power demand, there was a high peak of NOx, as shown in Figure 5.

Figure 5: NOx Emissions During Engine Start-Stop

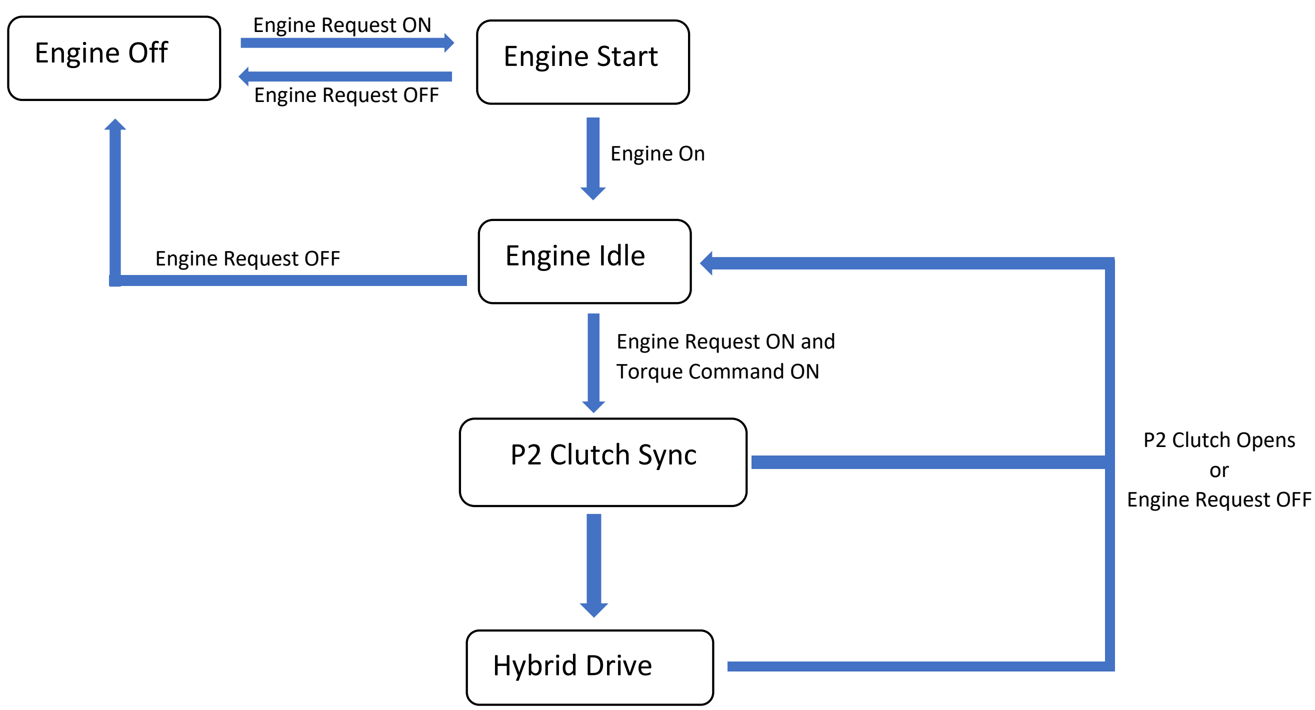


Engine OEM support is needed to understand this behavior and to find a way to control the NOx in the start phase. Once a control strategy for NOx emissions during startup is established, it could be implemented in the model and the start-stop logic may be activated with a simple calibration change in future development which, depending on the operating conditions, may offer up to a 10 percent fuel economy improvement.

Hybrid Drive Operation

In hybrid drive operation, there are five states: engine start, engine idle, engine off, engine sync, and hybrid drive. The engine starts in the engine idle state. But to go into the hybrid mode, the P2 clutch (Clutch 1) needs to be closed. To allow the P2 clutch closing, the engine speed needs to be in sync with the motor speed to prevent slip during clutch closing. Once the conditions to transition to hybrid drive mode state are true the initial state within that state is engine start, as shown in Figure 6. Once the engine is on and reaches a certain RPM threshold, a transition to engine idle state happens. If the EngOnReq status is "true" and the TrqCmd is greater than 0 and Clutch 1 is not closed (refer to Figure 7) for Clutch 1 location in the propulsion system), then the system will transit into the sync state (PHEV_SYNC), with OpMode value equal to four. In this state it is desirable to close the P2 clutch (Clutch 1), shown in Figure 7, by commanding a speed match between the engine and the motor.

Figure 6: Hybrid Drive Operation Modes

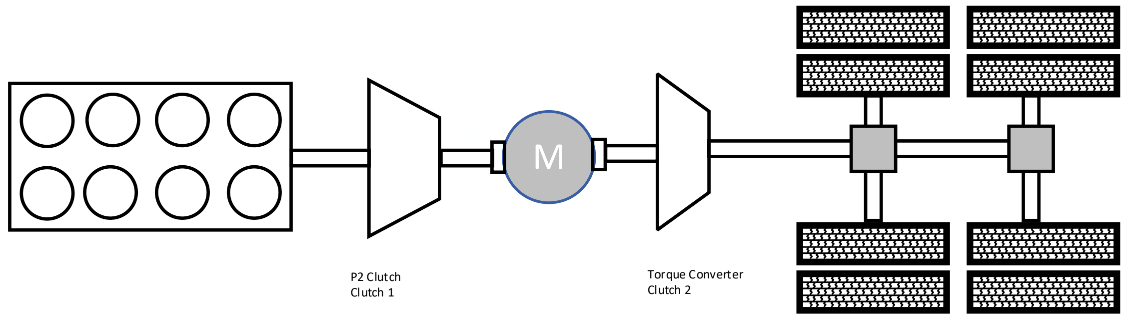


Source: FEV

P2 Clutch Closing (Sync Phase)

The previous decomposition and logic are structured in a way that considers the propulsion architecture shown in the following diagram, where the engine and the electric motor/generator are coupled through a P2 clutch (denoted in the controls logic as Clutch 1). The drive shaft is connected to the electric machine through a torque converter. An important part of the control strategy involves the engine and motor controls during the coupling through the P2 clutch. The engine speed and motor speed need to be synced to enable the safe closing of the P2 clutch.

Figure 7: System Architecture

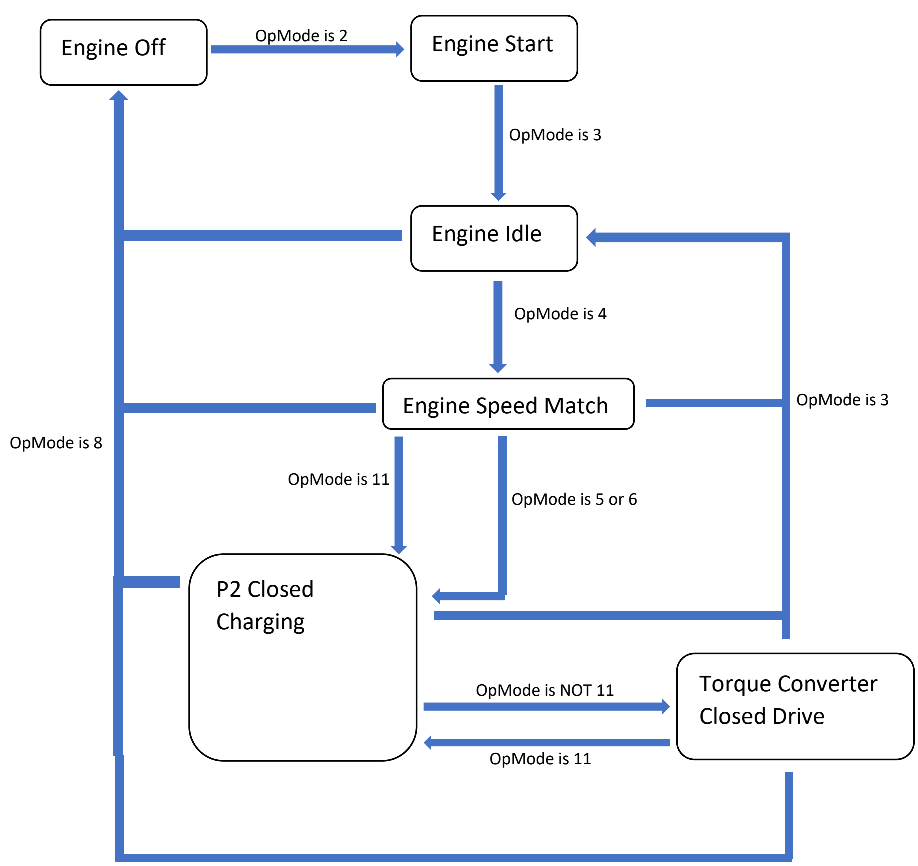


Source: FEV

Engine Control - Speed Matching

Since there are two other states (engine control and motor control) that are running in parallel with the operating modes states, the transition between the states (inside engine control and motor control states) depends on the OpModes. In the engine control mode, the speed match of the engine is managed by the state of a parameter called EngSpdMatch, as shown in Figure 8. The transition to this state is triggered when OpMode equals 4.

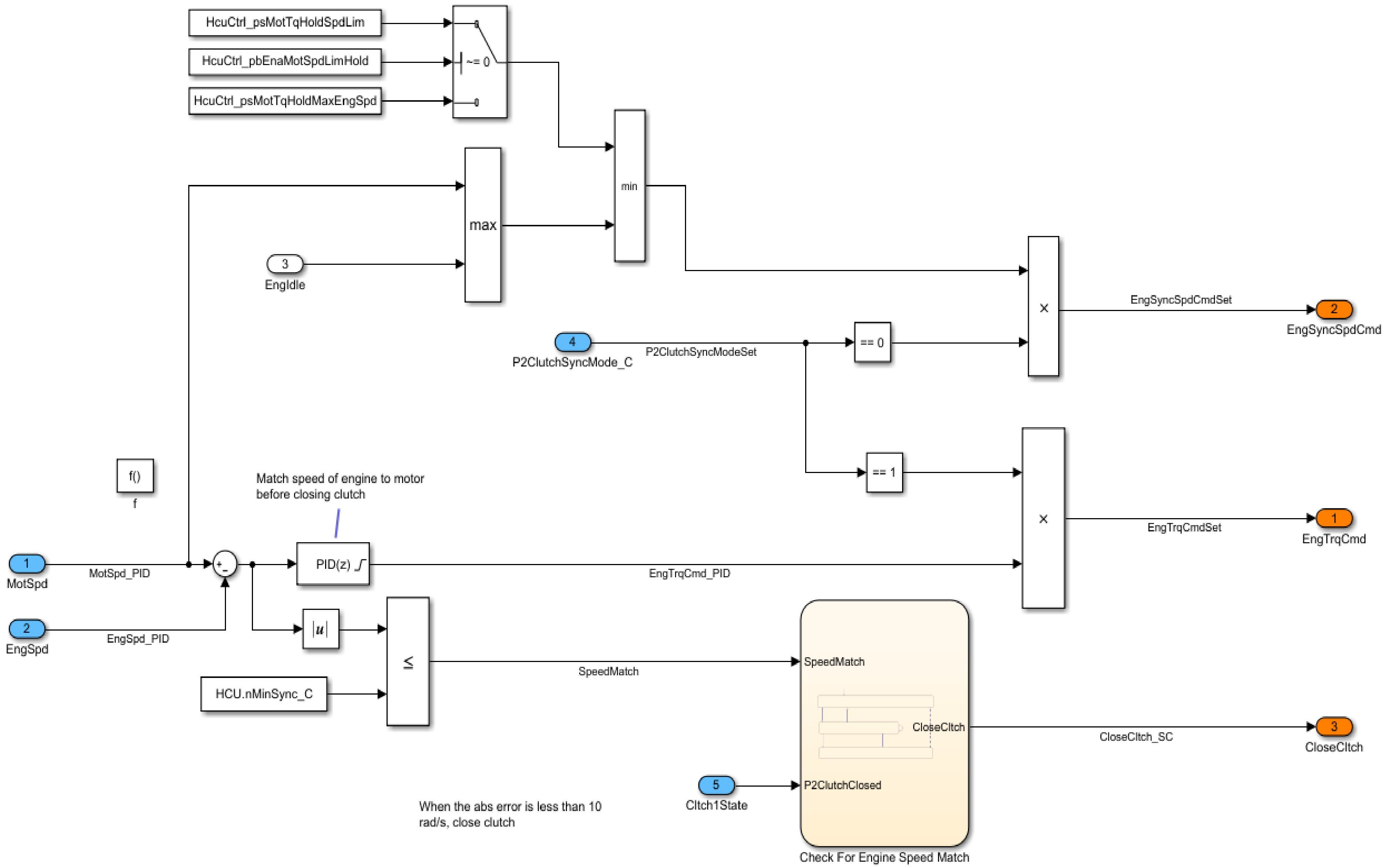
Figure 8: Engine Control Modes



Source: FEV

Once the OpMode 4 is triggered, there is a transition from engine idle to the engine speed match state. In the engine speed match state, there are two modes available: torque mode and speed mode to sync the speeds. Speed mode is used to match the engine speed with the motor speed in the control design. From the motor control the motor speed is brought near a certain threshold value so that the engine can ramp up and try to match up with the motor speed. As shown in Figure 9, the EngSyncSpeedCmdSet parameter is calculated by matching the engine speed with motor speed by constraining it between the engine idle speed and the threshold motor speed.

Figure 9: Speed Matching Simulink Model



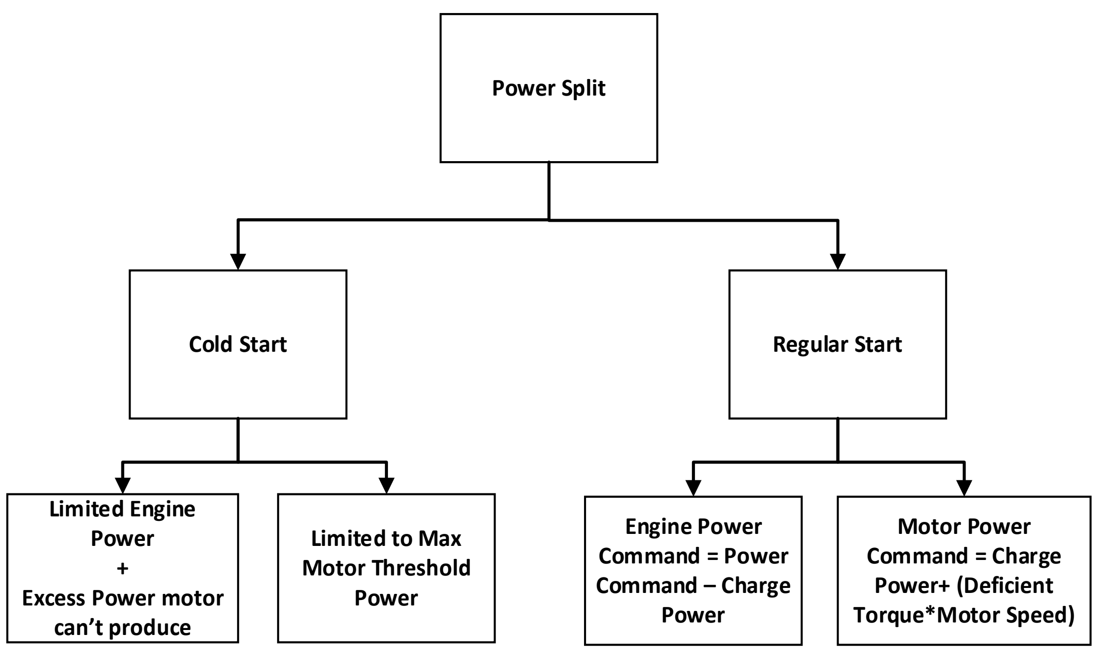
Source: FEV

Once the motor and engine speeds are in sync and the P2 clutch is closed, the engine can now contribute to delivering power to the propulsion system. Assuming that the torque converter is closed (Clutch 2), there are two possible modes of operation for the engine in that case: either the engine delivers power to charge the battery through the motor and provides power to the torque converter to drive the wheels, or the engine delivers power to the torque converter to drive the wheels while the motor is also delivering power to the torque converter to contribute to driving the wheels. The values of power requested from the engine and the motor (MotPwrCmd and EngPwrCmd) are calculated in the hybrid drive state in the operating mode state shown in Figure 6. The function for calculating the motor power command and engine power command depends on several variables, illustrated in the next section.

PHEV Drive – Power Command Split

There are two different modes for splitting power between the motor power command and engine power command during the hybrid drive state shown in Figure 6. These two modes are shown in Figure 10. It can be seen from Figure 10 and Figure 11 that power commands can be distributed between the motor and the engine, based on cold-start operation and regular operation.

Figure 10: Power Split Demonstration



Source: FEV

Cold Start Operation

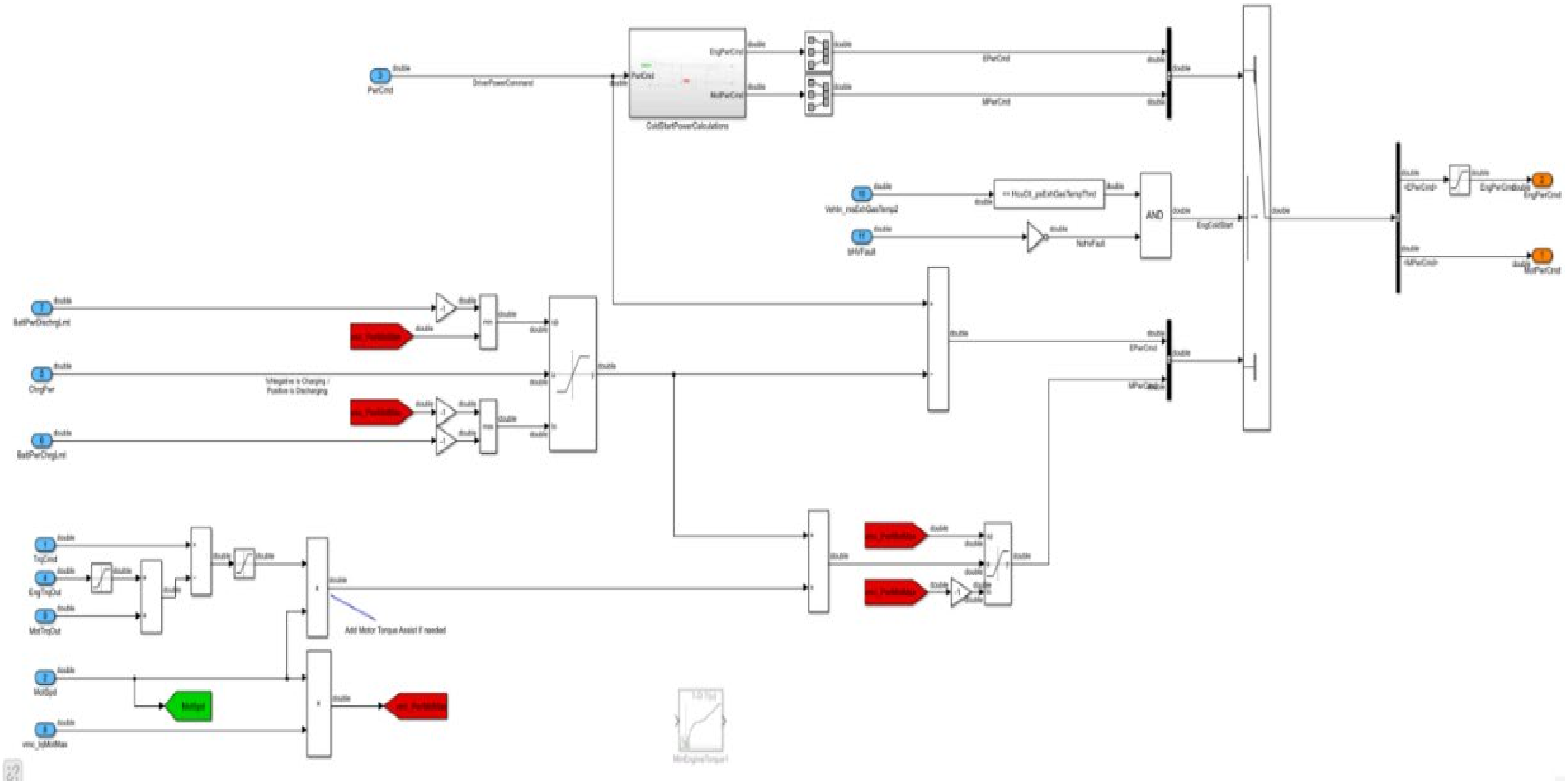
In the case of cold-start operation, the engine power command is limited to a threshold value until the exhaust gas temperature increases to a calibrated value. This threshold will hold if the total power command can be fulfilled by the motor (if the required power is less than the maximum motor power limit). However, if the requested motor power exceeds the motor power limit, then excess power would be provided by the engine and the threshold cannot be maintained.

$$Total\ Power\ =\ Engine\ Power\ +\ Motor\ Power;$$

$$Engine\ Power\ \leq\ MinEngOn\ Threshold\ ,$$
$$if\ (Total\ Power\ -\ Engine\ Power)\ <=\ Motor\ Power\ Limits$$

$$Engine\ Power\ =\ MinEngOn\ Threshold\ +\ (Requested\ Motor\ Power\ -\ Motor\ Limits)\ ,$$
$$if\ (Total\ Power\ -\ Engine\ Power)\ >\ Motor\ Power\ Limits$$

Figure 11: Engine and Motor Power Command Calculation: Cold-Start Operation



Source: FEV

Regular Start Operation

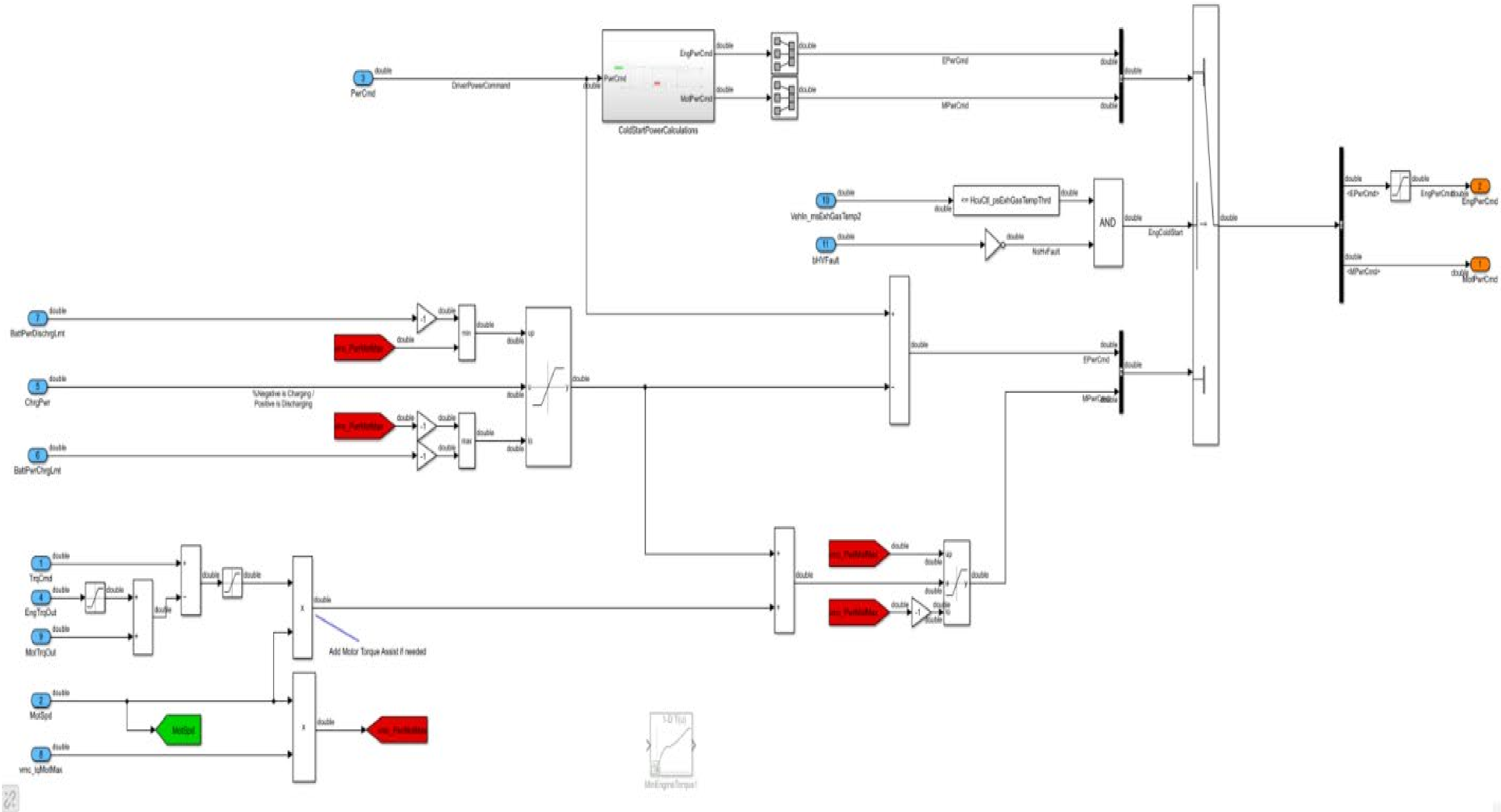
If the temperature of the exhaust gases becomes greater than a threshold value; if there is no fault for high voltage components, that would be regular start operation. In the case of regular start, the engine power command and motor power commands are calculated (Figure 12).

PHEV_DRIVE has two substates: PHEV_P2_CLOSED (OpMode = 5) and PHEV_TrqConv_ CLOSED (OpMode = 6). The transitions between these two states depend on whether the torque converter is open or closed.

$$Engine\ Power\ Command\ =\ Power\ Command - Charge\ Power$$

$$Motor\ Power\ Command = Charge\ Power\ +\ (Torque\ Command - (Motor\ Out\ Trq + Engine\ Out\ Trq) \times MotSpd$$

Figure 12: Engine and Motor Power Command Calculation: Regular Operation



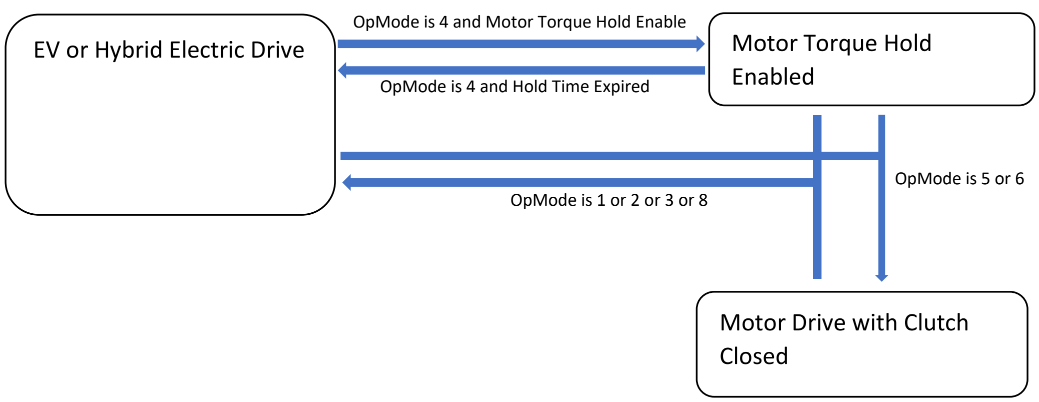
Source: FEV

Torque Calculation Based on Power Command

Once the power command is calculated, the clutch and torque converter are closed and there is a transition into OpModes 5 and 6, where the OpModes, the motor control and engine control states would calculate the torque based on the power command. Power split is the same in both modes, where the only difference is that in the OpMode 5 the torque converter is open; it closes when the OpMode 6 is actuated.

In the motor control state, as seen in Figure 13, once there is transition into OpMode 5 or OpMode 6 the motor drive with clutch closed state would calculate the motor torque command, as shown in Figure 14.

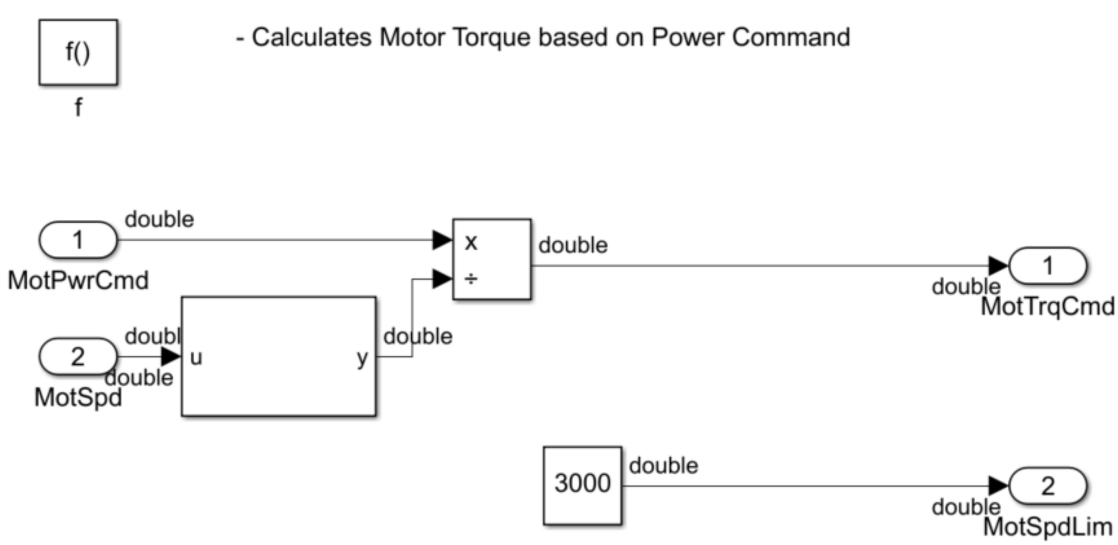
Figure 13: Motor Control State



Source: FEV

Figure 14: Motor Torque Command Calculation

$$Motor\ Torque\ Command\ =\ Motor\ Power\ Command /\ Motor\ Speed$$

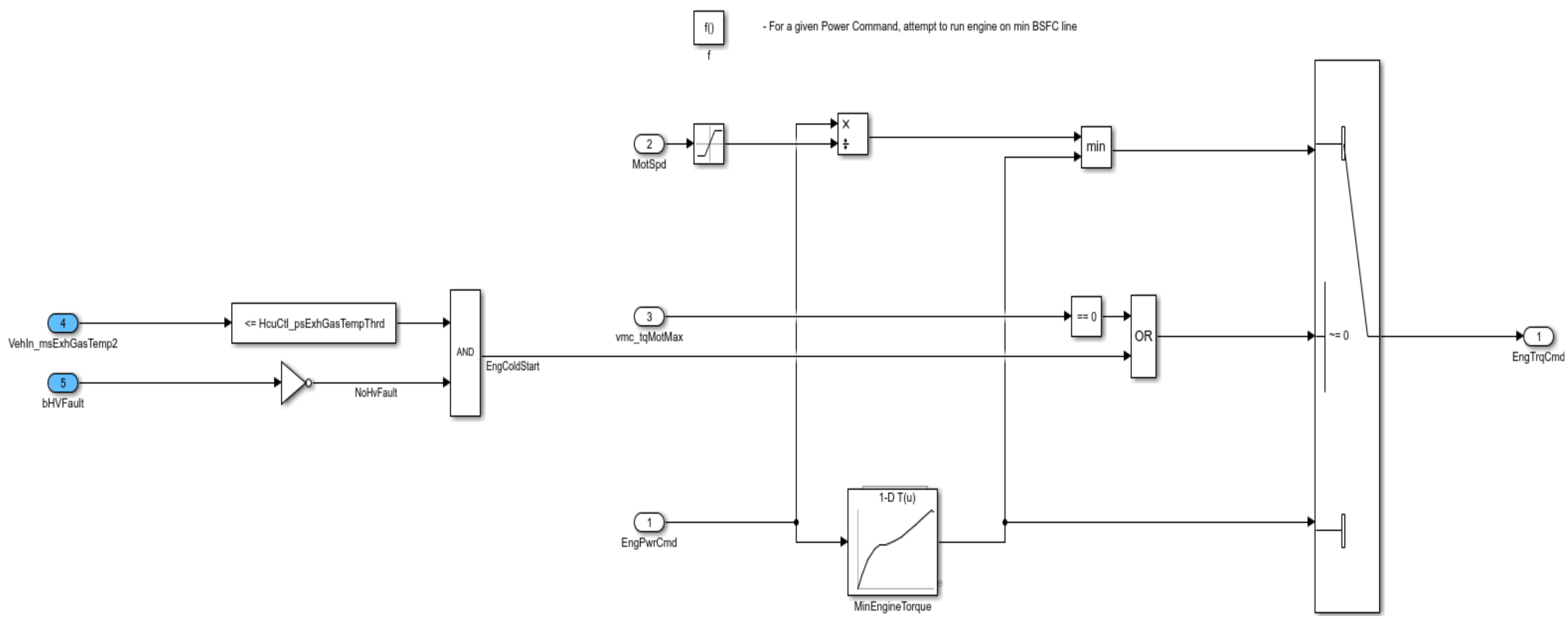


Source: FEV

Similarly, in the engine control state, as seen in Figure 8, the hybrid drive state calculates the engine torque command, as shown in Figure 15. Engine torque is calculated corresponding to the engine power command from the minimum BSFC map and is compared with the ratio of the engine power command and the motor speed, for which the minimum value is sent as the engine torque command.

$$\text{Engine torque} = \text{Min}(\frac{\text{EnginePower}}{Motor\ Speed}, \text{f}_{\text{BSFC}}(\text{Engine Power})$$

Figure 15: Engine Torque Command Calculation



Source: FEV

Engine and Motor Control Modes

The control strategy of the hybrid drive system depends on several variables. Some of them are the variables representing the state of the controls (Point 1). The supervisory control of the electric motor can be decomposed into two main states:

1. The Supervisory Control of the Engine Includes 6 Modes of Operation.
    a. Engine Off (EngMode = 1)
    b. Engine Start (EngMode = 2)
    c. Engine Idle (EngMode = 3)
    d. Engine Speed Match (EngMode = 4)
    e. PHEV P2 Closed Charging (EngMode = 5)
    PHEV Torque Converter Closed Drive (EngMode = 6)
2. The Supervisory Control of the Electric Motor Includes 4 Potential Modes of Operation.
    a. Electric Drive (MotMode=1)
    b. PHEV Torque converter Open Mot Drive (MotMode = 4)
    c. PHEV Torque converter closed Mot drive (MotMode = 3)
    d. PHEV P2 Closed Motor Charge (MotMode = 2)

The high-level supervisory control can be described by taking the driver demand (accelerator and brake pedal inputs) and then reviewing the engine and motor limitations to calculate the appropriate modes to best fulfill the demand.

Vehicle Drive Train Modifications

The test vehicle was originally manufactured in 2009 by Peterbilt with a Cummins ISL-G engine converted to parallel-hybrid configuration by US Hybrid in 2016. For this project, US Hybrid updated the vehicle power train to include the electrified power train components shown in Figure 16.

Figure 16: Hybrid Vehicle Power Train Layout

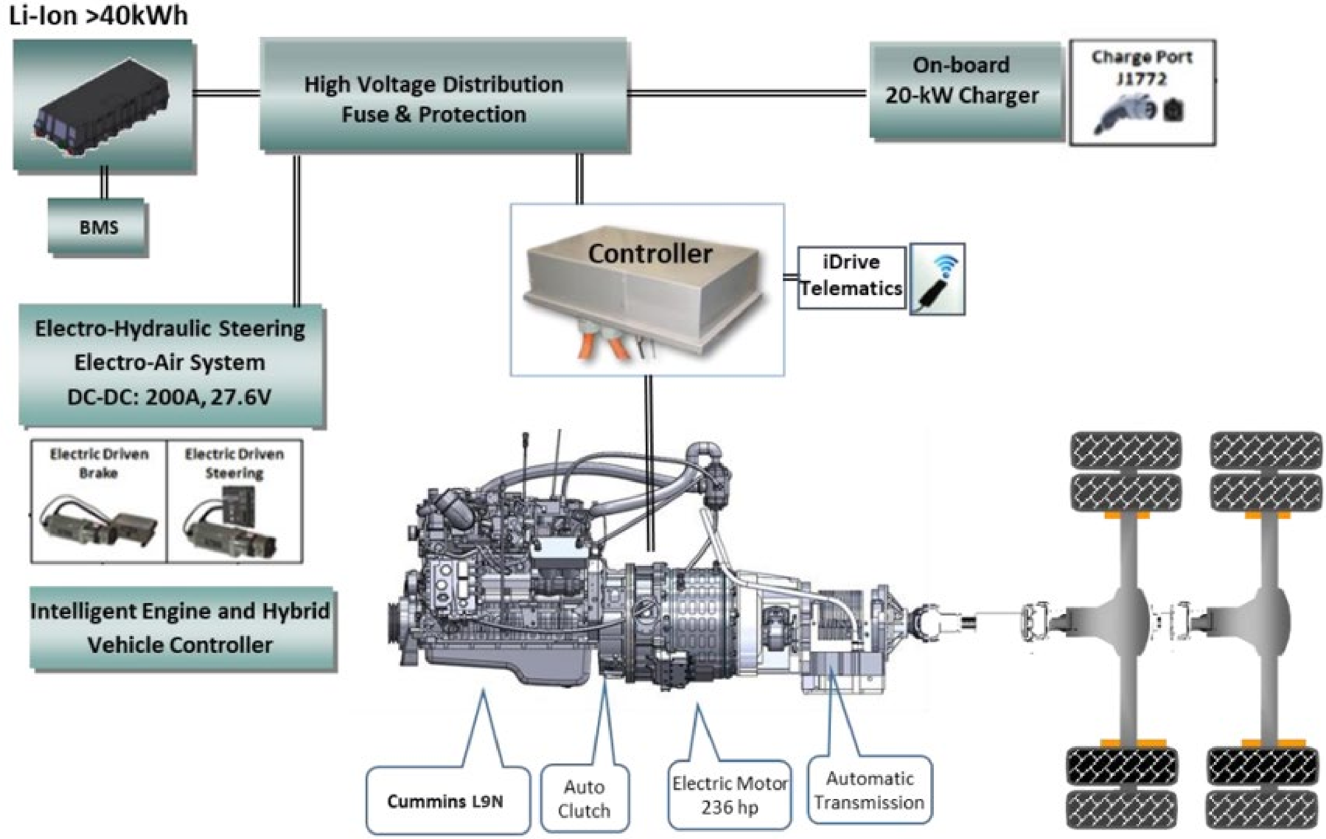


Figure 17: Hybrid Powertrain Component Names and Descriptions

Component Name	Part No, Description
Battery	5-Modules (5S1P) of 22S3P of 26AH NMC
Cooling Fans	Cooling VA03-AP70/LL-37A
Cooling	Water Pump WP29-12V
Air Compressor	3HP 7.1 SCFM 145 PSI SBB030700HP
Housing Assembly	Service
Charger	CMP390-02 20KW
DC-DC Converter	DC07B000AA - 13.7V 200A
Auxiliary Inverters (Integrated)	DA08 Triverter (Air, Hydraulic and A/C)

Source: US Hybrid

Figure 18: Bench Testing of New Battery Modules

Source: US Hybrid

Figure 19: New Battery Modules Integrated Into the Vehicle

Source: US Hybrid

The key system upgrade was a 31-kWh liquid-cooled Lithium-ion battery system, which required fabrication of a battery mounting system, harnesses, low-temperature cooling circuit, and other associated controls.

US Hybrid completed the hardware upgrades and verified the integrity of the system by testing the vehicle on UCR's chassis dynamometer. Upon successful hardware verification, the vehicle was shipped to FEV in Michigan for further development.

Engine Integration

Figure 20 shows the engine integration into the chassis along with the carried-over accessories, flywheel, and starter from the legacy engine.

Figure 20: New Engine Installation

Source: FEV

Source: FEV

Removal and replacement of the legacy cooling pack was required during engine integration. Additional coolant plumbing was installed to accommodate changes in engine component geometry. During this work, FEV mounted and plumbed the positive crankcase ventilation (PCV) filter/heater provided with the Cummins engine. Figure 21 and Figure 22 show the completed engine cooling pack with completed plumbing changes.

Figure 21: Engine Cooling Pack and Plumbing Completed – Driver Side

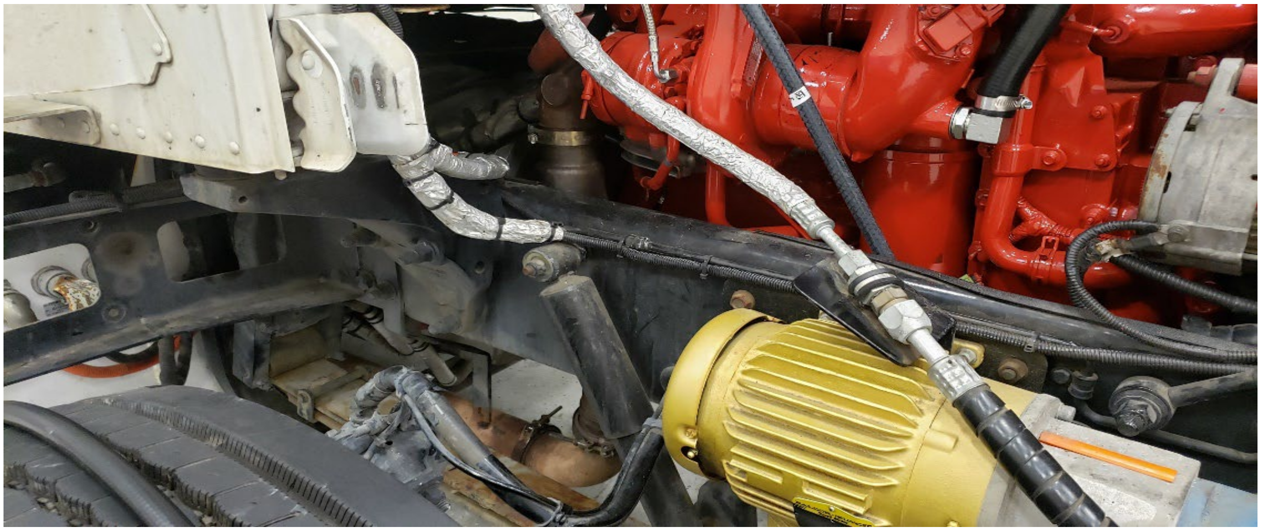
Source: FEV

Figure 22: Engine Cooling Pack and Plumbing Completed – Passenger Side

Source: FEV

Due to the changes in turbocharger and exhaust manifold orientation, FEV modified the charge air, exhaust, and cooling passages to fit the new layout, as shown in Figure 23 and Figure 24. The exhaust piping was modified to fit the legacy down tube and 90° bend to the catalyst. FEV also fabricated an extension of the charge air cooler (CAC) ducting at the compressor outlet and an extension of the cold air intake to compensate for the changes to the turbo orientation while maintaining package-critical legacy components.

Figure 23: Engine Exhaust Modification



Source: FEV

Figure 24: Engine Exhaust Modification

Source: FEV

Fabrication for Compressed Natural Gas (CNG) Tanks

The original vehicle was manufactured with a liquified natural gas (LNG) fuel system; however, the team was unable to source LNG fueling in Michigan. To continue the development, the FEV team modified the fuel system to operate on CNG, which was easier to source. FEV performed fabrication work to carry four CNG tanks at one time, and plumbed these tanks into the system for ”on-road” development. As shown in Figure 25, the four tanks were daisy-chained together, and a regulator was placed at the end of the daisy chain to limit the pressure from the tanks to 150 psi.

Figure 25: CNG Tank Mounting

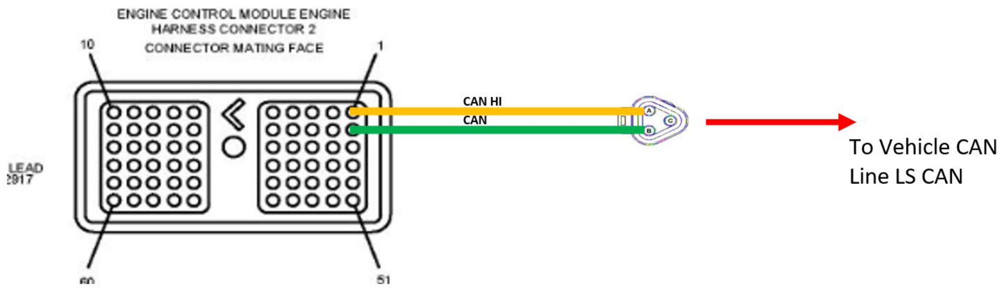
Source: FEV

Source: FEV

Engine Control Module (ECM) Controller Area Network (CAN) Wiring Modification

The ISL-G engine was replaced with a new L9N engine in the truck and the vehicle wiring harness was connected to the engine in the same manner as in the old engine. It was observed that the engine was not broadcasting all the controller area network (CAN) messages as expected by the vehicle and the hybrid control unit (HCU). Upon further inspection it was found that the electrical circuit for the new engine changed when compared with the previous engine. The CAN line from the engine that was previously used to communicate with the vehicle was the earlier 250k baud rate public line; in the new engine, it was the 250k baud private line that did not broadcast all the messages required. As shown in Figure 26, to access the 250k private line, CAN taps were made to the 60-pin connector of the ECM directly, and connected to the vehicle low-speed can line via a Deutsch 3-pin male connector.

Figure 26: ECM CAN Communication Wiring



Source: FEV

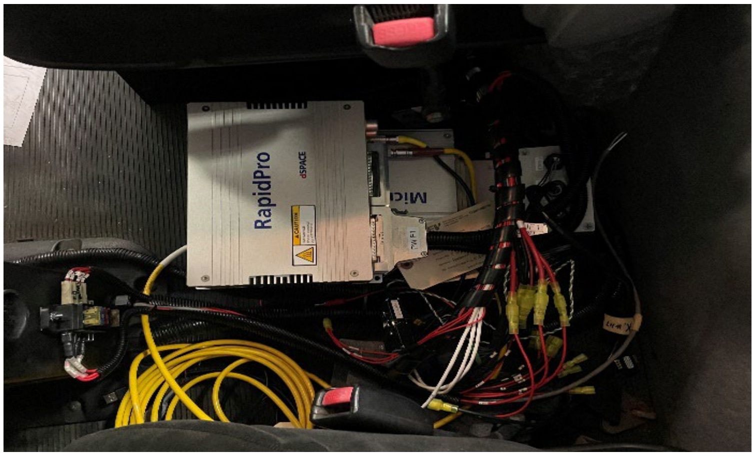
Microautobox Harness

The harness schematic from the vehicle to the Microautobox was developed and installed at FEV North America in Auburn Hills. The input and output (I/O) were tested and validated, both at FEV and on the chassis dynamometer (dyno) at UCR. Controller Setup

The controller (dSPACE Microautobox) was installed between the driver and passenger seats. As shown in Figure 27, Rapid Pro and I/O extension of the Microautobox were used to control the low side driver (LSD) relay setup that was done by US Hybrid. Microautobox has very limited LSD and is also limited on current capability on the digital I/O pins.

For the high-speed and low-speed CAN, taps were made from the existing US Hybrid Harness and pulled into the Microautobox harness. All the I/O were verified as functional.

Figure 27: Micrautobox and Rapid Pro Setup



Source: FEV

Ambient Temperature Sensor

A new ambient temperature sensor was installed on the passenger side mirror to provide the ambient temp reading to the new L9N engine. The old engine did not require an ambient temperature sensor and the existing sensor was only used for dash display. An additional sensor dedicated to the engine was installed because it was not clear whether the resistance from ECM and the dash would work with one sensor.

Test Article

The test vehicle was a plug-in hybrid CNG class-8 truck with a Cummins Westport L9N 320 CNG engine, a 240-kW electric motor, and 80 kWh battery storage with a 30-mile zero emissions range. This section describes the engine utilized in the test vehicle, the drive train motor, energy storage system and the vehicle inspection on-board diagnostic (OBD) system.

Engine

The vehicle was upgraded from a 0.2 g/bhp-hr NOx certified engine to a 0.02 g/bhp-hr NOx L9N 320 Cummins Westport Inc., (CWI) CNG engine (SN = 74622233). See Table 1 for specifics. CWI developed this engine as an ultra-low NOx demonstration engine where the NOx emissions have been reduced to 0.02 g/bhp-hr (90 percent below the 2010 NOx emissions standard). The released executive order for the near-zero configuration with engine family LCEXH0540LBL is 0.02 g/bhp-hr, where the actual certified value was 0.01 g/bhp-hr.

Table 1: Summary of Selected Main Engine Specifications

Mfg	Model	Year	Eng. Family	Rated Power (Hp @ Rpm)	Disp. (Liters)	Adv Nox Std G/Bhp-H	Pm Std. G/Bhp-H
CWI	L9N 320	2020	LCEXH0540LBL	320 @ 2000	8.9	0.02	0.01

Source: CARB

Drive Train and Motor

The electric traction motor was placed in-line with the engine and transmission, as shown in Figure 28. In battery mode, the engine is shut off, and the motor drives the truck. While operating in hybrid mode, the motor assists the engine to enhance its torque and power to increase fuel economy. The controllers also reduce transient emissions.

Figure 28: Drive Train

Source: US Hybrid

The overall development of the traction motor, located in the drive train, was refocused when a detailed engineering review was performed. Market use survey information and drive cycle studies showed the need for a higher continuous power rating and increased torque at lower speeds. For US Hybrid to meet these requirements, a dual motor system with integrated clutches was implemented. The motors are shown in Figure 29.

Figure 29: Motors and Controllers

Source: US Hybrid

Detailed engineering design and serviceability reviews, integration reviews, and cost reviews were completed for the individual motors, shafts, engine side clutch spline interfaces, connecting adapter plates, flywheel housing, clutch housing, clutch/flywheel interfaces, motor-spline interfaces, and clutch pull reaction bearings. The cable routing, protection, and connection with the inverters were established. The cooling line connection and routing were integrated.

Energy Storage System

The energy storage system is a 31 kWh Lithium-ion battery with a safety disconnect and fusing protection system, as shown in Figure 30. US Hybrid engineers designed the packaging of A123 battery modules and battery management systems into a custom-designed enclosure. The battery pack capacity is 31 kWh, with a maximum power capability of 240 kW.

Figure 30: Battery, Controller, Charger, and Auxiliary Drive Housing

Source: US Hybrid

Vehicle Inspection

Prior to testing, the vehicle was inspected for proper tire inflation and condition, vehicle condition, vehicle securing, and the absence of any OBD engine code emission faults. Although there were some initial OBD faults found with the vehicle (see discussion in the Issues section) the final vehicle inspection met UCR's specifications. UCR scanned the OBD system on the truck several times and was able to clear all the faults prior to testing using Silver Scan. All tests were performed within specification and without any engine code faults. Thus, the results presented in this report are representative of a properly operating vehicle, engine, and after-treatment system.

Test Fuel

Two types of fuel were utilized in this project: pure methane in cylinder bottles, as shown in Figure 32, and California pipeline fuel, which represents typical CNG available in Southern California. For the calibration phase of this project, methane cylinders were utilized. Due to a shortage of bottled methane gas, the fuel source was switched from methane gas in purchased cylinders to tank fuel from a CNG refueling station. Previous studies have shown that fuel quality does not impact vehicle NOx emissions due to the nature of the three-way catalyst after-treatment system.[3] The emissions results provided in this study are therefore representative of real-world CNG fuel use.

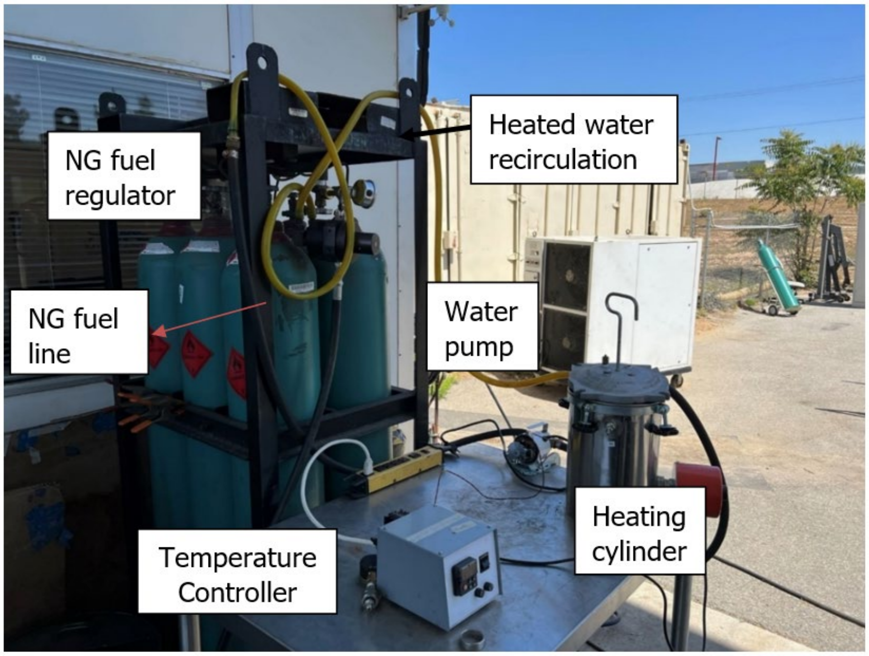
CH4 Cylinder Fuel

The calibration fuel utilized was from compressed gas cylinders. The gas utilized was 99.9 percent methane gas, supplied at around 2,200 psi in six packs. Since the fuel was separate from the vehicle, a heated regulator delivery system was needed to prevent the regulator supply from freezing. A commercially available vehicle CNG tank regulator was acquired and

[3] Johnson, K. Durbin, T., and Leonard J., 2021 Development, Demonstration and Testing of Advanced Ultra-Low-Emissions Natural Gas Engines in Port Yard Tucks, Final Report to the California Energy Commission PIR-16-016.

integrated, with a heating system that simulated hot coolant circulating through the regulator. The overall setup is shown in Figure 31 which includes the CNG fuel regulator, water pump, temperature controller, heating cylinder, compressed gas fuel lines, and hot water circulation water lines.

Figure 31: Onsite Fuel Preparation System Layout

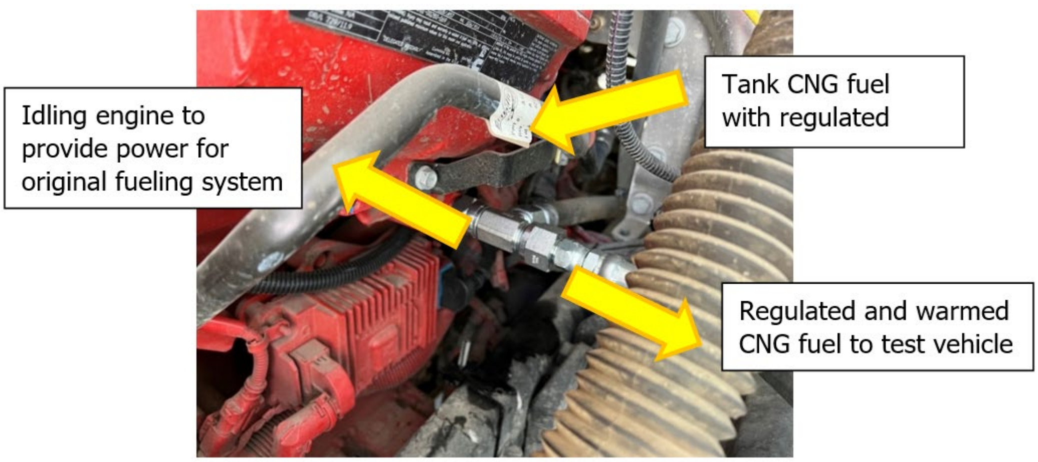


Source: UCR

CNG Fuel

To obtain pump CNG fuel with a regulated supply pressure of 80 psi, UCR acquired a Class 8 CNG truck and installed a "T" system after the low-pressure regulator and before the point where the fuel enters the engine, as illustrated in Figure 32. The tank fuel was regulated and warmed utilizing the onboard fueling system, with the truck idling.

Figure 32: Tank Fuel Flow Split Setup



Source: UCR

Test Cycles

The test vehicle utilized in this study was a Class 8 truck used for two typical vocations in the South Coast Air Basin: goods movement and port drayage. To characterize emissions and performance from this HEV system over the range of in-use applications, various cycles are typically performed for diesel and CNG trucks and buses. During previous CNG vehicle testing at UCR for a separate project, heavy duty vehicles were tested by simulating a port cycle (near dock, local, and regional), the Urban Dynamometer Driving Schedule (UDDS), and the Central Business District (CBD) bus cycle. These cycles are representative of Southern California driving. See more detailed cycle descriptions in Appendix B.

The UDDS test cycle resulted in the highest NOx emissions for cold and hot start during testing of other 0.02 g/bhp-hr certified CNG engines1,2. It was concluded that the high NOx emissions during the UDDS cycle were a result of the rapid torque event occurring during idling conditions1,2. In two cases the event occurred during acceleration and in one case it occurred during a deceleration event. The recommendation for minimizing the NOx spikes was to manage the rapid torque demand with an electric assist motor system (electric hybridization). To demonstrate that this optimized hybrid engine is working as planned, the UDDS test cycle was proposed. The UDDS cycle was utilized for optimization and for final emissions evaluation. The UDDS cycle is summarized in Table 2 and shown in Figure 33.

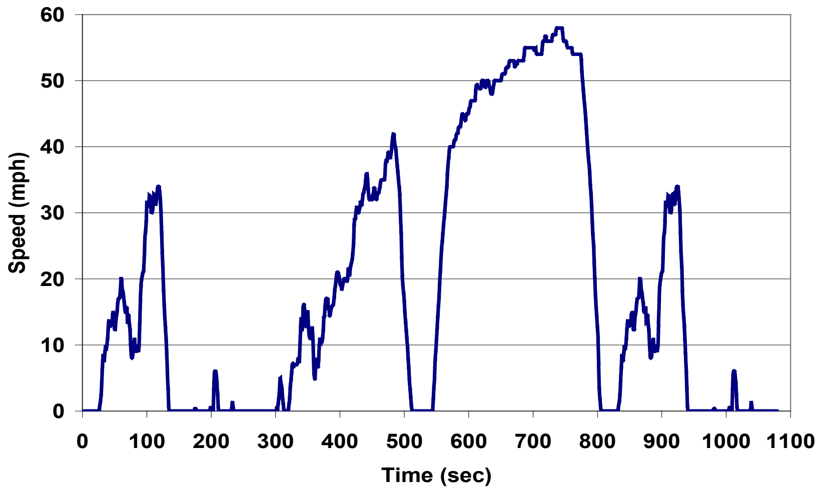
Table 2: Summary of Statistics for Various Proposed Driving Cycles

Day	Distance (mi)	Average Speed (mph)	Duration (sec)
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3661
UDDS	5.55	18.8	1061
CBDx3	2.0	12.6	560

Source: UCR

The federal heavy-duty vehicle UDDS is a driving cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel trucks. This cycle covers 5.55 miles with an average speed of 18.8 mph, a sample time of 1061 seconds, and a maximum speed of 58 mph. The speed/time trace for the UDDS is provided in Figure 33. Sometimes the UDDS is performed as a single UDDS (UDDS 1x) and other times as a double UDDS (UDDS 2x). For the testing performed in this study, the UDDS was performed as a single UDDS (UDDS 1x). It is important to note this since more than 90 percent of the emissions were formed from the cold or hot-start part of the cycle where a longer test cycle will have lower overall emissions. A discussion on real-world emissions impact is presented in the Emissions Results section to estimate the real-world emissions from these demonstration project results.

Figure 33: Speed Trace of Urban Dynamometer Driving Schedule (UDDS)



Source: UCR

Laboratories

The testing was performed on UCR's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside, California. This section describes the chassis dynamometer, which emissions measurement laboratories used for both evaluating the in-use emissions from the demonstration vehicle, and detailed work calculations based on engine and motor loads. Due to challenges of NOx measurement at and below 0.02 g/bhp-hr NOx emissions, additional sections are provided to describe potential NOx measurement improvements.

Chassis Dynamometer

UCR's chassis dynamometer (Figure 34) is an electric AC-type design that can simulate inertia loads from 10,000 lb to 80,000 pounds and covering a broad range of in-use medium and heavy-duty vehicles (see Appendix C). The design incorporates 48-inch rolls, vehicle tie down (to prevent tire slippage), and 45,000 pounds base inertia plus two large AC drive motors for achieving a range of inertias. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horsepower at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common. See Appendix C for more details.

Figure 34: UCR's Heavy Duty Chassis Eddy Current Transient Dynamometer

Source: UCR

Test Weight

The representative test weight for Class 8 trucks moving freight in California is 69,500 pounds (lbs). The small displacement (8.9 liter) CNG engine is not powerful enough to operate safely at these high loads in conventional mode but could operate in hybrid mode with an electric motor assist. The 69,500 lb test weight was used by UC Riverside and West Virginia University for other research projects with CNG, all electric, and diesel trucks. In summary, UCR utilized a testing weight of 29,600 lbs for all calibration tests (UDDS and port cycles) in conventional mode and 29,600 lbs and 69,500 lbs in hybrid mode. In addition, the UDDS was performed at 69,500 lbs in hybrid mode to consider performance benefits of the hybrid system compared to the conventional system. The Results section was limited to testing at the fully loaded condition (69,500 lbs) due to time constraints from delays with calibration. See the Issues section for details.

Emissions Measurements

The approach used for measuring emissions from a vehicle or engine on a dynamometer is to connect UCR's heavy-duty MEL to the total exhaust of the diesel engine. The details for sampling and the measurement methods of mass emission rates from heavy-duty diesel engines are described in Section 40, Code of Federal Regulations (CFR): Protection of the Environment, Part 1065. UCR's unique heavy-duty diesel MEL is designed and operated to meet those stringent specifications. The accuracy of MEL's measurements has been checked and verified against CARB's and Southwest Research Institute's heavy-duty diesel laboratories. The MEL routinely measures total hydrocarbons (THC), methane (CH4), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM) emissions from diesel engines. Design details of MEL are described in Appendix D.

Previous testing with ultra-Low NOx engines required upgrades to the MEL, as reported by UCR.[4,5] The MEL was, however, recently upgraded (completed in 2020) with a new Horiba state-of-the-art measurement bench for both raw and dilute measurements, with a special emphasis on low NOx measurements at and below 0.02 g/bhp-hr. The new design was targeted at measuring NOx emissions below 0.002 g/bhp-hr (90 percent below the 0.02 standard). The final emissions results provided in this report are based on these new low NOx measurements made with the upgraded MEL.

The MEL is equipped with a fully 1065-approved laboratory grade gaseous emissions analyzer and 1065-approved partial flow particulate matter portable emissions measurement systems for on-road and off-road applications. The MEL is a complex laboratory and a schematic of the major operating subsystems for MEL, shown in Figure 35. The analyzers are of the highest quality and utilize 24-bit analog to digital converters (ADC) with an effective 21 bits of usable resolution for each range, have low analyzer drift and interferences and are designed for raw and dilute CVS analyzers.

Gaseous measurements

The UCR MEL is equipped with a 1065-approved laboratory grade MEXA ONE bench manufactured by Horiba, and a laboratory grade quantum cascade laser (QCL) for the gaseous emissions. Included in the MEL MEXA ONE bench is both raw (tailpipe) and dilute (CVS) measurements with integrated close-coupled heated oven analyzers for improved accuracy. The raw bench includes two chemiluminescence analyzers, one set up for NO in the bench and another set up for NOx in the oven to calculate NO2, two non-dispersive infrared (NDIR) analyzers for measuring carbon monoxide low (CO_L), CO high (CO_H), carbon dioxide (CO_2), and two heated flame ionization detectors (HFID) for measuring total hydrocarbons (THC) and methane hydrocarbons (CH4) for the determination of non-methane hydrocarbons (NMHC). The CO emissions exceeded the CO_L analyzer range on a few modes, so CO emissions reported here are from the CO_H analyzer.

The dilute analyzers are similar in model to the direct bench, but with lower range capabilities. The dilute analyzers in the bench include CO_L, CO_2_L, THC, CH4, and NOx. The bench dilute NOx is Horiba's ultra-low NOx analyzer designed for concentrations with the lowest range of 0-1 ppm for the future 0.02 g/bhp-hr certified emissions levels expected. The dilute sample

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4 Li C, Han Y, Jiang Y, Yang J, Karavalakis G, Durbin TD, Johnson K. Emissions from advanced ultra-low NOx heavy-duty natural gas vehicles. SAE Technical Paper 2019; 2019-01-0751.

5 Zhu H., McCaffery C., Jiang Y, Yang J, Li C., Karavalakis G, Johnson K., Durbin TD, Characterizing emission rates of regulated and unregulated pollutants from two ultra-low NOx CNG heavy-duty vehicles. FUEL 277 (2020) 118192.

line also includes a close-coupled heated oven with heated THC, CH4 and NOx. For the setup of the dilute sample line the bench was configured for NOx and the heated oven for NO.

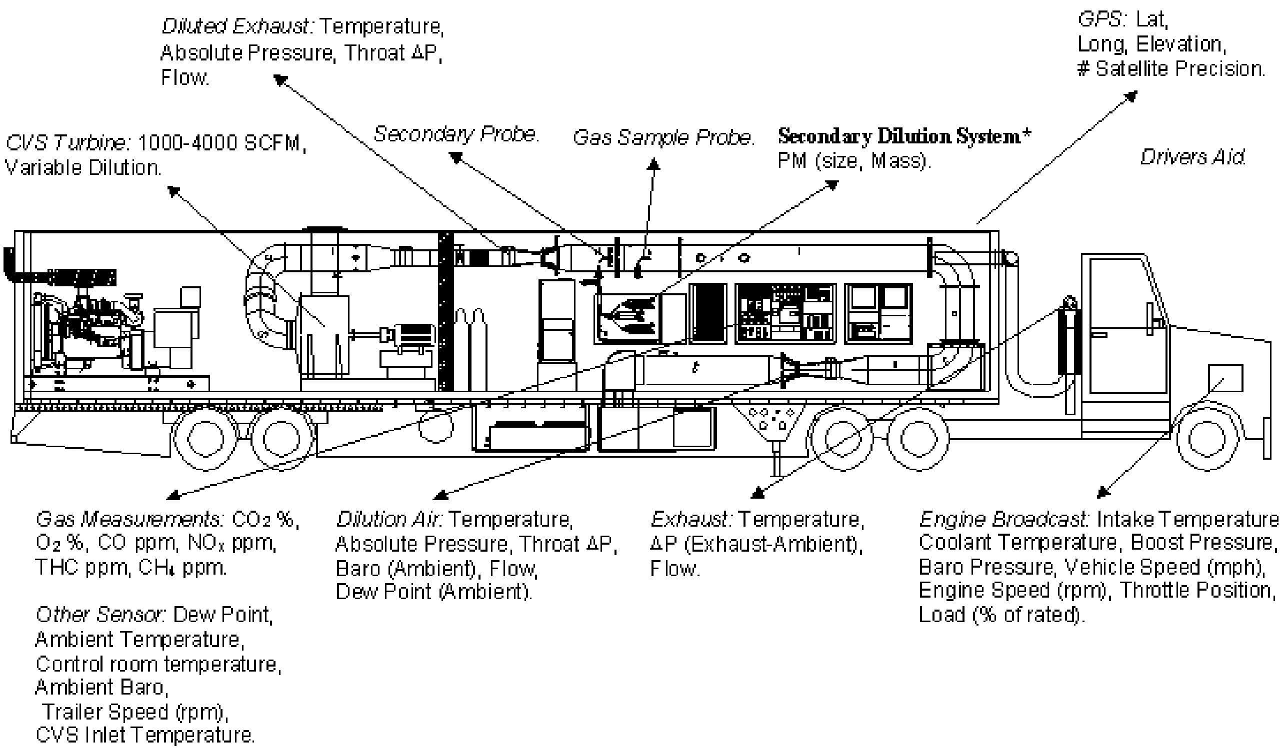
Particulate Matter Measurements

Particulate matter (PM) emissions were sampled on a Teflon filter and the mass was determined gravimetrically with a microbalance in a temperature and humidity-controlled weighing chamber. These emissions measurements follow 40 CFR Part 1065 and are used for regulating new engines for heavy duty and light duty applications. The sample for the PM filter is taken from the CVS system, which is diluted to an overall amount of ~ 7:1 at full load. Actual dilution will vary based on the selected duty cycle.

Unregulated Emissions

In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution (PSD) with TSI's Engine Exhaust Particle Sizer (EEPS) Model 3090, particle number (PN) with a TSI 3776 condensation particle counter (CPC), soot PM mass with AVL's Micro Soot Sensors (MSS 483) and nitrous oxide (N2O) and ammonia (NH3) emissions with a quantum cascade laser (QCL) system designed by Horiba. The PN measurement system used a low-cut point CPC (2.5 nm D50) because of the large PN concentrations reported below the PMP protocol CPC 23 nm measurement system (10, 11, and 12). The EEPS spectrometer displays measurements in 32 channels total (16 channels per decade) and operates over a wide particle concentration range, including down to 200 particles/cm3.

Figure 35: Major Systems Within UCR's Mobile Environmental Lab (MEL)



Source: UCR

Work Calculation

The reported emission factors presented are based on a gram-per-unit-work basis. The work is the sum of the engine power and electric motor power. This section provides the details on those calculations. The engine power is calculated utilizing actual torque, friction torque, and reference torque from broadcast J1939 ECM signals (hp_{eng}). The electric motor power (hp_{mot}) is calculated from the motor voltage and current averaged over the test cycle.

The following two formulas show the calculation used to determine engine brake horsepower (bhp) and work (bhp-hr) for the tested vehicle. The motor work is calculated directly from the signals populated in the motor control module. Note for the electric motor power, the negative power is representative of regenerative braking. The negative power would under-report the total work performed so the negative power was removed from the calculation. Thus, the final motor work calculation excluded the negative parts and reported the negative parts in a regenerative braking category. Distance was measured by the chassis dynamometer and the vehicle broadcast J1939 vehicle speed signal.

$$hp_{eng} = \frac{RPM_{eng}(Torque_{eng\_actual} - Torque_{eng\_friction})}{5252} \times Torque_{eng\_reference}$$

$$hp_{mot} = \frac{RPM_{mot} \times Torque_{mot}}{5252}$$

Where:

hp_{eng}	Instantaneous power from the engine; negative values set to zero.
RPM_{eng}	Instantaneous engine speed as reported by the ECM (J1939).
$Torque_{eng\_actual}$	Instantaneous engine actual torque (%): ECM (J1939)
$Torque_{eng\_friction}$	Instantaneous engine friction torque (%): ECM (J1939)
$Torque_{eng\_reference}$	Reference torque (ft-lb), as reported by the ECM (J1939)
hp_{mot}	Instantaneous power from the motor
RPM_{mot}	Instantaneous motor speed
$Torque_{mot}$	Instantaneous motor torque (ft-lb)

$$Work = \sum_{i=0}^{n} \frac{hp_{eng} + hp_{mot}}{3600}$$

Fuel Economy Calculation

The vehicle distance-specific fuel consumption was calculated based on a carbon balance[6] detailed in 40 CFR. Since this is for generic gaseous fuel, the idea of diesel gallon equivalence was applied with information from the Alternative Fuels Data Center[7] and from the Propane

[6] Richard Lawrence, 1981, Fuel Economy Measurement Carbon Balance Method, U.S. EPA Report # 420-D-81-103.

[7] https://afdc.energy.gov/fuels/equivalency_methodology.html

Education and Research Council. The governing equation for conventional fuel economy follows.

$$MPG_{NG} = \frac{CWF_{NG} \cdot DGE_{NG}}{CWF_{HC} \cdot HC + CWF_{CO} \cdot CO + CWF_{CO_2} \cdot CO_2}$$

In the above equation, CWF_{NG} represents the carbon weight fraction of the fuel; for natural gas 0.75 was applied. DGE_{NG} represents diesel gallon equivalent (DGE) of natural gas value of 6.37 lbs (2.889 Kg), based on energy balances that convert mass of natural gas consumed to equivalent diesel volume consumed, which equals 2081.04 gNG/DGE. CWF_{HC}, CWF_{CO} and CWF_{CO_2} represent the carbon weight fraction of the hydrocarbons CO and CO_2, respectively. HC, CO and CO_2 represent distance-specific mass in terms of g/mi.

As for the electric part of fuel economy, here we consider mainly the tank-to-wheels part of energy flow for electricity in charge-depleting mode. A direct conversion of electricity usage to diesel gallon equivalent is applied based on energy content balance. A generic heating value of lower heating value (LHV) sulfur diesel is 128,488 Btu/gal. Thus 1 kWh equals 0.0266 diesel gallons.

$$MPG_e = \frac{Distance\ travelled}{Electrical\ Work \cdot Fctr_{DGE}}$$

Where $Fctr_{DGE}$ represents the conversion factor of 0.0266 diesel gallon/kWh.

Based on the fuel economy from the natural gas part and the electrical part calculated earlier, the overall combined fuel economy can be calculated for the charge-depleting-mode tests. Note that this charge-depleting fuel economy calculation was developed from SAE J1711 and SAE J2711 and fit well for tank-to-wheels analysis purposes.

$$MPG_{comb} = \frac{Distance\ travelled}{\frac{Distance\ travelled}{MPG_{NG}} + \frac{Distance\ travelled}{MPG_e}} = \frac{1}{\frac{1}{MPG_{NG}} + \frac{1}{MPG_e}}$$

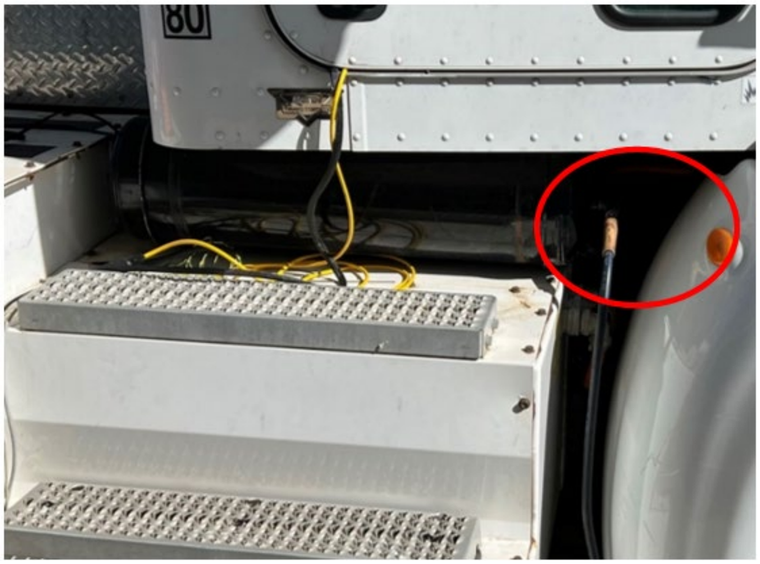
Issues

During calibration and emissions testing, various issues were identified with the vehicle, setup, and operation that are described briefly in this section. The issues delayed the overall program and led to changes in the approach to maintaining the schedule and budget.

Air Compressor Under Electric-Vehicle Mode

Power steering is supplied by an onboard electric compressor. This system was not functioning properly when laboratory-based shop air was provided for testing. It was determined the vehicle onboard inverter was not functioning properly, which led to a loss of auxiliary power controls such as the power steering and other controls during electric-vehicle mode operation. To keep the tests running, onsite shop air was provided and connected to a secondary air pressure cylinder directly to build up pressure for braking and clutch engagement.

Figure 36: Shop Air Supply to Onboard Secondary Compressor



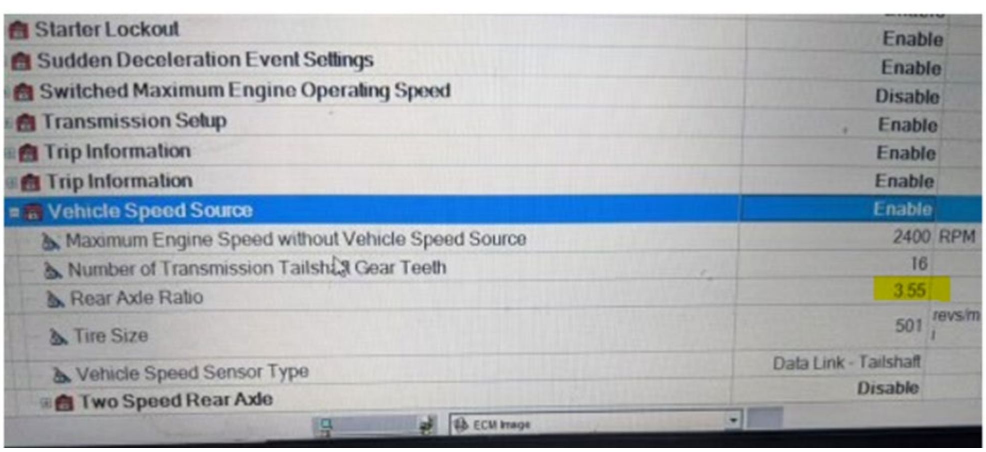
Source: UCR

Speed Calibration

A mismatched speed between the ECU wheel-based speed and dynamometer speed was identified during an early staged test run on March 25, 2022.

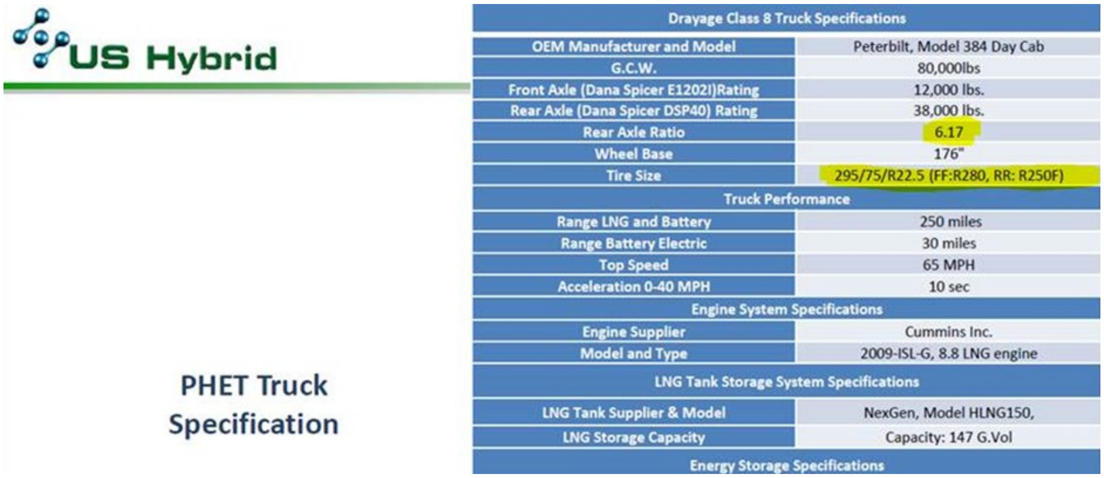
The UCR team contacted Cummins support and arranged for a Cummins field technician to visit. Various trips from the local field technician and discussions with corporate were needed to identify the problem. The problem was due to the default calibration file within the replacement CNG engine (the rear axle ratio was set to 3.55), which was not aligned with the original rear axle ratio setup of 6.17. The vehicle speed was therefore off by a factor of 1.7, which impacted all the calibration tables and models of the hybrid controller. After updating the calibration file on this engine, the speed aligned with the dynamometer configuration. Details are shown in Figure 37 and Figure 38. Once the repairs were completed the speed matched the chassis dynamometer, as shown in Figure 39 and Figure 40.

Figure 37: Engine Calibration Parameters from Cummins Insite



Source: UCR

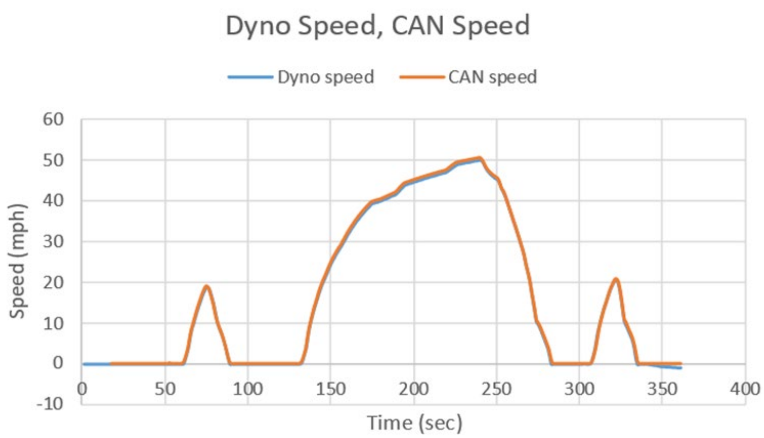
Figure 38: Default Parameters from US Hybrid



Drayage Class 8 Truck Specifications	
OEM Manufacturer and Model	Peterbilt, Model 384 Day Cab
G.C.W.	80,000lbs
Front Axle (Dana Spicer E1202I)Rating	12,000 lbs.
Rear Axle (Dana Spicer DSP40) Rating	38,000 lbs.
Rear Axle Ratio	6.17
Wheel Base	176"
Tire Size	295/75/R22.5 (FF:R280, RR: R250F)
Truck Performance	
Range LNG and Battery	250 miles
Range Battery Electric	30 miles
Top Speed	65 MPH
Acceleration 0-40 MPH	10 sec
Engine System Specifications	
Engine Supplier	Cummins Inc.
Model and Type	2009-ISL-G, 8.8 LNG engine
LNG Tank Storage System Specifications	
LNG Tank Supplier & Model	NexGen, Model HLNG150,
LNG Storage Capacity	Capacity: 147 G.Vol
Energy Storage Specifications	

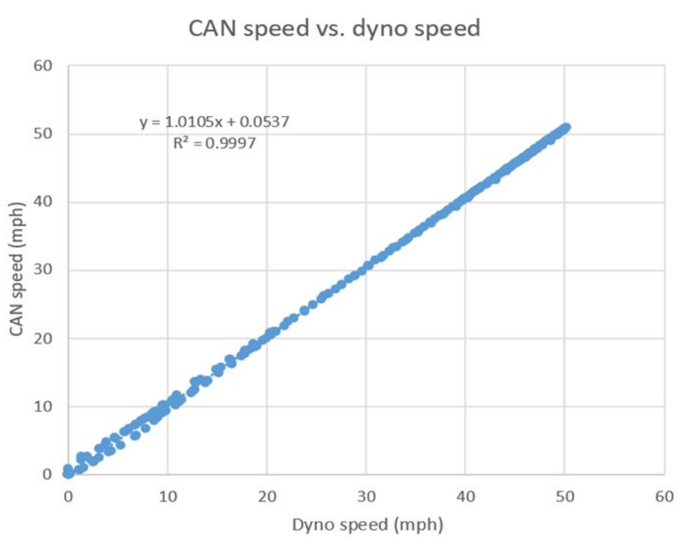
Source: US Hybrid

Figure 39: Speed Comparison Between CAN and Chassis Dyno Measurements



Source: UCR

Figure 40: Correlations Between CAN Speed and Chassis Dyno Measurements

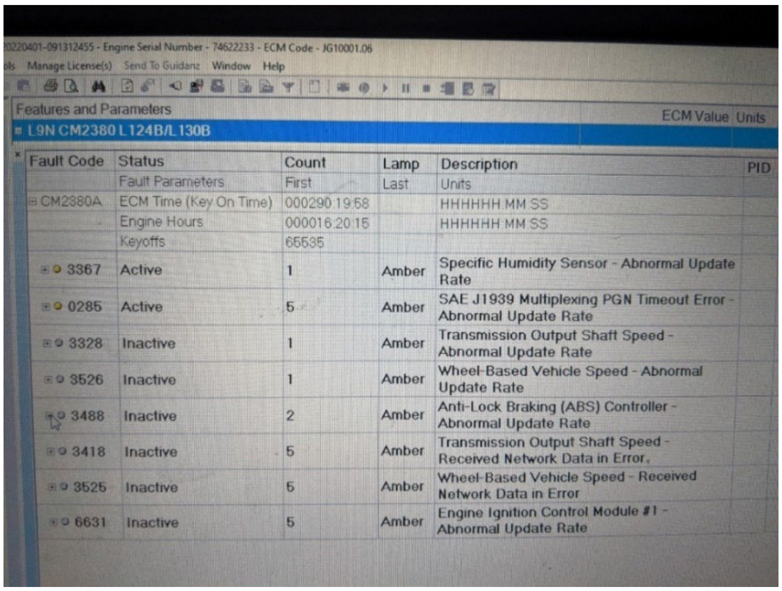


Source: UCR

Specific Humidity Sensor

An active amber fault code was identified for the specific humidity sensor (Figure 41). This fault was investigated with Cummins, and it was unclear if this issue would impact emissions and engine performance. This sensor was fixed with a circuit that was added to the wire harness at CE-CERT. See Figure 42 and Figure 43. Future applications of this engine should integrate the sensor into the OEM wire harness for robust in-use performance.

Figure 41: Summary of Active and Inactive Fault Codes During Emissions Testing

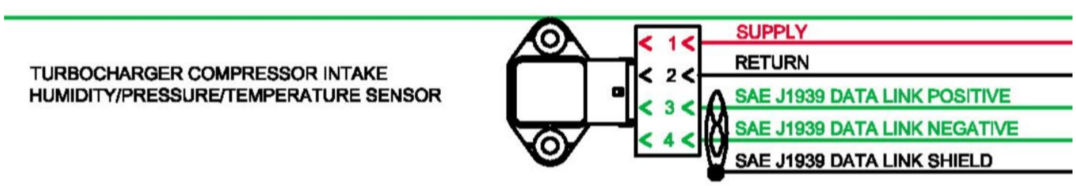


Fault Code	Status	Count	Lamp	Description
	Fault Parameters	First	Last	Units
CM2380A	ECM Time (Key On Time)	000290:19:58		HHHHHH:MM:SS
	Engine Hours	000016:20:15		HHHHHH:MM:SS
	Keyoffs	65535		
3367	Active	1	Amber	Specific Humidity Sensor - Abnormal Update Rate
0285	Active	5	Amber	SAE J1939 Multiplexing PGN Timeout Error - Abnormal Update Rate
3328	Inactive	1	Amber	Transmission Output Shaft Speed - Abnormal Update Rate
3526	Inactive	1	Amber	Wheel-Based Vehicle Speed - Abnormal Update Rate
3488	Inactive	2	Amber	Anti-Lock Braking (ABS) Controller - Abnormal Update Rate
3418	Inactive	5	Amber	Transmission Output Shaft Speed - Received Network Data in Error.
3525	Inactive	5	Amber	Wheel-Based Vehicle Speed - Received Network Data in Error
6631	Inactive	5	Amber	Engine Ignition Control Module #1 - Abnormal Update Rate

Source: UCR

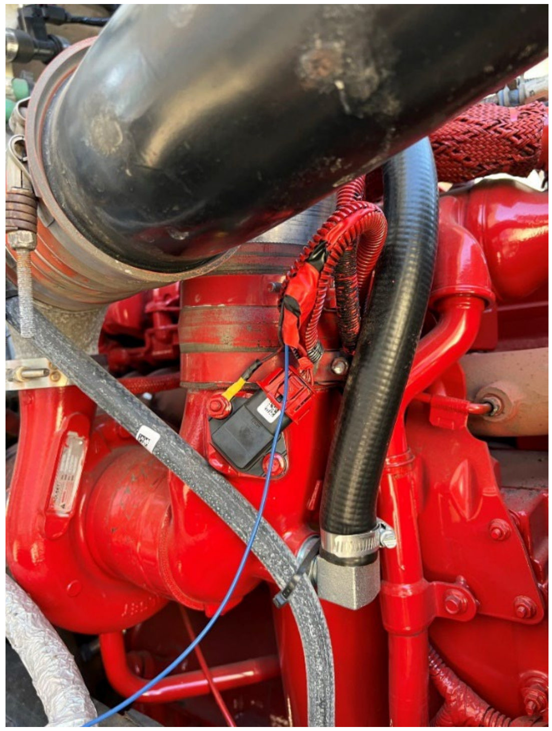
The issue was caused by the missing power harness (pin #25 of a 31-pin OEM connector) for that sensor. Due to the lack of access to the 31-pin OEM connector, a power line was introduced directly to the sensor with a 5-A fuse from the positive terminal, based on the wiring map of this engine, shown here. The current setup for this sensor is shown in Figure 42 and Figure 43. The amber fault was cleared after this wiring, as expected.

Figure 42: Specific Humidity Sensor Connector Line Map



Source: UCR

Figure 43: Powered Specific Humidity Sensor via 12 V Battery



Source: UCR

CHAPTER 3:
Project Results

Control System Verification

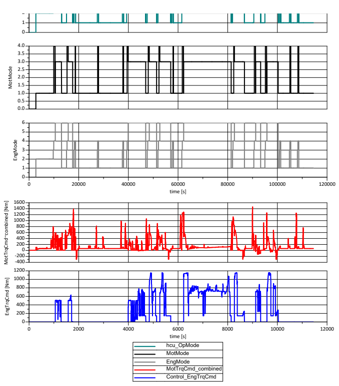
Operating Modes

In Figure 44, the different operating modes transition from OpMode 1, which is E-drive, to OpModes 5 and 6, where the torque split happens. It was observed that until a certain threshold is reached, the system operates in E-drive and all torque demand is fulfilled by the motor. Once power demand increases, the engine is turned on and the torque is split between engine and motor.

OpMode:

1. E-Drive
2. Engine Start
3. Engine Idle
4. SpeedSync
5. PhevDrive TqConv Open
6. PhevDrive TqConv Closed

Figure 44: Operating Mode Plots

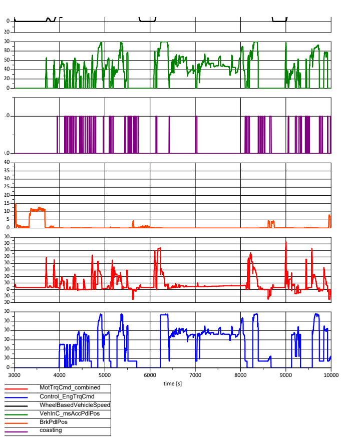


Source: UCR

Coasting and Regeneration

Figure 45 shows the regenerative braking during coasting and braking. Coasting and braking factors were calibrated during the dyno testing to command the maximum possible regenerative braking without causing a transmission fault. Due to lack of control over the transmission and torque converter, regen braking is often limited to below 400 Nm of regen torque. With a higher transmission torque capacity and control over the transmission shifts, regen braking performance could significantly improve.

Figure 45: Coasting and Regeneration Plots

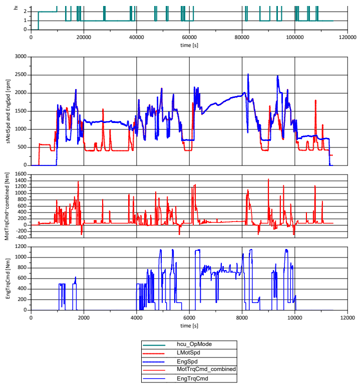


Source: UCR

Torque Command and Speeds

Figure 46 shows the HCU OpModes and corresponding engine torque commands with the motor and engine speeds. Whenever the system is in OpMode 5 or OpMode 6 (which is the actual torque split mode), the engine and the motor torques are split, per the optimization logic. The engine torque command follows the BSFC map to optimize fuel efficiency. During hybrid operation, the motor is supporting the torque demand, keeping the engine speed and torque well below the peak speed limit (3000 rpm) and the torque limit (1461 Nm).

Figure 46: Torque Command and Speed Plots

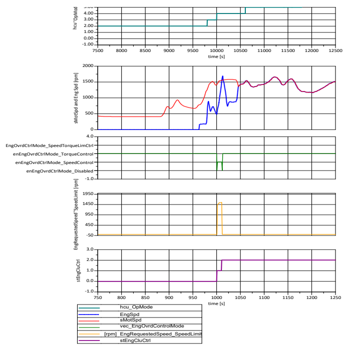


Source: UCR

Engine and Motor Sync - P2 Clutch Closing

Figure 47 describes the speed sync in progress. When the controller is in OpMode 4, the system is in the speed control for the engine. It then requests that the engine speed match the motor speed. Once the speeds are within 100 rpm, the clutch will close. The system starts the torque split once the speeds match.

Figure 47: Engine and Motor Sync Plots

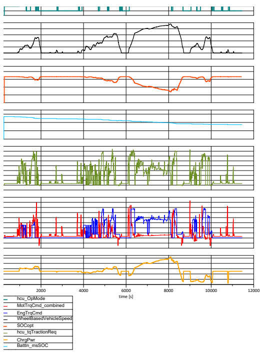


Source: UCR

SOC Opt and Charge Power

Figure 48 shows the SOC Opt (state of charge optimization) and charge power calculations in real time. At high speeds it can be seen that Soc Opt is reducing due to the nature of the function. More power is commanded from the motor so the engine can run at an efficient operating point. When Soc Opt is higher than actual SOC, the charge power is also negative, and the battery needs to be charged. The motor is commanded at negative torque to charge the battery SOC.

Figure 48: SOC Opt and Charge Power Plots

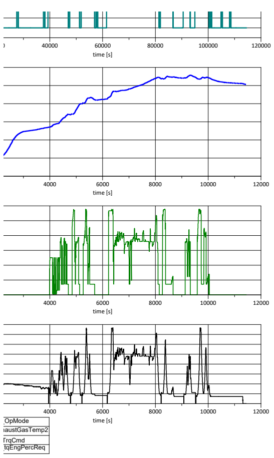


Source: UCR

Cold-Start Torque Split

The cold-start strategy is shown in Figure 49. The engine torque is limited to a threshold (500 nm) until the exhaust gas temperature is above 300°C. Once 300°C is reached, the regular torque split logic is enforced.

Figure 49: Torque Split in Cold-Start Operation



Source: UCR

Control System Verification Summary

Based on the project's control system testing, the team made the following observations:

1. The overall software is behaving close to what was initially intended, considering the system limitations.
2. All the controls features are working and validated.
3. To start in E-drive mode, the motor must first be rotated at >500 rpm to engage the gear in drive. The control logic for this was developed and is validated.
4. Upon testing, it was observed that the engine speed control logic was better than the torque control logic for the P2 clutch-closing speed-sync event. The clutch can be closed in ~5 seconds with speed control.
5. The cold-start strategy is working, and the engine torque is limited until the engine exhaust is heated, which increases NOx reductions.
6. The optimization logic uses the SOC Opt and charge power to command appropriate torques from the engine and motor.

7. The engine can follow the min BSFC curve without limiting the torque at the wheels.
8. The motor can cover any deficit in power by the engine in cases of high torque demand.
9. The optimization logic is working as intended; however, the optimization benefits are limited because certain controls features cannot be used to their fullest extent because of system limitations and unavailability of support from the suppliers. These include:
    a. Transmission – No control over the shifting logic
    b. Not having enough data on transmission torque capacity or the torque converter operation
    c. The P2 clutch does not have feedback or torque control, which results in a longer clutch closing of around 5 to 6 seconds. With both torque control and feedback, the clutch closing time may be reduced to an estimated 2-3 seconds.
    d. Significant lower brake regeneration due to unavailability of the master brake controller
    e. Since the transmission is the standard OEM transmission, torque capacity is low (1461 Nm) when compared with the combined torque capacity of the motor and engine (>2500 Nm).
10. In addition to those listed limitations, it was observed that the optimization for NOx is much better if the engine is kept on for the entire drive cycle and idled when not needed, compared with if the engine is fully stopped when the "engine off" request is present. The fuel-efficiency benefits are certainly reduced, but the NOx reductions are significantly better, so it was a tradeoff. It was ultimately decided to keep the engine idling when it's not needed.

Calibration Results

The calibration optimization focused on an effort to minimize NOx and GHG emissions simultaneously while at the same time maintaining performance. For this approach, various combinations of engine on/off, engine ramp-rate limitations, and torque limits were performed. These are described in the next sections.

Emission Results

Based on calibration test results, there was a clear tradeoff between lowest NOx emissions and GHG emissions while maintaining vehicle performance. The best strategy was to start the engine at the beginning of the test cycle and leave it on for the remainder of the test. In all cases, the highest NOx emissions occurred during the first 30 seconds of an engine restart, presumably because of a low catalyst temperature, thus suggesting it's better to not shut the engine off during a cycle to minimize NOx emissions. In fact, it was determined that the engine starting is the only time when significant NOx emissions were formed. Previously, it was found that rapid accelerations and engine starting caused NOx emissions spikes. The hybrid optimization appears to have removed rapid throttle NOx spikes, but not the engine starting spikes. To minimize NOx emissions, the engine was therefore started once and remained on for the rest of the test cycle. Future approaches for optimizing a CNG hybrid vehicle should include technologies that minimize engine startup emissions such as an electrically heated catalyst. The emission results presented in this report are based on the engine idling strategy.

Gaseous Emissions Over UDDS

Table 3 describes characteristics for each test, including the overall testing conditions, engine work, motor work, energy recycled from regenerative braking and the work measured from the chassis dynamometer. The average total vehicle work was 24.2 bhp-hr where 65 percent came from the engine and 35 percent from the electric motor. This is about 12 percent more work than during previous testing of the same vehicle with the older 0.2 certified engine.[8] The regenerative braking work is included in the electric motor work. The amount of regeneration resulted in approximately 1 percent of the total energy recovered over the 20-minute cycle. The amount of regenerative braking energy recovered is low compared with other all-electric vehicle studies, where energy recovery was demonstrated to range from 6 percent to 15 percent.[9] Thus, more attention on future projects should investigate higher amounts of regeneration to improve GHG reductions.

As discussed in the experimental section, the focus of the emissions testing was on the UDDS test cycle because this cycle resulted in the highest emissions of all the cycles tested previously by CE-CERT.[10,11] To investigate the full range of emissions, three types of starting conditions were performed for the UDDS test cycle. These are the cold-start, hot-start, and semi-hot-start test conditions. The cold-start condition represents a vehicle that was parked or soaking overnight for more than 8 hours. The hot-start condition represents a condition where a fully warmed-up vehicle is turned off (or soaked) for 20 minutes, then started for the next test. The 20-minute soak time is typical for emissions testing during certification and in-use chassis laboratory testing. In addition, a second soak time was incorporated into this study to study the performance of the hybrid system under real-world operations where a 40-minute delivery or 40-minute opportunity charge could be performed.

Table 3: Test Conditions and Works Over UDDS Test Cycles 1

Run ID	Starting Conditions	Soak Time (min)	Engine Work (bhp-hr)	Motor Work (bhp-hr)	Regen Work (bhp-hr)	Total Vehicle Work (bhp-hr)	Dyno Work (bhp-hr)
13	Cold		15.6	9.22	0.28	24.82	17.1
14	Semi hot	~ 40	15.7	8.50	0.28	24.20	17.3

[8] Johnson, K., Miller W., and Manley, T., Optimized Natural Gas Hybrid-Electric Drayage Truck Demonstration. Final Report to CEC Contract Number PIR-13-014, March 2018

[9] Johnson, K. Karavalakis, G., Li C., Ma T., Frederickson, C., and Scora, G., California Air Resources Board Zero and Near Zero Emissions Freight Facility (ZANZEFF) Grant" Final Report to CARB, July 2021. In Press

[10] Li C, Han Y, Jiang Y, Yang J, Karavalakis G, Durbin TD, Johnson K. Emissions from advanced ultra-low NOx heavy-duty natural gas vehicles. SAE Technical Paper 2019; 2019-01-0751.

[11] Zhu H., McCaffery C., Jiang Y, Yang J, Li C., Karavalakis G, Johnson K., Durbin TD, Characterizing emission rates of regulated and unregulated pollutants from two ultra-low NOx CNG heavy-duty vehicles. FUEL 277 (2020) 118192

Run ID	Starting Conditions	Soak Time (min)	Engine Work (bhp-hr)	Motor Work (bhp-hr)	Regen Work (bhp-hr)	Total Vehicle Work (bhp-hr)	Dyno Work (bhp-hr)
15	Semi hot	~ 40	15.6	8.87	0.18	24.47	17.0
16	Semi hot	~ 40	14.5	9.25	0.34	23.75	17.2
17	Hot	20	15.3	7.33	0.34	22.63	16.8
18	Cold		16.5	9.00	0.32	25.5	17.6
19	Hot	20	16.6	7.85	0.36	24.45	17.3
20	Hot	20	16.3	7.50	0.27	23.80	17.4

1 Test weight was set at 69,507 lb which is representative of a Class 8 goods movement truck as discussed in the Approach section.
Source: UCR

NOx Emissions

The NOx emissions are presented in Table 4 for all the UDDS cycles performed. The NOx emissions ranged from 0.003 to 0.032 g/bhp-hr for the hot- and cold-start tests, respectively. These results are 90 percent lower than the previous study on the 0.2 certified vehicle[8] and slightly lower than the 0.02 certified goods movement results tested at UCR[2]. The average NOx emissions for the semi-hot-start and hot-start tests were 0.005 and 0.007 g/bhp-hr, respectively (see Figure 50). The difference between the semi-hot and hot-start NOx emissions were small and not statistically significant based on the t-test p-value of 0.5. This suggests engine restarting soak times up to 40 minutes are similar to soak times of 20 minutes. It was observed during the calibration work that as the soak time is reduced the restart NOx emissions will be minimized if not eliminated. However, we did not quantify this restart time to evaluate what condition would be needed for an emissions-free restart. Future studies should evaluate the needed startup temperature to avoid a NOx emissions spikes and to allow for engine/off operation. In general, the NOx emissions were below the L9N 320 NOx certification standard of 0.02 g/bhp-hr for all tests, and below the in-use NTE standard of 0.030 g/bhp-hr. Emissions below the certification standard have been found by other investigators as well.[4,5]

The startup temperature for the catalyst was 12°C for the cold-start conditions and 300°C for the semi-hot tests, and 415°C for the hot-start tests. It is interesting that the emissions for the semi-hot and hot-start tests were similar even though the catalyst was about 115°C hotter for the hot-start test compared with the semi-hot start test. Keeping the engine idling kept the engine exhaust and ATS hot enough to mitigate any emissions spikes that would have occurred during the reduced transient throttle events designed into this calibration.

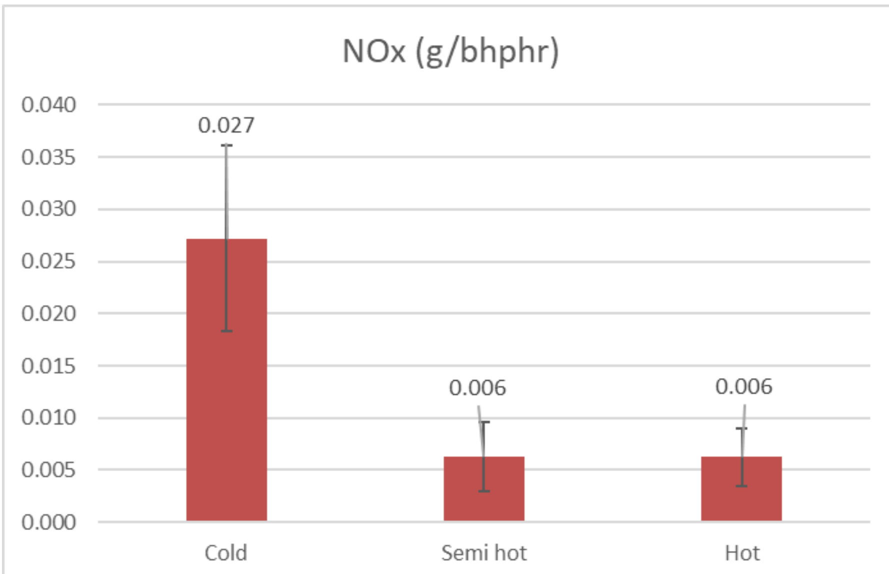
Table 4: Brake Specific NO, NO2 and NOx Emissions and Average After-Treatment System Temperatures

Run ID	Starting Conditions	Soak Time	kNO g/bhp-hr	kNO2 g/bhp-hr	kNOx g/bhp-hr	After treatment temperature (C)
13	Cold	-	0.036	0.0003	0.036	12

18	Cold	-	0.015	0.0029	0.018	12
14	Semi hot	~ 40	0.004	0.0001	0.004	285
15	Semi hot	~ 40	0.005	0.0063	0.011	313
16	Semi hot	~ 40	0.003	0.0003	0.004	303
17	Hot	20	0.005	0.0041	0.010	403
19	Hot	20	0.003	0.0002	0.003	411
20	Hot	20	0.006	0.0003	0.006	433

Source: UCR

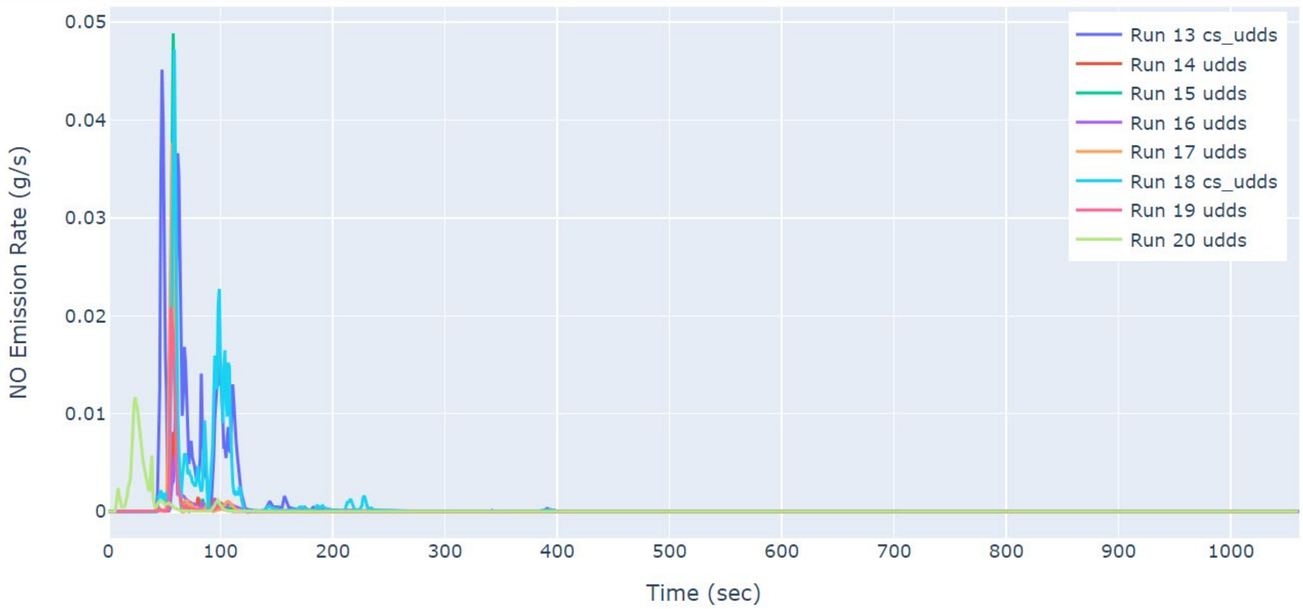
Figure 50: Brake Specific NO Emissions for Cold-Start, Semi-Cold Start, and Hot-Start



Source: UCR

Figure 51 shows the real time NO emission rates for all UDDS tests. The majority (>99 percent) of the NOx emissions occurred during the first 100 to 150 seconds after engine ignition, for all tests. For the hot-start tests, the NOx spike was narrower and occurred within the first 30 seconds. For the cold-start tests there were two peaks, one at engine starting and one at the start of the first hill of the test cycle. For the hot-start Test Run 20, early engine ignition was applied, where the engine ignited at the same time the cycle started, to investigate the impact of engine step-in timing. The early start reduced the peak of NO emissions yet caused a longer duration of the emissions event. In the end, the result of this test led to relatively higher NO emissions compared with other hot-start tests.

Figure 51: Real-Time NO Emissions for all Final Tests



Source: UCR

Other Gaseous Emissions

The CO_2, CO and CH4 emissions are summarized in Table 5. The CO emissions were 90 percent lower than the 0.2 certified hybrid tests,[8] but about the same as the 0.02 certified chassis tests performed at UCR.[1,2] The THC emissions were similar to both other studies.[4,5,8] The CO_2 emissions were significantly lower in comparison with both the previous hybrid CNG testing[8] and the conventional CNG vehicle testing.[4,5] The average hot and semi-hot start CO_2 emissions were 351.5 g/bhp-hr, which is a reduction of 34 percent and 38 percent compared with previous tests with similar test weights,[5,8] respectively. The 34 percent reduction in CO_2 compared with the other studies may be a result of the energy utilized from the electric motor, which averaged 45 percent for the UDDS test cycle.

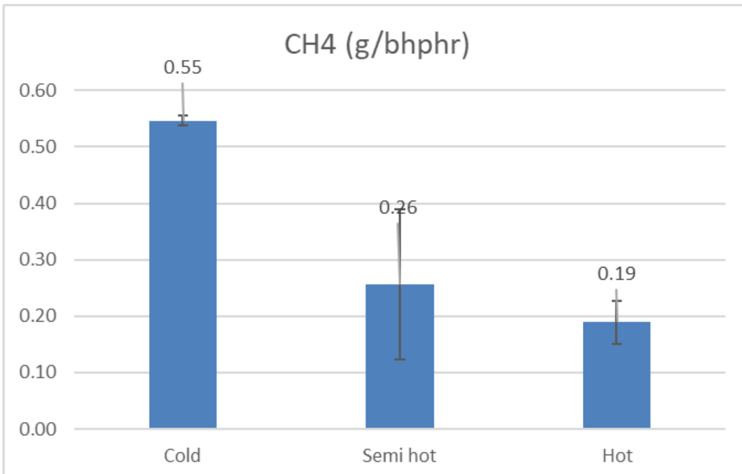
Table 5: Other Gaseous Brake Specific Emissions for Final Tests

Run ID	Starting Conditions	Soak Time	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	CH4 (g/bhp-hr)
13	Cold	-	344.1	2.57	0.54
18	Cold	-	334.5	1.66	0.55
14	Semi hot	~ 40	338.2	1.14	0.38
15	Semi hot	~ 40	329.9	1.07	0.31
16	Semi hot	~ 40	326.1	1.10	0.07
17	Hot	20	333.8	0.95	0.24
19	Hot	20	321.2	0.92	0.19
20	Hot	20	329.6	1.00	0.14

Source: UCR

Since the engine is burning a CNG fuel, the THC and CH_4 emissions are similar; only CH_4 is presented here. The CH_4 emissions are presented in Figure 52. The CH_4 emissions are highest for the cold-start tests when compared with the hot-start tests. For all the hot tests the CH_4 was below the standard and similar to previous testing of a conventional CNG low-NOx engine,[5] and much lower (0.5 vs 2.5 for the UDDS cycle) than the work presented in the previous CEC study (with the same vehicle and older ISL G CNG engine[8]).

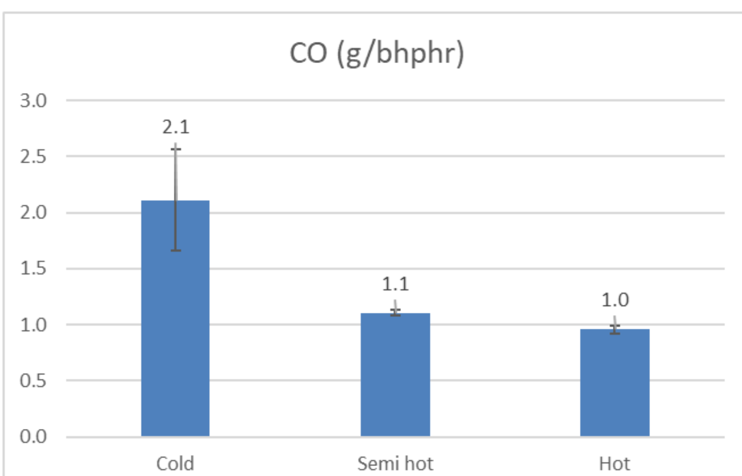
Figure 52: Brake Specific CH4 Emissions for Cold-Start, Semi-Cold Start, and Hot-Start Tests



Source: UCR

Figure 53 shows the CO emissions on a g/bhp-hr basis. The CO emissions average 2.1 g/bhp-hr for the cold-start UDDS test cycles. The CO emissions were 1.1 to 1.0 g/bhp-hr for the semi-hot and hot-start UDDS test cycles. The CO emissions are similar to the work reported on other studies with the low-NOx CNG engine,[5] and about eight times lower compared with this same vehicle but with the older ISL G CNG engine.[8]

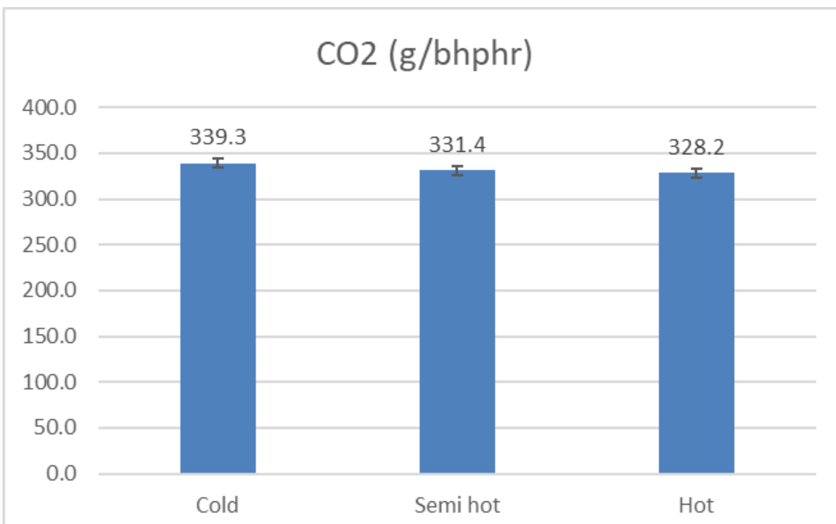
Figure 53: Brake Specific CO Emissions for Cold-Start, Semi-Cold Start, and Hot-Start Tests



Source: UCR

Figure 54 shows CO_2 emissions were close to each other for the different condition of the UDDS test cycles. The CO_2 emissions ranged from 339 to 328 g/bhp-hr for the different tests. The CO_2 emissions were lowest for the hot-start tests compared with the cold-start test, which was expected since extra fuel was used to start a cold engine. CO_2 emissions are regulated by the United States Environmental Protection Agency (U.S. EPA), with the FTP and SET test cycles. The FTP certification engine test is similar to the chassis UDDS test. The CO_2 standard and family emission limits (FEL) values are 576 g/bhp-hr and 490 g/bhp-hr respectively for this displacement engine. See Appendix A. The standard is the target value, and the FEL values are the values the manufacturer targets to stay under them. The chassis UDDS test showed the lowest CO_2 emissions were below 576 g/bhp-hr (FTP standard) and below the certified FEL value (490 g/bhp-rh) reported by the manufacturer. Vehicle CO_2 emissions varied slightly between different conditions where only the cold-start tests showed a statistically higher CO_2 emission rates. It is suggested that the low-CO_2 emission rate could be a result of the support from the electric motor, which demonstrates the improvement in fuel efficiency from the hybrid system. The CO_2 emissions are 46 percent lower when compared with the previous work reported in the CEC study,[8] and 40 percent lower than the previous chassis study at UCR5.

Figure 54: Brake Specific CO Emissions for Cold-Start, Semi-Cold Start, and Hot-Start Tests

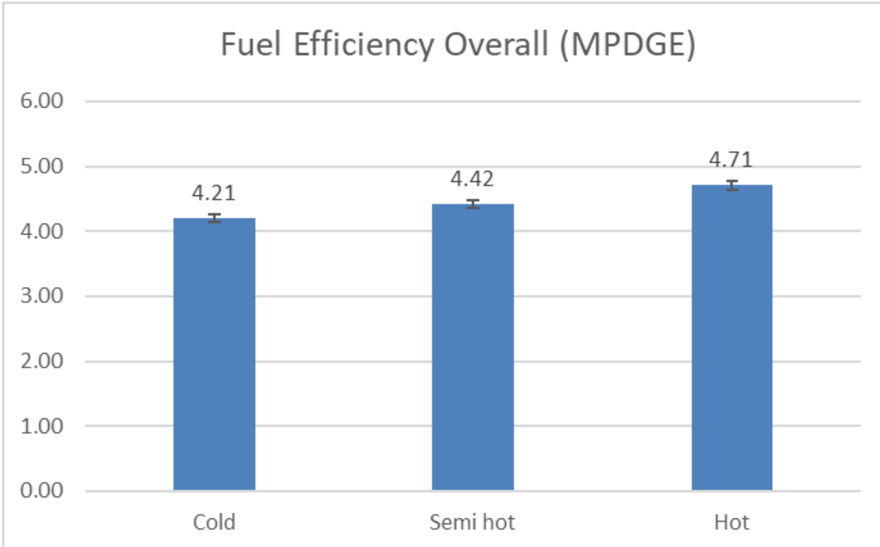


Source: UCR

Fuel Economy

The vehicle mpg on a diesel gallon equivalent (MPG_{de}) basis showed 4.7 mpg_{de} for the hot-UDDS. Previous testing with this engine was based on a lighter test weight of 56,000 lb versus the test weight in this study (69,500 lb), so a direct comparison on a mpg basis is not possible. As such, during the previous ISL G-NZ testing, fuel economy was found to range from 4.5 mpg_{de} (with 25 percent less payload) for the regional port cycle (DPT3) to 2.5 mpg_{de} for the CBD cycle, with a test weight of 56,000 GVW.[8] The Class 8 goods movement 0.02 certified engine CNG truck tested by UCR with a test weight of 69,500 lb showed a UDDS fuel economy of 3 mpg_{de}[5] which is 36 percent lower than the hybrid tested in this study.

Figure 55: Fuel Economy for Cold-Start, Semi-Cold-Start, and Hot-Start Tests



Source: UCR

Estimating Real World NOx Emissions

Real world vehicle operation can range from 4 hours to more than 12 hours with multiple shifts. Laboratory testing with test cycles represents a snippet of data of typically around 20 minutes long, similar to the UDDS test cycle. For this project, 99 percent of the emissions occurred in the first 150 seconds for the cold-start test and within the first 30 seconds of a hot-start test. The true real-world emissions of this hybrid vehicle would be much lower than what was reported and would be proportional to the cold- and hot-start emissions weighted with different durations. This section was added to estimate the real-world emissions impact from the hybridized CNG vehicle. It should be noted that this evaluation would not benefit conventional 0.02 CNG trucks since those trucks all demonstrated large emissions spikes from rapid throttle events in addition to engine start spikes.[12,13]

The approach to estimating real-world NOx emissions first requires breaking up the UDDS emissions into phases and determining the emissions for each phase, then taking those emissions contributions and extending that with a distance-weighting function for real-world driving cycles. The emissions are recombined and compared to quantify the real-world NOx emission factor estimate. This section describes the details of the estimation and a summary of the results.

Phase Determination

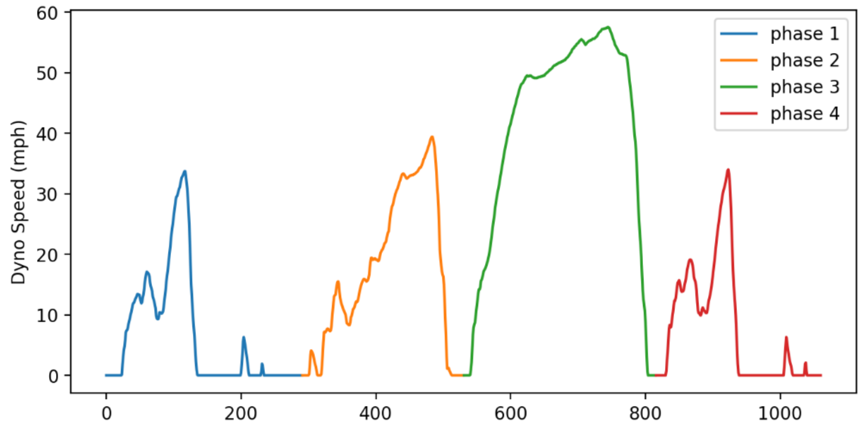
To estimate the real-world NOx emissions, the NOx emissions were analyzed at a higher resolution, where the UDDS cycle was divided into four phases, as shown in Figure 56. These phases were selected to represent the cold-or hot-start condition (Phase 1, then Phase 2 and

[12] Li C, Han Y, Jiang Y, Yang J, Karavalakis G, Durbin TD, Johnson K. Emissions from advanced ultra-low NOx heavy-duty natural gas vehicles. SAE Technical Paper 2019; 2019-01-0751.

[13] Zhu H., McCaffery C., Jiang Y, Yang J, Li C., Karavalakis G, Johnson K., Durbin TD, Characterizing emission rates of regulated and unregulated pollutants from two ultra-low NOx CNG heavy-duty vehicles. FUEL 277 (2020) 118192.

Phase 3) to represent higher speed operation, and Phase 4 to represent Phase 1, but without the engine cranking emissions.

Figure 56: Speed Trace of Components from UDDS, Divided into 4 Phases



Source: UCR

Phased NOx emissions were summarized and presented in Table 6. For all the runs, more than 99 percent of total NOx emissions were identified during Phase 1 (blue part of Figure 56), where the engine was started. Detailed NO emissions, with mass fractions for each phase, are reported in Table 7. The remaining emissions were spread out over phases 2, 3, and 4. This suggests that any real-world test cycle is really composed of the emissions based on the number of times the current calibrated truck is started; once for the cold-start and then for the number of hot starts. Real world operation includes one cold-start a day and a range of hot starts representative of goods delivered.

The repeatability of the engine and motor work for each phase is presented in Figure 57. This figure shows that the variation in engine work and motor work is similar for each test, spread out across the different phases. For Phase 1, there are slightly different fractions of engine work compared to those from other phases, yet those variations could be a result of cold-start versus hot-start conditions. The consistent work is useful in allowing extension of the emissions factors from the phases to in-use, real-world test conditions.

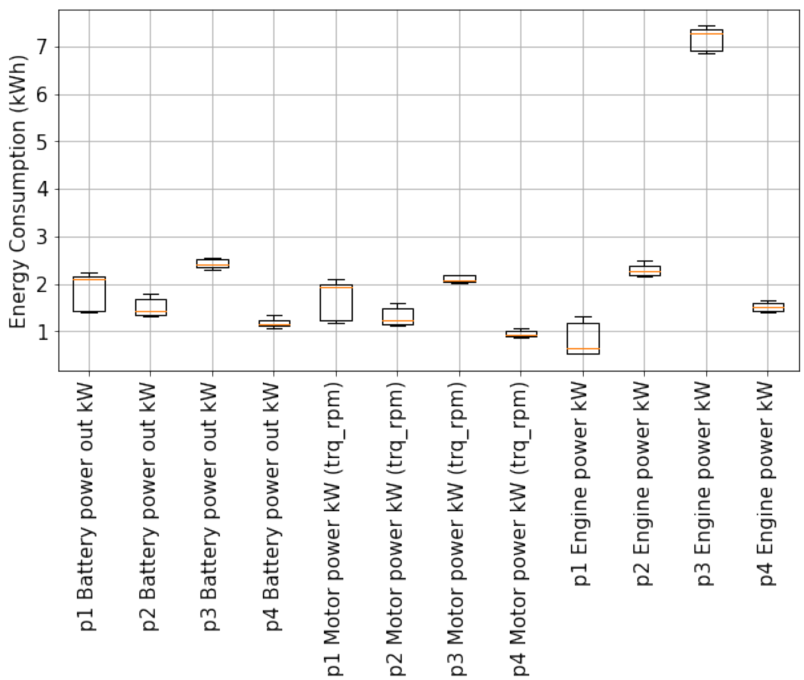
Table 6: NO Mass for Each Phase

Run ID	Starting Conditions	Soak Time	Phase 1 NO mass (mg)	Phase 2 NO mass (mg)	Phase 3 NO mass (mg)	Phase 4 NO mass (mg)
13	Cold		782.1	3.50	3.69	2.21
14	Semi hot	~ 40	76.1	0.03	0.03	0.08
15	Semi hot	~ 40	229.3	0.26	0.06	0.23
16	Semi hot	~ 40	70.8	0.20	0.02	0.01
17	Hot	20	212.0	0.85	0.02	0.15
18	Cold		608.8	3.15	0.69	0.61

Run ID	Starting Conditions	Soak Time	Phase 1 NO mass (mg)	Phase 2 NO mass (mg)	Phase 3 NO mass (mg)	Phase 4 NO mass (mg)
19	Hot	20	114.2	0.39	0.15	0.11
20	Hot	20	170.0	0.06	0.00	0.00

Source: UCR

Figure 57: Phased Battery Work, Motor Work, and Engine Work for All Final Tests



Source: UCR

Table 7: NO Mass Fractions for Each Phase

Run ID	Starting Conditions	Soak Time	Phase 1 NO mass %	Phase 2 NO mass %	Phase 3 NO mass %	Phase 4 NO mass %
13	Cold		98.82%	0.44%	0.47%	0.28%
14	Semi hot	~ 40	99.82%	0.04%	0.04%	0.10%
15	Semi hot	~ 40	99.76%	0.12%	0.03%	0.10%
16	Semi hot	~ 40	99.67%	0.28%	0.03%	0.02%
17	Hot	20	99.53%	0.40%	0.01%	0.07%
18	Cold		99.28%	0.51%	0.11%	0.10%
19	Hot	20	99.43%	0.34%	0.13%	0.10%
20	Hot	20	99.96%	0.04%	0.00%	0.00%

Source: UCR

Real World Routes

Four real-world in-use routes were selected representing real service industries such as grocery distribution, drayage operations, and goods movement. The chosen routes are representative of typical goods movement operations, which include long stops at deliveries, changes in elevation to deliver goods on long (yet regional) pulls, and a mix of stop and go traffic with some cruise conditions. In addition to the four identified routes, "loading-unloading" areas were identified where vehicle stoppage for loading and unloading of goods was simulated. These routes were designed and utilized by a parallel multi-year study of in-use emissions of 200 heavy-duty vehicles sponsored by SCAQMD, CARB, and CEC (200 vehicle study).[14]

This simulation represented the time of engine shutdown during the "loading-unloading" process and not the change in weight of the test vehicle, which is similar to how the study was performed for the 200-vehicle study. The combined weight of the trailer plus the mobile emissions laboratory is typically in the range of 65,000 lbs. There may be variations in the combined weight of the trailer and the transportable emissions measurement system due to the trailer cab configuration (sleeper versus day cab). A summary of basic information about the test routes is provided in in Table 8. The grocery route includes up to four stops and the port and goods movement routes have one stop while the highway route has zero stops.

Table 8: Four Real-World Routes Characteristics

Routes	Stops	Distance (miles)	Time (hours)	Average Speed (mph)
Grocery Distribution route	4	177.8	6.74	26.4
Port-Drayage route	1	156.7	6.56	23.9
Goods Movement with Elevation Change route	1	109.8	3.12	35.2
Highway Goods Movement route	0	176.0	4.63	38.0

Source: UCR

UDDS Weighting Fractions

Based on the results from previous sections, a new evaluation was applied to estimate NOx emissions of typical operations in the real world. Here, two approaches were applied, one is distance-based and the other is time-based.

Ratios of total distance between real-world routes and the UDDS route were calculated and applied as multipliers of NO emissions and vehicle output work. Thus, the ratio between the distance of the four real-world routes and those of UDDS can be added up to simulate the real-world routes. Ratios are summarized in Table 9, along with the stop numbers for each route. Each route included one cold-start to simulate the actual fleet operations. For each stop

[14] Leonard, Jonathan; Couch, Patrick; Durbin, Thomas; Besch, Marc; Cao, Tanfeng; 2022. "In Use Emissions Testing and Activity Profiles for On-Road Heavy-Duty Engines: Summary of 200 Heavy-Duty Vehicle Emissions Testing Program from the University of California, Riverside and West Virginia University." California Energy Commission. Publication Number: CEC-500-2023-002.

along the routes, the assumption was made that there will be a 30-minute engine off for each stop to simulate loading and unloading operations, which can be well presented by the hot-start assumption.

Table 9: Distance-Base and Time-Base Ratios Between Real-World Routes and UDDS

Routes	Stops	Cold Start #	Hot Start #	Distance Ratio
Grocery Distribution route	4	1	4	**32.0**
Port-Drayage route	1	1	1	**28.2**
Goods Movement with Elevation Change route	1	1	1	**19.8**
Highway Goods Movement route	0	1	0	**31.7**

Source: UCR

Real-World Emissions Estimates

The four simulated real-world emissions are shown in. For all cases, the NO emissions are lower than the NO emissions from the UDDS test cycle, and ranged from 0.0018 to 0.0009 g/bhp-hr. The emissions were highest for the grocery route where the vehicle was stopped and started four times and lowest for the route that didn't have a restart. If the start-stop emissions could be eliminated with advanced technologies, the CNG hybrid vehicle could achieve emissions below 0.001 g/bhp-hr, as suggested in the previous CEC study.[8]

Table 10: Simulated NO Emissions Based on UDDS Test Results

Routes	Distance-based Warm Running #	NO emission rate (g/bhp-hr)
Grocery Distribution route	27.0	**0.0018**
Port-Drayage route	26.2	**0.0013**
Goods Movement with Elevation Change route	17.8	**0.0018**
Highway Goods Movement route	30.7	**0.0009**

Source: UCR

Summary

In summary, the UDDS emissions averaged 0.006 g/bhp-hr for the hot-start tests and 0.028 g/bhp-hr for the cold-start tests. When the results from this study are utilized based on real-world driving, as demonstrated during the 200 vehicle study,[16] the UDDS cold-start, warm-start, and hot-running emissions average about 2.3 mg/bhp-hr (0.002 g/bhp-hr). This very low NOx emission rate meets the expectations of a hybrid CNG engine optimized for minimizing rapid torque loads, as found during previous studies of conventional CNG trucks. Future hybrid optimizations should include management of cold-start and hot-start strategies. These optimizations (optimization of conventional start-stop, use of high-speed start-stop utilizing an integrated traction motor, optimized thermal management of catalyst, use of electric catalyst heater, and optimized transmission shift schedules) may even further reduce NOx emissions. The individual impacts of optimizations mentioned here are not well understood, and they may not be cumulative but rather require tradeoffs, so more research is needed to quantify these opportunities. The team estimates that a solution for hot- and cold-start emission spikes would also allow engine shutdowns, offering CO_2 emissions reductions of up to 14 percent (the NOx spikes during start-stop events prevented attainment of potential CO_2 benefits from start-stop).

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Production Readiness Assessment

Since the focus of this project was on optimization of the control system, the team did not perform an assessment of production readiness of the vehicle or power train hardware. Previous work suggests an approximate cost of the hybrid vehicle at $330,000.[15] However, the last five years have shown significant reductions in the cost of battery packs, electric motors, and power electronics, so the team anticipates the cost of the vehicle to be under $300,000.

The control system for this project was developed as a proof-of-concept in a rapid prototyping environment; however, the FEV team estimates that bringing this technology to serial production would require the following effort:

- Develop a Production-Ready Controller with Base Software
  - Production controller cost (one controller = $10-15k)
  - Base software ~ 3000 hours
  - Hardware costs, vary with vehicle volume
- Complete System and Compliance Requirements and Validation
  - 6 fulltime employees (FTE) for 5-6 months for requirement definition, implementation, and validation
- Conduct Functional Safety and Design Failure Mode Effects Analysis (DFMEA)
  - 5 FTE for 6 months for requirement definition
  - 3 FTE for 4 months of controls implementation and testing
- Provide compliance support for the power train to OEMs and suppliers
- Conduct HIL Testing and Powertrain Calibration Including Drivability and Validation
  - 5 FTE for 6 months

[15] Manley, Tyler. Kent Johnson, and Wayne Miller. 2021. Optimized Natural Gas Hybrid-Electric Drayage Truck Demonstration. California Energy Commission. Publication number: CEC-500-2021-054. https://www.energy.ca.gov/publications/2021/optimized-natural-gas-hybrid-electric-drayage-truck-demonstration

Technology/Knowledge Transfer

The team shared project findings in the following forums.

- Natural Gas Vehicle Technology Forum led by the National Renewable Energy Laboratory (NREL) in partnership with the United States Department of Energy (DOE) and the California Energy Commission (CEC)
- Utilization Technology Development (UTD) Technology Project Committee. UTD is a not-for-profit scientific research organization comprised of 20 gas distribution company members who direct a program of near-term applied research to develop, test, and demonstrate safe, energy efficient, environmentally friendly, and cost-effective end-use technologies that benefit their more than 37 million gas customers in North America, in collaboration with many partners.
- NGV America Annual Conference. NGV Conference is the only dedicated natural gas transportation alternative fuels conference focused on the North American market. On road, off road and everything in between will be featured, from traditional freight, refuse, and transit applications to growing marine, rail, and construction use.
- Coordinating Research Council (CRC) Real World Emissions workshop

Future knowledge transfer opportunities include presenting findings at Clean Cities Coalitions forums and events related to alternative fuels.

CHAPTER 5: Conclusions/Recommendations

This project demonstrated that a properly optimized heavy-duty truck using a CNG hybrid-electric power train can achieve extremely low emissions of all criteria pollutants (especially NOx and PM, which are associated with detrimental health effects) while also delivering substantially improved fuel efficiency and CO_2 reductions. If the truck is fueled with renewable natural gas (RNG), net CO_2 emissions are further reduced. Vehicles that adopt this technology will therefore come closer to achieving net-zero emissions from all regulated pollutants.

The UDDS NOx emissions varied from 0.003 to 0.032 g/bhp-hr for hot- and cold-start emissions during laboratory testing. Since more than 99 percent of the emissions resulted from the cold-start and warm-start conditions, the project team used these results to estimate real world emissions from a recent in-use study funded by the CEC 200 Vehicle Study, where four routes were performed representing goods and drayage operations. In-use estimated hybrid CNG engine emissions based on these real-world drive conditions are estimated at 2.3 mg/bhp-hr (0.002 g/bhp-hr). This very low NOx emission rate meets the expectations of a hybrid CNG engine optimized for minimizing rapid torque loads found during previous studies of conventional CNG trucks. Future hybrid optimizations could include management of cold-start and hot-start strategies, such as an electrically heated catalyst. These cold-start optimizations would further reduce NOx emissions, perhaps even by another order of magnitude (0.2 mg/bhp-hr). In addition, a solution for hot- and cold-start emissions would allow engine shutdowns, thus reducing CO_2 emissions even further.

The fuel economy for the optimized truck was 4.7 mpg_{de} for the hot UDDS, where previous testing of a conventional truck on the same test cycle and test weight showed a fuel economy of 3 mpg_{de},[5] which is 36 percent lower than the hybrid tested in this study. Fuel economy can also be reported as CO_2, which was reduced by 40 percent in this optimization and was 40 percent lower than a conventional CNG truck equipped with a low-NOx engine. Methane emissions, which contribute to GHGs, were reduced by five times when compared with the non-optimized CNG hybrid engine, due in part to both the updated engine and optimized control calibration.

The other gaseous and PM emissions were similar to the work reported during other studies at UCR but were as much as eight times lower when compared with the older non-optimized truck with the 2010 certified ISL G CNG engine.

CHAPTER 6:
Benefits to Ratepayers

The CEC's ratepayer funded Gas Research and Development Program has supported previous projects to develop and demonstrate low NOx CNG engines, with the goal of certifying to the 0.02 g/bhp-hr standard. Since the conclusion of some of these projects, engine manufacturers such as Cummins Inc., have released commercial products and 0.02 g/bhp-hr certified CNG heavy-duty vehicles have been successfully deployed in California. Parallel studies have shown that in-use performance of 0.02 g/bhp-hr certified technology can limit real world emission reductions depending on operational characteristics such as idling time and duty cycles.[16] This project built on these past efforts by investigating the potential role of hybrid-electric power trains in further reducing in-use emissions. Specifically, the project developed optimized CNG hybrid electric vehicle controls to further reduce in-use NOx emissions beyond the 0.02 g/bhp-hr level. If widely deployed, this technology can contribute to reduced ozone concentrations in ambient air and improve public health. Additionally, the hybridization technology enabled a fuel economy improvement of 40 percent, reducing CO_2 emissions by 40 percent.

[16] Leonard, Jonathan; Couch, Patrick; Durbin, Thomas; Besch, Marc; Cao, Tanfeng; 2022. "In Use Emissions Testing and Activity Profiles for On-Road Heavy-Duty Engines: Summary of 200 Heavy-Duty Vehicle Emissions Testing Program from the University of California, Riverside and West Virginia University." California Energy Commission. Publication Number: CEC-500-2023-002. https://www.energy.ca.gov/sites/default/files/2023-03/CEC-500-2023-002.pdf

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ADC	Analog-to-Digital Converter
ATS	Aftertreatment System
BSFC	Brake Specific Fuel Consumption
CAC	Charge Air Cooler
CAN	Controller Area Network
CARB	California Air Resources Board
CBD	Central Business District
CEC	California Energy Commission
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
CVS	Constant Volume Sampler
CWI	Cummins Westport, Inc.
DE	Diesel Equivalent
DFMEA	Design Failure Mode and Effect Analysis
DGE	Diesel Gallon Equivalent
ECM	Engine Control Module
EEPS	Engine Exhaust Particle Sampler
ERDD	Energy Research and Development
FEL	Family Emissions Limit
FEV	German-based automotive and energy consulting company
FID/HFID	Flame Ionization Detector/Heated Flame Ionization Detector
FTE	Full Time Equivalent
FTP	Federal Test Procedure
GFO	Grant Funding Opportunity
GHG	Greenhouse Gases
GTI	Gas Technology Institute (former name of GTI Energy)
HCU	Hybrid Control Unit
HP	Horsepower
HV	Hybrid Vehicle
I/O	Input-Output
LHV	Lower Heating Value

Term	Definition
Li-NMC	Lithium – Nickel, Manganese, Cobalt – Elements used in batteries
LNG	Liquified Natural Gas
LSD	Low Sulfur Diesel
MEL	Mobile Emissions Laboratory
MPG	Miles Per Gallon
NDIR	Non-Dispersive Infrared
NG	Natural Gas
NMHC	Non-Methane Hydrocarbons
NOx	Nitrogen Oxide/Oxides of nitrogen
NTE	Not-to-Exceed
NZE	Near-Zero Emissions
OBD	On-Board Diagnostics
PCV	Positive Crankcase Ventilation
PEMS	Portable Emissions Monitoring System
PHEV	Prototype Hybrid Electric Vehicle
PM	Particulate Matter
PN	Particle Number
PSD	Particle Size Distribution
SOC	State of Charge
THC	Total Hydrocarbons
UCR	University of California at Riverside
UDDS	Urban Dynamometer Driving Schedule
UTD	Utilization Technology Development
VCU	Vehicle Control Unit

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ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Engine Certification Data, Labels, and Upgrades

February 2024 | CEC-500-2024-005

APPENDIX A:
Engine Certification Data, Labels, and Upgrades

This appendix includes the Cummins, Inc. L9N engine's executive order Figure A-1 as listed on the CARB website.[17]

Figure A-1: Emissions Certification Levels for CNG Engine Onboard

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.02	0.02	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.01	0.000	0.01	0.004	*	*	1.5	0.3	0.002	0.000	*	*
NTE	0.21		0.03		*		19.4		0.02		*	

4 g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET= Supplemental emissions testing; NTE=Not-to-Exceed; STD=standard or emission test cap; FEL=family emission limit; CERT=certification level; NMHC/HC=non-methane/hydrocarbon; NOx=oxides of nitrogen; CO=carbon monoxide; PM=particulate matter; HCHO=formaldehyde

in g/bhp-hr	EPA CERTIFICATE OF CONFORMITY LCEXH0540LBL-004		PRIMARY INTENDED SERVICE CLASS TRACTOR / VOCATIONAL	
	CO_2		CH_4	N_2O
	FTP	SET		
STD	576	487	0.10	0.10
FCL	476	418	*	*
FEL	490	431	0.65	0.10
CERT	465	414	0.56	0.02

4 g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET=Supplemental emissions testing; STD = standard or emission test cap; FEL=family emission limit; FCL=family certification level; CERT=certification level; CO_2=carbon dioxide; CH_4=methane; N_2O=nitrous oxide; VOCATIONAL=vocational engine; TRACTOR=tractor engine

Source: CARB

[17] California Air Resources Board. Executive Order A-021-0713. https://ww2.arb.ca.gov/sites/default/files/classic/msprog/onroad/cert/mdehdehdv/2020/cummins_mhdd_a0210713_8d9_0d02_ng.pdf

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: Test Cycle Descriptions

February 2024 | CEC-500-2024-005

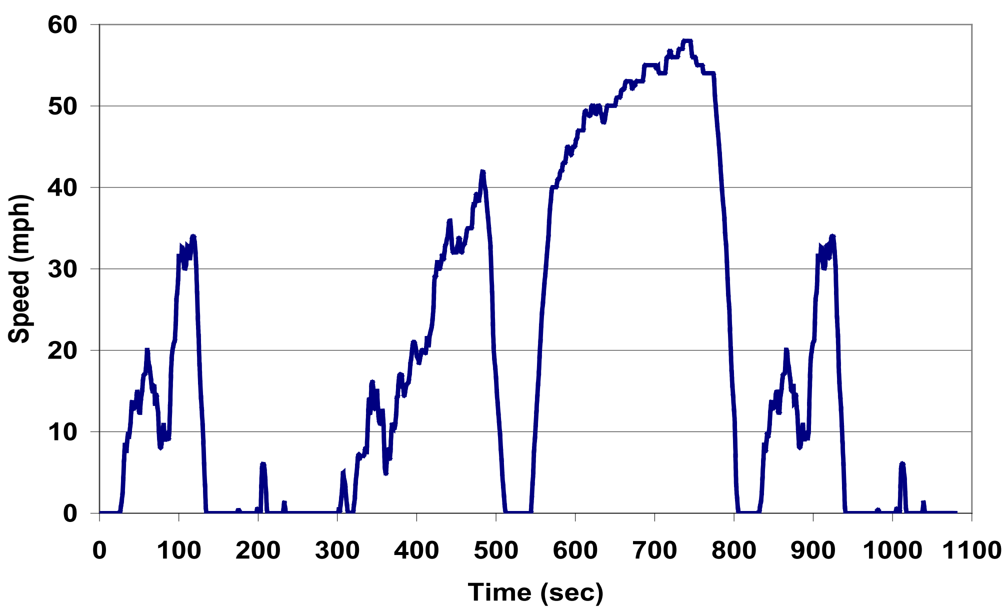
APPENDIX B:
Test Cycle Descriptions

This appendix lists the different test cycles typically performed on heavy duty trucks that operate with a conventional 8.9-liter engine and shows how it compares with a 12-liter goods movement truck.

Urban Dynamometer Driving Schedule (UDDS)

The Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel trucks. This cycle covers 5.55 miles with an average speed of 18.8 mph, sample time of 1061 seconds, and maximum speed of 58 mph. The 1x speed/time trace for the UDDS is provided below in Figure B-1.

Figure B-1: UDDS Speed Trace



Source: UCR

Drayage Truck Port (DTP)

TIAX, the Port of Long Beach, and the Port of Los Angeles developed the port cycle. Over 1,000 Class 8 drayage trucks at these ports were data-logged for trips over a four-week period in 2010. Five modes were identified based on several driving behaviors: average speed, maximum speed, energy per mile, distance, and number of stops. These behaviors are associated with different driving conditions such as queuing or on-dock movement, near-dock, local or regional movement, and highway movements (see Table B-1 for the phases). The data was compiled and analyzed to generate a best-fit trip (combination of phases). The best-fit trip data was then additionally filtered (eliminating accelerations over 6 mph/s) to allow operation on a chassis dynamometer.

The final driving schedule is called the drayage port truck (DPT) cycle and is represented by 3 modes where each mode has three phases to best represent near-dock, local, and regional driving as shown in Tables B-1 and B-2 and Figure B-2. The near-dock (DTP-1) cycle is composed of phase 1, 2, and 3a from Table B-1. This gives the complete near-dock cycle listed in Table B-2. Similarly, for the Local and Regional cycles (DPT-2 and DPT-3) the main difference is phase 3, which changes to 4 and 5 respectively. Phases 1 and 2 remain the same for all three cycles where creep and low speed transients are considered common for all the port cycles. For this testing it is recommended to perform phase 1 through 5 individually and to calculate the weighted emissions from the combined phases for an overall weighing impact. They will be performed in order from 1, 2, 3, 4, and 5.

Table B-1: Drayage Truck Port Cycle by Phases

Description	Phase #	Distance mi	Ave Speed mph	Max Speed mph	Cycle length
Creep	1	0.0274	0.295	4.80	335
low speed transient	2	0.592	2.67	16.8	798
short high speed transient	3	4.99	9.39	40.6	1913
Long high speed transient	4	8.09	13.07	46.4	2229
High speed cruise	5	24.6	35.04	59.3	2528

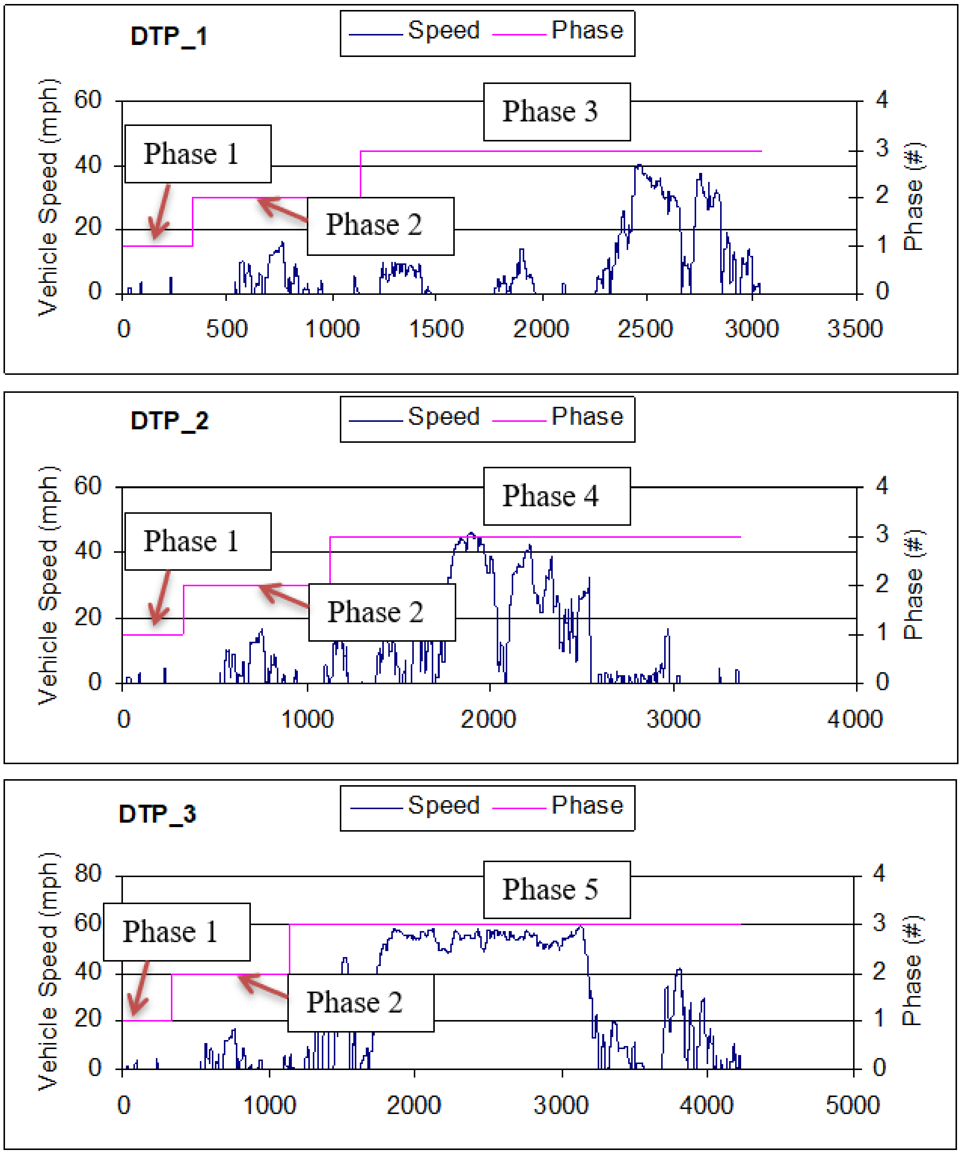
Source: UCR

Table B-2: Drayage Truck Port Cycle by Mode and Phases

Description	Distance mi	Ave Speed mph	Max Speed mph	Mode 1	Mode 2	Mode 3
Near-dock PDT1	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient
Local PDT2	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient
Regional PDT3	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise

Source: UCR

Figure B-2: Drayage Truck Port Cycle Near Dock, Local, and Regional



Source: UCR

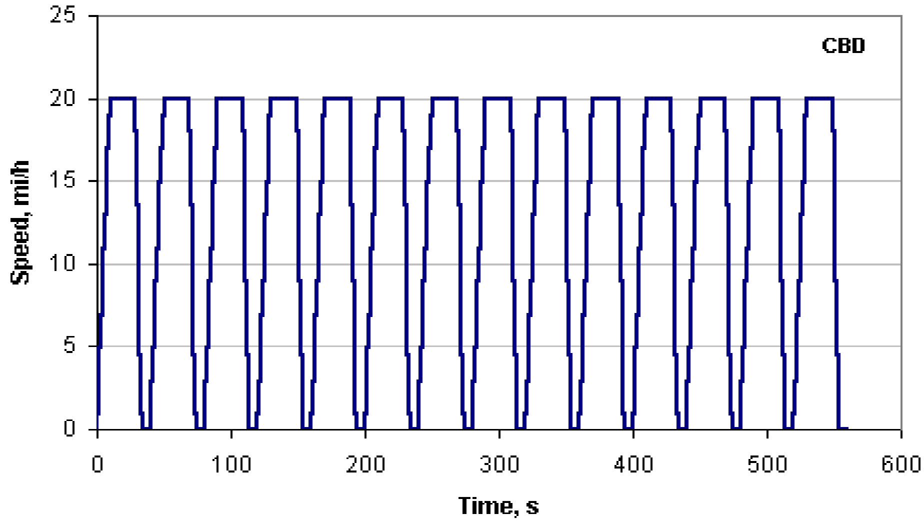
Central Business District (CBD)

The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes. The following are characteristic parameters of the cycle:

- Duration: 560 s
- Average speed: 20.23 km/h
- Maximum speed: 32.18 km/h (20 mph)
- Driving distance: 3.22 km
- Average acceleration: 0.89 m/s^2
- Maximum acceleration: 1.79 m/s^2

Vehicle speed over the duration of the CBD cycle is shown in Figure B-3.

Figure B-3: Speed Trace for the CBD Cycle



Source: UCR

ARB Cycles HHDDT (TBD)

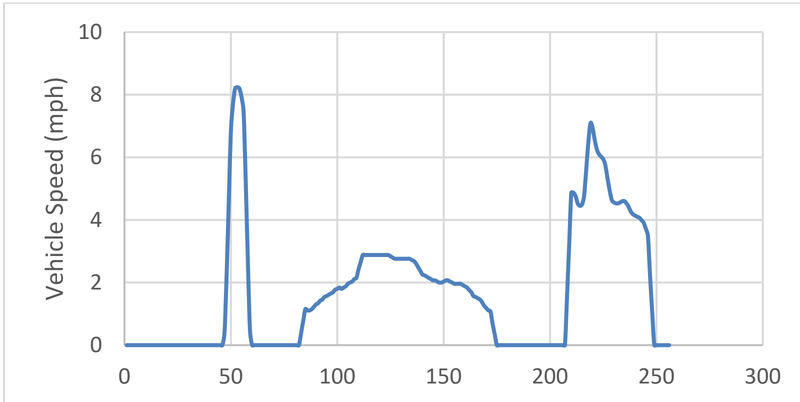
The other three cycles tested were the ARB Creep, Transient, and Cruise cycles denoted HHDDT_Creep, HHDDT_Transient, and HHDDT_Cruise. The details of the cycle are summarized in Table B-3 and are presented in Figures B-4, 5, and 6. The creep and transient cycles were performed as 3x cycles. The cruise was performed as a 1x cycle. The triple cycle operation was performed to obtain sufficient PM mass on the integrated filter which typically needs around 20 minutes.

Table B-3: ARB Cycle Details

Cycle	Total Time Sec	Total Time (Hour)	Average Speed	Distance	Max Acceleration	Max Speed
Creep	256	0.071	1.75	0.124	2.30	8.24
Transient	668	0.186	15.4	2.85	2.90	47.5
Cruise	2083	0.579	39.9	23.1	2.14	59.3

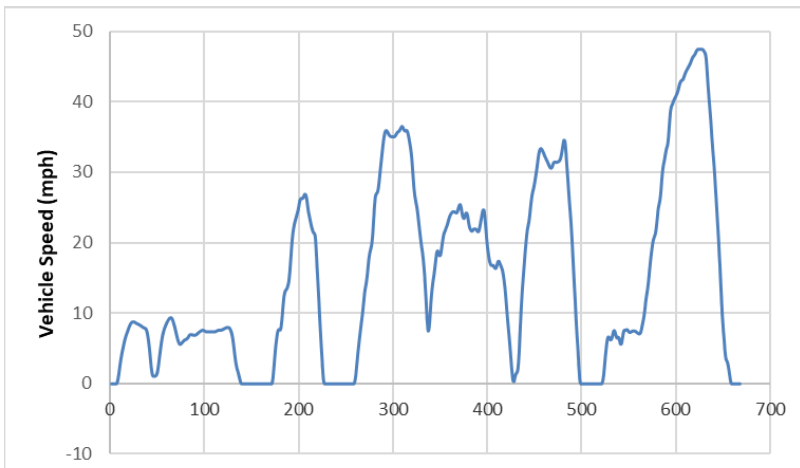
Source: UCR

Figure B-4: Speed Trace for the HHDDT Creep Cycle



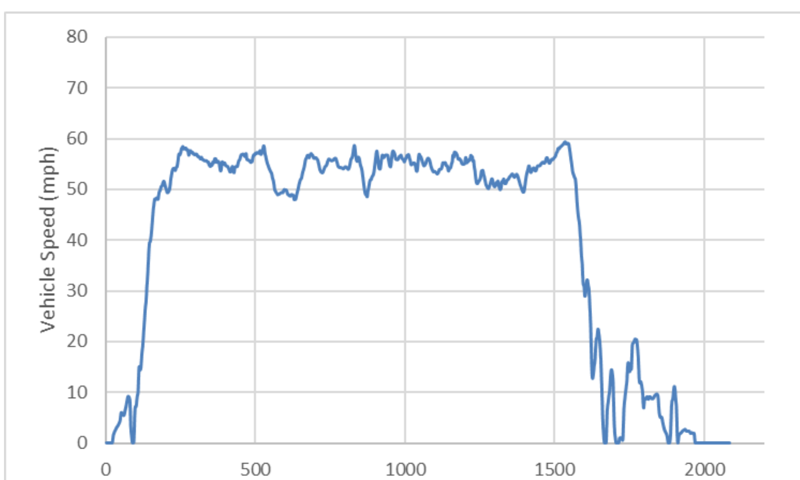
Source: UCR

Figure B-5: Speed Trace for the HHDDT Transient Cycle



Source: UCR

Figure B-6: Speed Trace for the HHDDT Cruise Cycle



Source: UCR

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Appendix C: Chassis Dynamometer Specifications

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APPENDIX C: Chassis Dynamometer Specifications

Dynamometers ("dynos") are essential equipment for the accurate measurement of emission factors. These very useful tools are designed to measure torque and rotational speed (rpm) from which the power produced by an engine can be calculated from the product of torque (τ) and angular velocity (ω) values or force (F) and linear velocity (v). Dynamometers come in various configurations. A dyno directly coupled to an engine is known as an engine dyno. An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel) and does not need to account for power losses in the drivetrain, such as the gear-box, transmission or differential as the engine values are directly measured. An engine dyno can either be a power absorbing or motoring type. The power absorbing-type is limited to steady-state cycles while a dyno with a motoring design can test either steady-state or transient cycles.

A dyno that measures torque and power delivered by the powertrain at the wheels of a vehicle without removing the engine from the vehicle is a chassis dyno. With a chassis dyno, the vehicle operates with its wheels on rollers, where the output power from the engine is measured. While engine dynamometers provide the most accurate measurement of engine operation, a chassis dynamometer is often the most practical approach as it measures the power and torque of an engine without removing the engine, thus saving time and money. The main issue with the chassis dynamometer is that the measured power and torque at the wheels is less than the values at the engine flywheel (e.g., brake horsepower), due to the frictional and mechanical losses in the various components. For example, drive train transmission, gearbox, and tire friction are all factors that need to be considered. The rear wheel brake horsepower is generally estimated to be 15-25 percent less than the brake horsepower due to frictional losses. Fortunately, many current engines have an Electronic Control Module that is calibrated by the engine manufacturer to report brake power, enabling measurement of power both at the wheels and at the fly wheel.

HDVs are generally certified by having their engines tested on an engine dynamometer prior to being installed on a vehicle chassis. More recently, regulatory agencies have moved from this type of engine dyno testing to measurements based on emissions during actual work cycles. Although these new in-use regulations require vehicle compliance on-road, performing on-road tests is difficult and not reproducible. Chassis dynamometers are used for certification of light duty vehicles and are a common tool for research on in-use HDVs.

CE-CERT's Heavy-Duty Engine Dynamometer Test Facility is designed for a variety of applications including verification of diesel ATS devices, certification of alternative diesel fuels, and fundamental research in diesel emissions and advanced diesel technologies. The chassis dynamometer is pictured in Figure C-1. UCR's chassis dynamometer is a 48" electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb, which covers a broad range of in-use medium and heavy-duty vehicles. The dynamometer includes dual, direct-connected, 300-horsepower motors attached to each roll set. The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance, as would be experienced under typical driving conditions. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horsepower at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common. The dynamometer can perform a full range of driving conditions for different vocations.

Figure C-1: UCR's Heavy Duty Chassis AC Transient Dynamometer

Source: UCR

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Appendix D: MEL Measurements

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APPENDIX D: MEL Measurements

The approach used for measuring the regulated emissions from a vehicle is to connect UCR's heavy-duty mobile emission lab (MEL) to the total exhaust of the diesel engine. The details for sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in Code of Federal Regulations (CFR): Protection of the Environment, Section 40, Part 1065. UCR's unique heavy-duty diesel mobile emissions laboratory (MEL) is designed and operated to meet those stringent specifications within a 53-foot tractor trailer. MEL is a complex laboratory and a schematic of the major operating subsystems for MEL are shown below. The accuracy of MEL's measurements has been verified against the Air Resources Board (ARB), Southwest Research Institute's (SwRI), and the National Renewable Energy Laboratory (NREL) heavy-duty diesel laboratories.

The MEL was recently upgraded with a new Horiba state-of-the-art measurement bench for both raw and dilute measurements with a special emphasis on low NOx measurements at and below 0.02 g/bhp-hr. These low measurements were identified during previous testing of the low NOx engines where emission results were observed at and below 0.002 g/bhp-rh (90 percent below the 0.02 standard)

Emissions Measurements

The MEL is equipped with a fully 1065-approved laboratory grade gaseous emissions analyzer and 1065-approved partial flow particulate matter portable emissions measurement systems for on-road and off-road applications. The analyzers are of the highest quality and utilize 24-bit analog to digital converters (ADC) with an effective 21 bits of usable resolution for each range, low analyzer drift and interferences, and is designed for raw and dilute CVS analyzers.

Gaseous Measurements

The UCR MEL is equipped with a 1065-approved laboratory-grade MEXA ONE bench manufactured by Horiba and a laboratory-grade quantum cascade laser (QCL) for the gaseous emissions, see Figure D-1. Included in the MEL MEXA ONE bench is both raw (tailpipe) and dilute (CVS) measurements with integrated close coupled heated oven analyzers for improved accuracy. The raw bench includes two chemiluminescence analyzers, one setup for NO (in the bench) and another setup for NOx (in the oven) in order to calculate NO_2. It has two non-dispersive infrared (NDIR) analyzers for measuring carbon monoxide low (CO_L), CO high (CO_H), and carbon dioxide (CO_2), and two heated flame ionization detectors (HFID) for measuring total hydrocarbons (THC) and methane hydrocarbons (CH4) for the determination (by difference) of non-methane hydrocarbons (NMHC), see Table D-1 and D-2. The CO emissions exceeded the CO_L analyzer range on a few modes, so CO emissions reported here are from the CO_H analyzer. Figure D-1 shows a picture of the MEXA ONE bench (left) housing the raw and dilute analyzers and the raw oven (right) housing the heated close coupled analyzers.

Table D-1: Horiba MEL Analyzers Direct Measurements

Analyzers				
Model	Constituent(s)	Principle	Dynamic Range(s)	Type
AIA-11	CO(L)	NDIR	0-50 to 0-5000 ppm	Half 19 inch
AIA-33	CO(H) CO2	Dual NDIR	0-0.5 to 0-12 % 0-0.5 to 0-20 %	Half 19 inch
MPA-01	O2	MPD	0-1 to 0-25 %	Half 19 inch
CLA-01	NO/NOx	CLD	0-10 -1000 and 0-2000-10,000 ppm	Half 19 inch

Source: UCR

The dilute analyzers are similar in model to those in the direct bench, but with lower range capabilities. The dilute analyzers in the bench include CO_L, CO_2_L, THC, CH4, and a NOx. The bench dilute NOx is Horiba's ultra-low NOx analyzer designed for concentrations with the lowest range of 0-1 ppm for the future 0.02 g/bhp-hr certified emissions levels expected. The dilute sample line also includes a close-coupled heated oven with heated THC, CH4 and NOx. For the setup of the dilute sample line the bench is configured for NOx and the heated oven is configured for NO.

Figure D-1: MEXA-ONE Gaseous Emissions Measurement System

Source: UCR

Table D-2: Horiba MEL Analyzers Direct Oven Heated Measurements

Analyzers				
Model	Constituent(s)	Principle	Dynamic Range(s)	Type
OVN-22H	THC CH4 NO/NOx (Dry)	Heated FID NMC Heated CLD	0-50-1000 and 0-2000-60,000 ppmC 0-50-1000 and 0-2000-25,000 ppm 0-10 to 0-10,000 ppm	Oven

Source: UCR

Table D-3: Horiba MEL Analyzers Dilute Measurements

Analyzers				
Model	Constituent(s)	Principle	Dynamic Range(s)	Type
AIA-11	CO(L)	NDIR	0-50 to 0-5000 ppm	Half 19 inch
AIA-22	CO2 (L)	NDIR	0-0.1 to 0-6 %	Half 19 inch
FIA-01	THC	FID	0-10-1000 and 0-2,000- 30,000 ppmC	Half 19 inch
GFA-01	CH4	GC-FID	0-50-1000 and 0-2,000-25,000 ppmC	Half 19 inch
CLA-01SL	NO/NOx (Wet)	CLD	0-1 -20 and 0-50-500 ppm	Half 19 inch

Source: UCR

Table D-4: Horiba MEL Analyzers Dilute Oven Heated Measurements

Analyzers				
Model	Constituent(s)	Principle	Dynamic Range(s)	Type
OVN-32H	THC CH4 NO/NOx (Dry)	Heated FID NMC Heated CLD	0-10-1000 and 0-2000-5,000 ppmC 0-10-1000 and 0-2000-5,000 ppm 0-10 to 0-1,000 ppm 0-2000-10,000 ppm	OVN-22H

Source: UCR

Un-Regulated Emissions

The un-regulated emissions are available from the MEL as described in *Cocker et al* with the following slight differences. Toxic samples are extracted from the MEL secondary (similarly to PM measurements) and the NH3 emissions are sampled from the raw exhaust using UCR’s tunable diode laser (TDL) spectroscopy measurement system.

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Appendix E: PEMS Measurements Zero Drift

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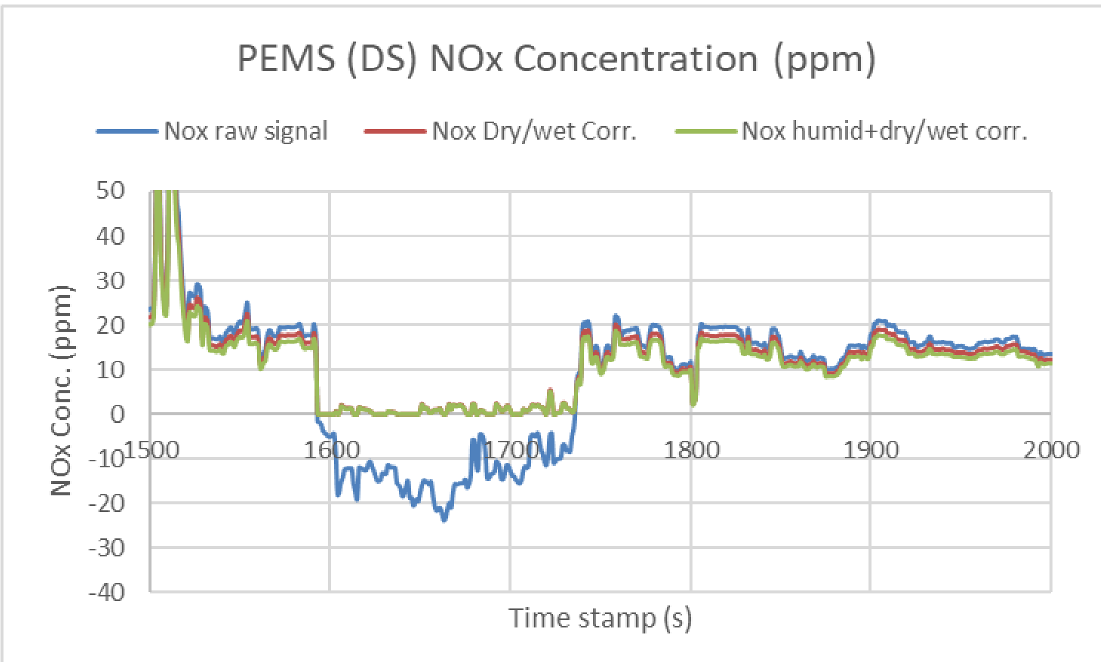
APPENDIX E: PEMS Measurements Zero Drift

During the calibration tests for the vehicle, zero drift from the PEMS unit (DS) was identified as shown in the Figure E-1 below. The raw NOx signal dropped below zero while testing. With certain corrections to the data, the values below zero were trimmed to zero normally, yet here, certain fluctuations were found, and these small deviations would affect overall NOx emissions measurements, as the true level of NOx emissions is reaching the limit of this PEMS unit.

Figure E-1: Zero Drift in NOx Calibration



Source: UCR

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Appendix F: Real-world Routes

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APPENDIX F:
Real-world Routes

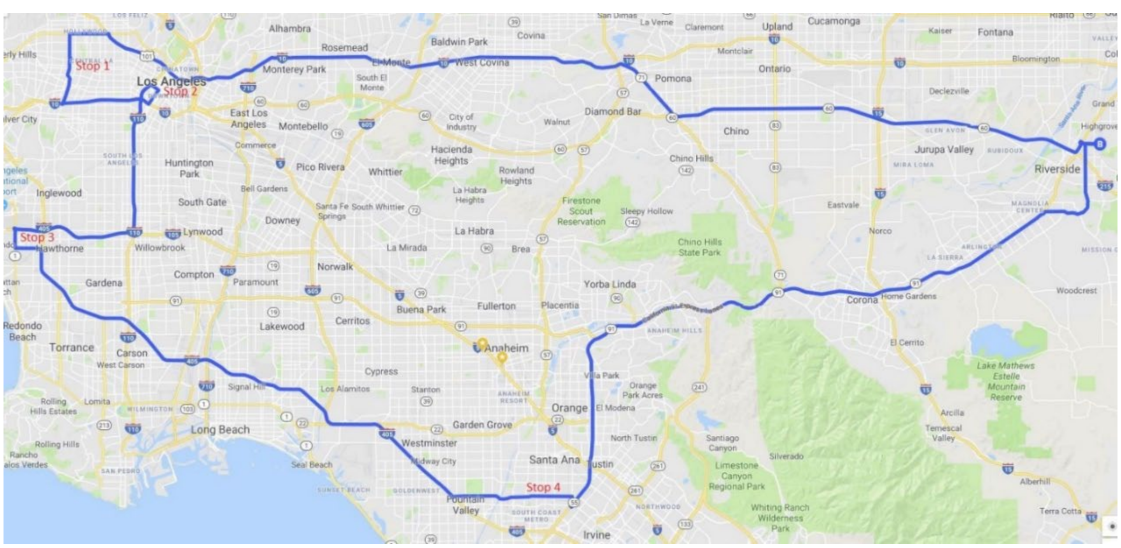
Routes	Distance (miles)	Time (hours)	Average Speed (mph)
Grocery Distribution route	177.8	6.74	26.4
Port-Drayage route	156.7	6.56	23.9
Goods Movement with Elevation Change route	109.8	3.12	35.2
Highway Goods Movement route	176.0	4.63	38.0

Source: UCR

Grocery Route

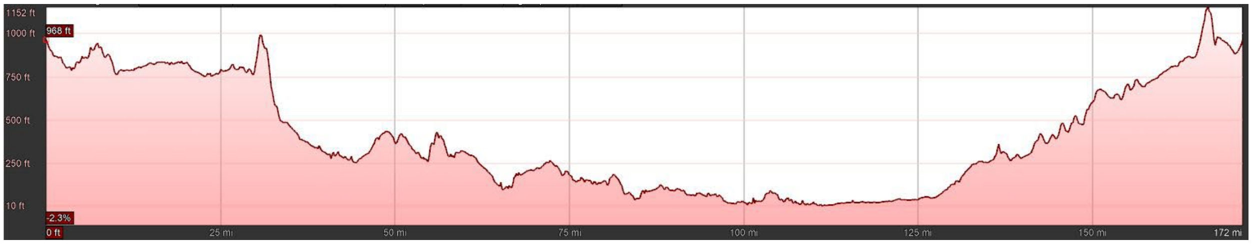
The grocery distribution route starts in Riverside at CE-CERT's laboratory facility on Columbus Avenue and follows typical daily operation of a grocery distribution truck used by the Ralph's Grocery Distribution Center in Moreno Valley. The route includes four stops near Grocery stores to simulate the unloading of goods at the truck docks. Based on activity data collected during a previous SCAQMD-funded project, the average durations for the goods unloading process were calculated and will be used as part of this route to simulate cool-down of the after-treatment system while the vehicle operator is unloading goods. Two of the stops are in the downtown Los Angeles area, one in the vicinity of Los Angeles airport and the fourth in the Santa Ana area. This route has modest elevation changes going up to 1,000 ft and down to 100 ft with an average speed of 26 mph. A topological map of this route is provided in Figure F-1, with the elevation profile provided in Figure F-2.

Figure F-1: Grocery Route, mix of Urban, Rural, and Highway Driving Including 4 Stops



Source: UCR

Figure F-2: Elevation Profile of the Grocery Route

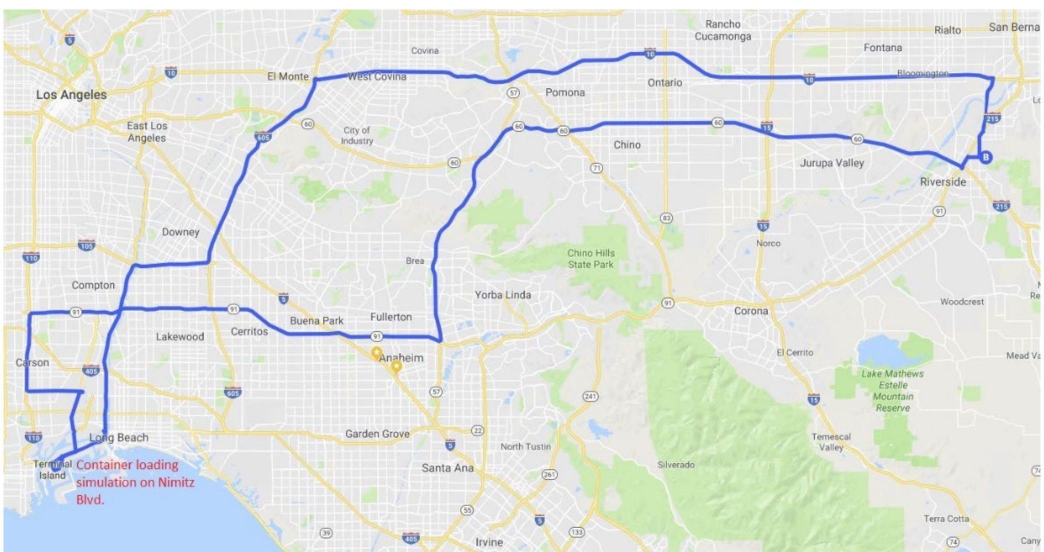


Source: UCR

Port Drayage Route

The port-drayage route simulates typical daily operation of trucks operating between the port of Long Beach and inland warehouses to deliver shipping containers. The route includes simulation of port activity (i.e., extended idle and creep operation) while waiting at the port terminals to receive shipping containers. This simulation was performed on the publicly accessible Nimitz Pier inside the harbor of Long Beach. This route has modest elevation changes going up to 1,000 ft and down to 30 ft with an average speed of 23 mph. A topological map of this route is provided in Figure F-3, with the elevation profile provided in Figure F-4.

Figure F-3: Port-Drayage Route, Port Operation, Urban, and Highway Driving



Source: UCR

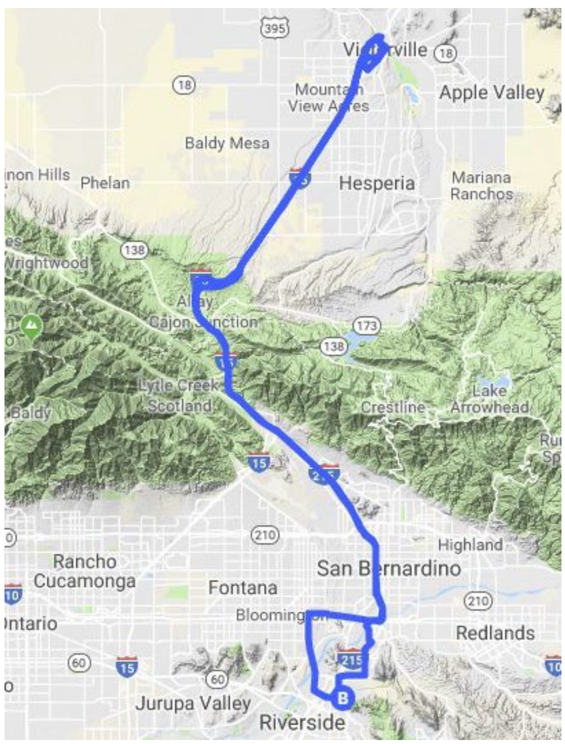
Figure F-4: Elevation Profile of the Port-Drayage Route

Source: UCR

Goods Movement with Elevation Change Route

This route simulates typical operation of UPS shipment delivery trucks that operate on the I-15 corridor between the Ontario, CA and Las Vegas, NV through the Cajon Pass. The route comprises extended highway operation with significant changes in elevation (i.e., total elevation changes of ~4,200 ft) while ascending and descending the Cajon Pass. The beginning and end of this route reflect short rural vehicle operation activities to adequately represent the linkage between the highway and final UPS distribution centers that the trucks drive through during regular revenue service operation. This route represents a route with higher loads and possibly lower NOx emissions. Additionally, this route includes more than one hour at a high elevation to evaluate the impact of a zero span at elevation. In addition, it is suggested to add a 30-minutes to 1-hour stop on this route to simulate a delivery up in a hot area to force a zero under these conditions. A topological map of this route is provided in Figure F-5. with the elevation profile provided in F-6.

Figure F-5: Goods Movement Route, Extended Highway Driving Including Larger Elevation Changes



Source: UCR

Figure F-6: Elevation Profile of Goods Movement Route with Elevation Change

Source: UCR

This route simulates typical operation of longer haul goods movement vehicles, such as delivery of garbage from transfer facilities to distant landfills (e.g. EDCO, CR&R) or movement of goods between different distribution centers (e.g. AJR) or production facilities (e.g. Food Express) which are primarily characterized by extended highway operation with short portions of urban operation when moving between the highway exit/entrance and the final destinations (i.e. warehouse, factory, distribution centers, etc.). Accordingly, the route comprises extended highway driving between Riverside and Indio on I-10 with short urban road links at the beginning and end of the highway operation. This route was selected as it may represent the lowest emissions result of all the routs and be subjected to higher drift impacted results due to the low emission rate. The average speed is highest at 36 mph covering a modest range of elevation from 900 ft to 2500 ft. A topological map of this route is provided in Figure F-7, with the elevation profile provided in F-8.

Figure F-7: Highway Goods Movement Route, Extended Highway Operation with Short Urban Links

Source: UCR

Figure F-8: Elevation Profile of Highway Goods Movement Route

Source: UCR