IMPACT COMPLIANCE & TESTING

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AIR EMISSION TEST REPORT

Title:	Air Emission Test Report for the Verification of Carbon Monoxide and Nitrogen Oxides Emissions from Engine Dynamometer Test Cells
Report Date:	August 7, 2019
Test Date(s):	July 11, 2019

Facility Information	
Name:	Ricardo, Inc.
Street Address:	40000 Ricardo Drive
City, County:	Van Buren Township, Wayne County
Phone:	(734) 397-6666

Facility Permit Information	
State Registration Number:	N6962
Permit To Install No.:	370-08C

Testing Contractor	
Company	Impact Compliance & Testing, Inc.
Mailing Address	37660 Hills Tech Drive Farmington Hills, Michigan 48331
Phone	(734) 464-3880
Project No.	1900171

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AIR EMISSION TEST REPORT
FOR THE
VERIFICATION OF
CARBON MONOXIDE
AND NITROGEN OXIDES EMISSIONS
FROM ENGINE DYNAMOMETER TEST CELLS

1.0 INTRODUCTION

Ricardo, Inc. (Ricardo) State Registration Number (SRN) N6962 retained Impact Compliance & Testing, Inc. (ICT) to conduct a testing program for the determination of carbon monoxide (CO) and nitrogen oxides (NO_x) emissions from the exhaust of one (1) compression ignited (CI) internal combustion (IC) diesel fueled engine and one (1) spark ignited (SI) IC gasoline fueled engine at the Ricardo facility located at 40000 Ricardo Drive, Van Buren Township, Wayne County, Michigan.

Testing was conducted on a diesel fueled CI-IC engine operated in EU-TESTCELL-01 and on a gasoline fueled SI-IC engine operated in EU-TESTCELL-04, following the provisions specified in Michigan Department of Environment, Great Lakes, and Energy-Air Quality Division (EGLE-AQD) Permit to Install (PTI) No. 370-08C. Condition V.1. for Flexible Group FG-TESTCELLS of the PTI requires Ricardo to verify CO and NO_x emission rates and applicable emission factors from a representative engine in FG-TESTCELLS.

The compliance testing was performed by ICT, a Michigan-based environmental consulting and testing company. ICT representatives Tyler J. Wilson and Brad Thome performed the field sampling and measurements July 11, 2019.

The exhaust gas sampling and analysis was performed using procedures specified in the Test Plan that was reviewed and approved by the EGLE-AQD in the June 14, 2019 Test Plan Approval Letter. EGLE-AQD representatives Ms. Regina Angellotti and Ms. Jill Zimmerman observed portions of the testing project. Appendix A contains a copy of the Test Plan Approval Letter.

Questions regarding this emission test report should be directed to:

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Report Certification

This Test Report was prepared by Impact Compliance & Testing, Inc. based on field sampling data collected by Impact Compliance & Testing, Inc. Facility process data were collected and provided by Ricardo employees or representatives. This test report has been reviewed by Ricardo representatives and approved for submittal to the EGLE-AQD.

I certify that the testing was conducted in accordance with the approved test plan unless otherwise specified in this report. I believe the information provided in this report and its attachments are true, accurate, and complete.

Report Prepared By:

Tyler J. Wilson
Senior Project Manager
Impact Compliance & Testing, Inc.

I certify that the facility operating conditions were in compliance with permit requirements or were at the maximum routine operating conditions for the facility. Based on information and belief formed after reasonable inquiry, the statements and information in this report are true, accurate and complete.

Responsible Official Certification:

Nick Fortino
Engineering Manager – Powertrain Development
Ricardo, Inc.

2.0 SUMMARY OF TEST RESULTS

Performance testing for the exhaust of EU-TESTCELL-01 and EU-TESTCELL-04 verified the NO_x and CO emission rates to be used in emissions calculations for CI and SI fuels.

The exhausts from EU-TESTCELL-01 and EU-TESTCELL-04 were each monitored for three (3) one-hour test periods during which the CO, NO_x, oxygen (O_2), and carbon dioxide (CO_2) exhaust gas concentrations were measured using instrumental analyzers. Exhaust gas moisture content was determined by water weight gain in chilled impingers. Velocity pressure measurements were performed once for each test using a Pitot tube for exhaust gas velocity determination. The testing was performed while the IC engines operated at normal/maximum, representative operating conditions, as a worst-case scenario, as discussed with EGLE-AQD representatives. A summary of the measured CO and NO_x emission rates for Ricardo are presented in Table 2.1.

Table 2.1 Summary of measured CO and NO_x emission rates for the diesel fueled CI-IC engine and the gasoline fueled SI-IC engine

Test ID	Diesel Fueled CI Engine CO Emission Rate (lb/1000 gal)	Diesel Fueled CI Engine NO_x Emission Rate (lb/1000 gal)	Gasoline Fueled SI Engine CO Emission Rate (lb/1000 gal)	Gasoline Fueled SI Engine NOx Emission Rate (lb/1000 gal)
Test No. 1	6.67	165	1,583	43.6
Test No. 2	6.96	165	1,796	44.1
Test No. 3	6.89	161	1,795	40.3
Average	6.84	164	1,725	42.7

3.0 SOURCE DESCRIPTION

3.1 General Process Description

Ricardo operates twelve (12) engine dynamometer test cells at its Van Buren Township facility (identified as Flexible Group FG-TESTCELLS). Each cell has the capacity to test engines using either CI fuels (e.g., diesel, biodiesel, kerosene) or SI fuels (gasoline, ethanol, methanol, CNG). The engine exhaust manifolds are connected to the test cell exhaust system and engine exhaust gases are released to atmosphere through vertical exhaust stacks. Each test cell has a dedicated exhaust system and vertical exhaust stack.

3.2 Rated Capacities, Type and Quantity of Raw Materials Used

During the performance testing a:

- 12.4L, 354 kilowatt (kW), Inline-6 (6-cylinder) diesel engine was operated in EU-TESTCELL-01.
- 2.0L, 214 horsepower (hp), Inline-4 (4-cylinder) gasoline engine was operated in EU-TESTCELL-04.

These engines are representative of the typical size and power of engines operated at Ricardo. Table 3.1 presents a summary of the specifications for the engines that were included in the testing program.

Table 3.1 Specifications for engines included in the testing program

Test Cell	Fuel	Engine Size / Displacement	Engine Power	No. of Cylinders
EU-TESTCELL-01	Diesel	12.4 Liters	354 kW	6
EU-TESTCELL-04	Gasoline	2.0 Liters	214 hp	4

Typical fuel use for the diesel fueled (CI) IC engine is 19 gallons per hour. Typical fuel use for the gasoline fueled (SI) IC engine is 4.1 gallons per hour.

3.3 Emission Control System Description

The IC engines are permitted to operate with and without catalytic converters. The permitted emission rates are based on operation without catalytic control; therefore, during the performance testing the IC engines were operated without catalysts.

3.4 Process Operating Conditions During the Compliance Testing

During the compliance testing program the CI-IC engine was operated at an average engine speed of 1,500 revolutions per minute (rpm) and average engine torque of 2,060 Newton-meters (Nm). The average diesel fuel use rate was 19.4 gallons per hour (gph).

During the compliance testing program the SI-IC engine was operated at an average engine speed of 3,998 rpm and average engine torque of 251 Nm. The average gasoline fuel use rate was 4.07 gph.

Appendix B provides operating records for the CI and SI IC engines.

4.0 SAMPLING AND ANALYTICAL PROCEDURES

A Test Plan for the compliance testing was prepared by Ricardo and ICT, and reviewed by the EGLE-AQD. This section provides a summary of the sampling and analytical procedures that were used during the test and presented in the Test Plan.

4.1 Sampling Locations (USEPA Method 1)

The sampling location for the vertical EU-TESTCELL-01 (diesel fueled IC engine) exhaust stack satisfied the USEPA Method 1 criteria for a representative sample location. The inner diameter of the stack is 6.50 inches. The stack is equipped with two (2) sample ports, opposed 90°, that provided a sampling location 16.0 inches (2.46 duct diameters) downstream and 43.0 inches (6.62 duct diameters) upstream from any flow disturbance.

The sampling location for vertical EU-TESTCELL-04 (gasoline fueled IC engine) exhaust stack satisfied the USEPA Method 1 criteria for a representative sample location. The inner diameter of the stack is 6.50 inches. The stack is equipped with two (2) sample ports, opposed 90°, that provided a sampling location 16.0 inches (2.46 duct diameters) downstream and 43.0 inches (6.62 duct diameters) upstream from any flow disturbance.

Velocity pressure traverse locations for the sampling points were determined in accordance with USEPA Method 1.

Appendix C provides diagrams of the performance test sampling locations.

4.2 Exhaust Gas Velocity Determination (USEPA Method 2)

Exhaust gas velocity pressure and temperature were measured at the sampling locations once for each one-hour sampling period in accordance with USEPA Method 2. An S-type Pitot tube connected to a red-oil manometer was used to determine velocity pressure. Gas temperature was measured using a K-type thermocouple mounted to the Pitot tube. The Pitot tube and connective tubing were leak-checked on-site, prior to the test event, to verify the integrity of the measurement system.

The absence of cyclonic flow for both sampling locations was verified using the S-type Pitot tube and oil manometer. The Pitot tube was positioned at selected velocity traverse points with the planes of the face openings of the Pitot tube perpendicular to the stack cross-sectional plane. The Pitot tube was then rotated to determine the null angle (rotational angle as measured from the perpendicular, or reference, position at which the differential pressure is equal to zero).

4.3 Exhaust Gas Molecular Weight Determination (USEPA Methods 3A and 4)

CO_2 and O_2 content in both exhaust gas streams was measured continuously throughout each one-hour test period in accordance with USEPA Method 3A. The exhaust gas CO_2

content was monitored using a Servomex 1440D single beam single wavelength (SBSW) infrared gas analyzer. The exhaust gas O_2 content was monitored using a Servomex 1440D gas analyzer that uses a paramagnetic sensor.

During each one-hour pollutant sampling period, a continuous sample of the exhaust gas stream was extracted from the stack using a stainless steel probe connected to a Teflon® heated sample line. The sampled gas was conditioned by removing moisture prior to being introduced to the analyzer; therefore, measurement of O_2 and CO_2 concentrations correspond to standard dry gas conditions. The instrument was calibrated using appropriate calibration gases to determine accuracy and system bias (described in Section 4.6.1 of this document).

Moisture content of the exhaust gas was determined in accordance with the USEPA Method 4 chilled impinger method. During each pollutant sampling period, a gas sample was extracted at a constant rate from the source using a non-heated, stainless steel sample probe followed by chilled impingers containing DI water, where moisture was removed from the sample stream. At the conclusion of each sampling period, the moisture gain in the impingers was determined gravimetrically.

4.4 NO_x and CO Concentration Measurements (USEPA Method 7E and 10)

NO_X and CO pollutant concentrations in both exhaust gas streams was determined using a Thermo Environmental Instruments, Inc. (TEI) Model 42c High Level chemiluminescence NO_X analyzer and a TEI Model 48i NDIR CO analyzer.

Three (3) one-hour sampling periods were performed for each test cell exhaust. Throughout each one-hour test period, a continuous sample of the engine exhaust gas was extracted from the stack using the Teflon® heated sample line and gas conditioning system described in Section 4.3 of this document, and delivered to the instrumental analyzers. Instrument response for each analyzer was recorded on an ESC Model 8816 data logging system that monitored the analog output of the instrumental analyzers continuously and logged data as one-minute averages. Prior to, and at the conclusion of each test, the instruments were calibrated using appropriate upscale calibration and zero gas to determine analyzer calibration error and system bias (described in Section 4.6 of this document).

4.5 Instrumental Analyzer Quality Assurance Verification

4.5.1 Instrument Calibration and System Bias Checks

At the beginning of the testing program for each IC engine, initial three-point instrument calibrations were performed by injecting calibration gas directly into the inlet sample port for each instrument. System bias checks were preformed prior to and at the conclusion of each sampling period by introducing the appropriate upscale calibration gas and zero gas into the sampling system (at the base of the stainless steel sampling probe prior to the particulate filter and Teflon® heated sample line) and verifying the instrument response against the initial instrument calibration readings.

The instruments were calibrated with USEPA Protocol 1 certified concentrations of CO_2, O_2, NO_x and CO and zeroed using nitrogen. A STEC Model SGD-710C 10-step gas divider was used to obtain intermediate calibration gas concentrations as needed.

4.5.2 Sampling System Response Time Determination

The response time of the sampling system was determined prior to the compliance test program by introducing upscale gas and zero gas, in series, into the sampling system using a tee connection at the base of the sample probe. The elapsed time for the analyzer to display a reading of 95% of the expected concentration was determined using a stopwatch.

The TEI Model 48i NDIR CO analyzer exhibited the longest system response time at 50 seconds. Results of the response time determinations were recorded on field data sheets. For each test period, test data were collected once the sample probe was in position for at least twice the maximum system response time.

4.5.3 NO_x Converter Test

The NO_2 – NO conversion efficiency of the Model 42c analyzer was verified prior to the testing program. A USEPA Protocol 1 certified concentration of NO_2 was injected directly into the analyzer, following the initial three-point calibration, to verify the analyzer's conversion efficiency. The analyzer's NO_2 – NO converter uses a catalyst at high temperatures to convert the NO_2 to NO for measurement. The conversion efficiency of the analyzer is deemed acceptable if the measured NO_X concentration is at least 90% of the expected value.
The NO_2 – NO conversion efficiency test satisfied the USEPA Method 7E criteria (measured NO_X concentration was greater than 90% of the expected value as required by Method 7E).

4.5.4 Gas Divider Certification (USEPA Method 205)

A STEC Model SGD-710C 10-step gas divider was used to obtain appropriate calibration span gases. The five-step gas divider was NIST certified (within the last 12 months) with a primary flow standard in accordance with Method 205. When cut with an appropriate zero gas, the ten-step STEC gas divider delivered calibration gas values ranging from 0% to 100% (in 10% step increments) of the USEPA Protocol 1 calibration gas that was introduced into the system. The field evaluation procedures presented in Section 3.2 of Method 205 were followed prior to use of gas divider. The field evaluation yielded no errors greater than 2% of the triplicate measured average and no errors greater than 2% from the expected values.

4.5.5 Instrumental Analyzer Interference Check

The instrumental analyzers used to measure NOx, CO, O_2, and CO_2 have had an interference response test preformed prior to their use in the field (July 26, 2006 and April 3, 2012), pursuant to the interference response test procedures specified in USEPA Method 7E. The appropriate interference test gases (i.e., gases that would be encountered in the exhaust gas stream) were introduced into each analyzer, separately and as a mixture with the analyte that each analyzer is designed to measure. All of analyzers exhibited a composite deviation of less than 2.5% of the span for all measured interferent gases. No major analytical components of the analyzers have been replaced since performing the original interference tests.

4.5.6 Meter Box Calibrations

The Nutech Model 2010 sampling console, which was used to extract a measured amount of exhaust gas from the stack for moisture determinations, was calibrated prior to and after the testing program. This calibration uses the critical orifice calibration technique presented in USEPA Method 5.

Appendix E presents test equipment quality assurance data (NO_2 – NO conversion efficiency test data, instrument calibration and system bias check records, calibration gas and gas divider certifications, interference test results, meter box calibration records, stratification checks, cyclonic flow determinations sheets, Pitot tube, scale, and barometer calibration records).

5.0 TEST RESULTS AND DISCUSSION

5.1 Operating Conditions During the Compliance Test

During the compliance testing program the CI-IC engine in Test Cell No. 1 was operated at an average engine speed of 1,500 rpm and average engine torque of 2,060 Nm. The average diesel fuel use rate was 19.4 gph.

During the compliance testing program the SI-IC engine Test Cell No. 4 was operated at an average engine speed of 3,998 rpm and average engine torque of 251 Nm. The average gasoline fuel use rate was 4.07 gph.

5.2 Air Pollutant Sampling Results

5.2.1 Diesel Fueled CI-IC Engine Test Results

The gas stream exhausted from the engine operated in Test Cell No. 1 (diesel fueled IC engine) was sampled for three (3) separate one-hour test periods during the compliance testing performed July 11, 2019. Instrumental analyzers were used to measure concentrations of NO_x, CO, O_2, and CO_2 in the exhaust. Moisture content was determined by gravimetric weight gain in chilled impingers and velocity pressure measurements were performed once for each sampling period using a Pitot tube for exhaust gas velocity determination.

The average measured NO_X and CO concentrations in the exhaust gas were 707 and 48.5 parts per million by volume, dry basis (ppmvd), respectively. This results in calculated emission rates of 164 pounds of NO_x per 1,000 gallons of fuel combusted (lb/1,000 gal) and 6.84 lb CO/1,000 gal based on the measured average exhaust gas volumetric flowrate of 626 dry standard cubic feet per minute (dscfm) and average diesel fuel use rate of 19.4 gph. The average moisture content of the exhaust gas was 10.7% and the average O_2 and CO_2 concentrations of the exhaust gas were 7.01 and 10.8%, respectively.

Tables 5.1 presents measured exhaust gas conditions and pollutant emission rates for the diesel fueled CI-IC engine operated in Test Cell No. 1.

5.2.2 Gasoline Fueled SI-IC Engine Test Results

The gas stream exhausted from the engine operated in Test Cell No. 4 (gasoline fueled IC engine) was sampled for three (3) separate one-hour test periods during the compliance testing performed July 11, 2019. Instrumental analyzers were used to measure concentrations of NO_x, CO, O_2, and CO_2 in the exhaust. Moisture content was determined by gravimetric weight gain in chilled impingers and velocity pressure measurements were performed once for each sampling period using a Pitot tube for exhaust gas velocity determination.

The average measured NO_X and CO concentrations in the exhaust gas were 140 and 9,264 ppmvd, respectively. This results in calculated emission rates of 42.7 lb NO_x/1,000 gal and 1,725 lb CO/1,000 gal based on the measured average exhaust gas volumetric flowrate of 174 dscfm and average gasoline fuel use rate of 4.07 gph. The average moisture content of the exhaust gas was 13.5% and the average O_2 and CO_2 concentrations of the exhaust gas were 0.12% and 13.8%, respectively.

Tables 5.2 presents measured exhaust gas conditions and pollutant emission rates for the gasoline fueled SI-IC engine operated in Test Cell No. 4.

Appendix F provides field data and calculations for the diesel fueled CI-IC and gasoline fueled SI-IC engine exhaust gas streams.

Appendix G provides raw instrumental analyzer response data for each test period.

5.3 Emission Compliance Determination

For CI fuels, PTI No. 370-08C specifies NO_x and CO emission factors of 72.8 and 94.0 lb/1,000 gal, respectively. For SI fuels, PTI No. 370-08C specifies NO_x and CO emission factors of 279 and 641 lb/1,000 gal, respectively. The permit indicates that Ricardo shall use the permitted emission factors until test-derived emission factors are available.

PTI No. 370-08C specifies annual NO_x and CO emission limits of 34.5 and 74.6 tons per year (tpy), respectively. Ricardo will use the emission factors determined during this emissions test program to determine compliance with the permitted annual emission limits.

5.4 Variations from Normal Sampling Procedures or Operating Conditions

The testing for all pollutants was performed in accordance with the approved Test Plan. The CI-IC and SI-IC engines operated near maximum output and no variations from the normal operating conditions of the engines occurred during the test periods

Test Nos. 1-3 for the gasoline fueled SI-IC engine recorded some CO one-minute average data points over span (7,984 ppm). The CO concentration measurements for the SI-IC engine were relatively unstable, so a span of 7,984 was selected to best capture accurate measurements of the estimated fluctuating in-stack CO concentration during testing. Since some CO one-minute average data points were over span, an additional system bias check for CO was performed after each of the tests for the SI-IC engine. The additional CO calibration gas cut used to challenge the system and CO instrument was 9,845 ppm (CO calibration gas cut closest to test averages). The post-test system bias check responses for Test Nos. 1-3 were 9,873, 9,862, and 9,832, respectively. All three (3) of these responses were within 0.3% of the expected concentration (9,845 ppm). This procedure was discussed with, and approved by, EGLE-AQD representative Ms. Regina Angellotti.

A different diesel fueled CI-IC engine was tested than the engine originally proposed in the Test Plan and approved EGLE-AQD Test Plan Approval Letter. This was discussed with, and approved by, EGLE-AQD representatives prior to the test event.

The Test Plan Approval Letter specifies that the CI-IC and SI-IC engines will be tested while operating on a representative cycle. EGLE-AQD representatives Ms. Jill Zimmerman and Ms. Regina Angellotti requested that testing of the CI-IC and SI-IC engines be performed while the engines were operating near full load as a worst-case scenario, while on-site, the morning of test day.

Table 5.1 Measured exhaust gas conditions and air pollutant emission rates for the diesel fueled compression-ignited IC engine operated in EU-TESTCELL-01

Test No. Test date Test period (24-hr clock)	1 7/11/2019 834-934	2 7/11/2019 947-1047	3 7/11/2019 1100-1200	Three-Test Average
Engine Power (kW)	324	323	324	324
Diesel fuel use rate (gph)	19.3	19.4	19.4	19.4
Engine speed (rpm)	1,500	1,500	1,500	1,500
Engine torque (Nm)	2,060	2,059	2,062	2,060
Exhaust gas composition				
CO_2 content (% vol)	10.8	10.8	10.8	10.8
O_2 content (% vol)	7.01	7.02	6.99	7.01
Moisture (% vol)	11.8	10.3	10.0	10.7
Exhaust gas flowrate (scfm)	704	711	687	701
Exhaust gas flowrate (dscfm)	620	638	619	626
Carbon monoxide emission rates				
CO conc. (ppmvd)	47.6	48.4	49.5	48.5
CO emissions (lb/hr)	0.13	0.13	0.13	0.13
CO emissions (lb/1,000 gal) †	6.67	6.96	6.89	6.84
Nitrogen Oxides emission rates				
NO_x conc. (ppmvd)	716	699	705	707
NO_x emissions (lb/hr)	3.18	3.20	3.13	3.17
NO_x emissions (lb/1,000 gal) †	165	165	161	164

† The current permitted CO and NO_x emission factors specified for the combustion of CI fuel are 94.0 lb CO/1,000 gal and 72.8 lb NO_x/1,000 gal, respectively.

Table 5.2 Measured exhaust gas conditions and air pollutant emission rates for the gasoline fueled spark-ignited IC engine operated in EU-TESTCELL-04

Test No.	1	2	3	
Test date	7/11/2019	7/11/2019	7/11/2019	Three-Test
Test period (24-hr clock)	1313-1413	1438-1538	1600-1700	Average
Engine Power (kW)	106	105	105	105
Gasoline fuel use rate (gph)	4.06	4.10	4.04	4.07
Engine speed (rpm)	3,998	3,996	4,000	3,998
Engine torque (Nm)	252	250	251	251
Exhaust gas composition				
CO_2 content (% vol)	13.7	13.9	13.8	13.8
O_2 content (% vol)	0.11	0.12	0.12	0.12
Moisture (% vol)	13.7	13.5	13.2	13.5
Exhaust gas flowrate (scfm)	220	201	199	207
Exhaust gas flowrate (dscfm)	174	174	172	173
Carbon monoxide emission rates				
CO conc. (ppmvd)	8,464	9,694	9,634	9,264
CO emissions (lb/hr)	6.43	7.37	7.25	7.02
CO emissions (lb/1,000 gal) †	1,583	1,796	1,795	1,725
Nitrogen Oxides emission rates				
NO_x conc. (ppmvd)	142	145	132	140
NO_x emissions (lb/hr)	0.18	0.18	0.16	0.17
NO_x emissions (lb/1,000 gal) †	43.6	44.1	40.3	42.7

† The current permitted CO and NO_x emission factors specified for the combustion of SI fuel are 641 lb CO/1,000 gal and 279 lb NO_x/1,000 gal, respectively.