REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04-02-2016	Final	

4. TITLE AND SUBTITLE	
Test Operations Procedure (TOP) 02-2-700A Laboratory Test of Reciprocating Internal Combustion Engines	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Automotive Directorate (TEDT-AT-AD) U.S. Army Aberdeen Test Center 400 Colleran Rd Aberdeen Proving Ground, MD 21005	TOP 02-2-700A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Range Infrastructure Division (CSTE-TM) US Army Test and Evaluation Command 2202 Aberdeen Boulevard Aberdeen Proving Ground, MD 21005-5001	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** Same as item 8

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Defense Technical Information Center (DTIC), AD No.:

This TOP supersedes TOP 02-2-700, Laboratory Tests of Reciprocating Internal Combustion Engines, dated 24 January 1985.

Marginal notations are not used in this revision to identify changes, with respect to the previous issue, due to the extent of the changes.

14. ABSTRACT

This TOP prescribes procedures for analyzing the performance and endurance of reciprocating internal combustion engines. Test equipment includes engine dynamometers, precision fuel flow meters, oil conditioners, coolant conditioners, exhaust gas analyzers, and metrological monitors. Major factors to be considered when testing for performance include, but are not limited to, differences in fuels, lubrication, temperatures, engine control module parameters, component wear, exhaust, and air intake systems. Power train component such as transmissions and transmission steering devices are not covered in this TOP.

15. SUBJECT TERMS

Engine Control Module (ECM) torque horsepower engine speed boost turbocharger throttle injector power curve exhaust gas recirculation (EGR) fuel consumption

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**B. ABSTRACT**	**C. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	38	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 02-2-700A 4 February 2016
DTIC AD No.

LABORATORY TEST OF RECIPROCATING INTERNAL COMBUSTION ENGINES

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*This TOP supersedes TOP 02-2-700, Laboratory Tests of Reciprocating Internal Combustion Engines, dated 24 January 1985.

1. SCOPE.

1.1 Purpose.

This Test Operations Procedure (TOP) describes the general procedures for dynamometer testing of reciprocating internal combustion engines used to power both military and civilian ground vehicles. The procedures described within are intended to provide a guideline to engine setup, testing, and analysis, but cannot possibly cover all applications or specific test scenarios. All relevant information cannot be provided in any one document, so it is encouraged to refer to the references cited in this TOP as well as manufacturer-specific documentation. The successful and safe testing of engines requires both a basic understanding of fundamental automotive principles, and the ability to operate and understand heavy machinery. This document describes engine test cell setup, safety, installation, testing, and analysis. The purpose of the requested test determines what specific measurements are to be recorded, fuel selection, loading, duration, sampling, and parameter settings. Therefore, not all of the specific instructions included in this document are required for each engine test. The details of every individual test are not included in this TOP. Specific test procedures are referenced as needed and should be reviewed to fully understand the individual test conditions, instrumentation requirements, data presentation, and analysis techniques. This TOP does not address engine testing in high altitude conditions.

1.2 Background.

a. Tactical and civilian vehicles, aircraft, marine vessels, generator sets, and Auxiliary Power Units (APUs) are predominantly powered by reciprocating internal combustion engines. Although some alternative technologies are being considered, the internal combustion engine remains heavily relied upon for military and civilian applications. The internal combustion engine has evolved greatly since the proceeding TOP 02-2-700 was published in 1985. Nearly all modern engines are controlled electronically by the Engine Control Modules (ECM) or otherwise referred to as Engine Control Units (ECU). Originally, diesel engines were naturally aspirated, but most have evolved to include forced induction devices (turbochargers) to produce more power and greater efficiency.

b. For the purpose of this TOP, the term diesel engine will be used to also describe similar fuel types such as JP-8 and F-24. Dynamometer testing of gasoline engines will also be included to explain the considerations of test cell safety. Although gasoline engines aren’t often used in traditional combat vehicles, they are used by the Department of Defense (DOD) as support vehicles and in some special applications.

c. Understanding the operation of engines to include performance characteristics, limitations, and power to weight correlations is essential to ensure proper drivetrain component selection. Successful matching of the components is critical to the overall vehicle system to ensure it meets safety, performance, and reliability objectives. Improperly matched hardware, inadequate maintenance, change in payload, change in centers of gravity (CG), or ECM parameters can lead to hazardous conditions and a negative effect on performance and reliability.

2. FACILITIES AND INSTRUMENTATION.

2.1 Test Cells.

a. The size and number of test cells depends on a variety of factors. Often, manufacturing processes use multiple test cells for end of line checkout and/or break-in. Research, development, and testing applications may have fewer, but more advanced test cells. Typically, engines in advanced test cells are set-up for operation over longer periods of time and have more instrumentation installed to record specific data sets. Some applications may even use dual-ended dynamometers to maximize the efficiency of an individual test cell.

b. There are several types of dynamometers. Numerous considerations must be made in selecting the best size and type of dynamometer for specific applications. The types, advantages, and disadvantages of common dynamometers are outlined in Table 1. A primary selection criteria is if the application will require the dynamometer to have four-quadrant capability to motor the engine. Other determining factors can be related to physical space or required range of operation. Most research, development, and testing applications will require four-quadrant operation, low inertia, and rapid response to automated control. It is recommended to meet with several manufacturers to discuss applications, commercial off the shelf (COTS) or specialized solutions, and pricing.

TABLE 1. DYNAMOMETERS: ADVANTAGES AND DISADVANTAGES OF AVAILABLE TYPES, SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) ENGINE TESTING 4th EDITION[**1]

DYNAMOMETER TYPE	ADVANTAGES	DISADVANTAGES
Froude sluice plate	Cheap, robust.	Obsolete, slow response, manual control.
Variable-fill water brake	High loads, medium speed load changes, automated control, robust, and tolerant of overloads.	“Open” water system required. Can suffer from cavitation or corrosion.
“Bolt-on” variable fill water brake	Cheap and simple Installation. Up to 1000 kilowatts (kW).	Lower accuracy of measurement and control than most fixed machines.
Disk-type hydraulic	Suitable for high speeds such as required in small turbine testing.	Poor low speed performance.
Hydrostatic	For special applications, provides four-quadrant performance.	Mechanically complex, noisy, and expensive. System contains large volumes of high pressure oil.
Direct current (DC) electric motor	Mature technology, four-quadrant performance. Limited in automotive top-speed range.	High inertia, commutator and brushes require maintenance, harmonic distortion of supply possible.

** Superscript numbers correspond to Appendix C, References.

TABLE 1. CONTINUED

DYNAMOMETER TYPE	ADVANTAGES	DISADVANTAGES
Asynchronous motor alternating current (AC)	Now mature technology, lower inertia for same rating than DC. Four-quadrant performance. Higher speed range than DC.	Expensive. Large drive cabinet needs suitable housing. Care must be taken in environment of the drive unit and power system.
Permanent magnet motor	Lowest inertia, most dynamic four quadrant performance. Small size in cell.	Very Expensive. Large drive cabinet needs suitable housing.
Eddy current, water cooled	Low inertia (disk type air gap) well adapted to computer control. Mechanically simple.	Vulnerable to poor cooling supply. Not suitable for sustained rapid changes in power (thermal cycling).
Friction brake	Special purpose applications for very high torques at low speed.	Limited speed range.
Air brake	Cheap, very little support service needed.	Noisy, limited control accuracy.
Hybrid	Possible cost advantage over sole electrical machine.	Complexity of construction and control.

c. The selection of the bedplate and engine mounting system must take into consideration any forces, vibrations, and noise developed by the engine. It must also be able to withstand the environment of test cell and transient forces that may be caused by earthquakes, unexpected abrupt shutdowns, and shock from neighboring firing programs, test course vibrations, or local heavy equipment operations. Temperature fluctuations, humidity, and flooding must also be considered and addressed. Dynamometer manufacturers will usually provide technical requirements specific to size and type of dynamometer they produce. Many manufacturers and some third party companies also provide consulting and design services to aid in this part of the test cell construction.

d. Much consideration should be given to the layout of the test cell. Several factors need to be considered such as:

(1) Location of the emergency exits.

(2) Ability to move the engine in and out of the test cell.

(3) Access to the dynamometer for calibration and maintenance.

(4) The location of make-up air inlets and exhaust outlets.

(5) The location and connections of supporting equipment such as coolant, charge air, and fuel lines.

(6) The proximity of fire and heat detectors, and fire suppression systems.

(7) The location, open view, and composition of the observation window.

(8) The location of toxic fume detectors for heavy and light combustion gases.

(9) Adequate lighting.

(10) Clearance for personnel to perform maintenance, install instrumentation, and handle fluids from the engine.

e. The energy balance in the cell must also be considered when determining the size and volume of the test cell. Considerations should be taken to ensure there is enough volume and air flow to maintain desired temperature set points and operating ranges. Some factors to consider for maintaining energy balance in the test cell are:

(1) Air intake inlets should be unrestricted and adequately sized to provide fresh air to the engine intake as well as the test-cell area. Ideally, they will have the ability to be variable depending on demand.

(2) The engine generates significant amounts of thermal heat. Inlet air should be located in close proximity or ducted in such a manner that it is forced to pass over the engine and then be evacuated from the cell via an exhaust fan. The air volume in the cell, and the ability to vary the speed of the exhaust fan, can help to ensure more constant temperatures for longer periods of testing.

(3) The conditioning systems also radiate thermal heat. This heat can be introduced into the cell via return fuel, coolant, oil, or charge-air plumbing. Insulating these pipes and hoses can help reduce the amount of thermal heat, but additional make up air is usually required.

(4) The engine exhaust can generate a large volume of heat (and toxic fumes), and therefore should be directly plumbed to a safe location outside the test cell. This location must be high enough and located such that it will not be able to be drawn back into the facility via make-up air inlet or heating, ventilation, and air conditioning (HVAC) system. Care must be taken to match back pressure, as the engine would be subjected to fluctuations by the original equipment manufacturer (OEM) exhaust system for its intended application. Excessive back pressure or vacuum may affect the engine performance.

f. The fuel system can be as simple as an approved containment tank plumbed into the engine feed (and return if applicable). However, most dynamometer applications for research, development, and testing require extremely accurate fuel consumption measurement, and the ability to temperature condition the fuel. Most dynamometer manufacturers and several other companies make equipment suitable for the supply, conditioning, and measurement of the consumed fuel. It is preferred to have the equipment integrated with the dynamometer control software so fuel usage is in the same data stream as test item and other supporting equipment and instrumentation in the test cell. Consideration should be taken to ensure that the integration is possible and the cost to do so is considered. The fuel system usually requires process water to cool the fuel, high current capacity electric supply for heaters, and pneumatic supply to operate solenoid valves. The plumbing must be carefully sized to suit the application. If the plumbing is insufficient, it can starve the engine, and too large diameter and/or too long of distance may cause the fuel system to not be able to maintain temperature controls. The plumbing must be made of a durable material, such as stainless steel, and have high quality connections and valves. The fuel supply must be properly vented to the outside of the building, and away from any source of combustion. A spark arrestor is usually required as an additional safety precaution and to meet local codes. All fuel sources located inside the building should have some sort of fire barrier and be constantly monitored by an automated fire suppression system. The fuel storage in the facility must meet state and local regulations as defined by the local fire department. The fuel storage in the facility must also meet environmental requirements and should have some sort of secondary containment.

g. The test cell control system can be as basic as a manual control, but is usually much more sophisticated. Systems such as iTest, from A&D Technology Inc.[***], are developed to give the operator the ability to author very specific automated test schedules by controlling the engine and dynamometer. Additionally, these systems also communicate with safety features such as over-speed limits, toxic gas monitors, and feedback from supporting equipment to verify that the system is operating correctly throughout the test. The ability to understand and program control software gives the operator the ability to design and execute very specific tests, and maintain extremely repeatable conditions. Training is often available through the software manufacturer and is usually offered at training facilities or onsite. It is critical that the operator be proficient in the software prior to running a test involving the dynamometer or engine under test. Software limits and ramp-rates should be established by qualified personnel prior to use by inexperienced operators.

h. The test cell should be equipped with combustion gas monitors that automatically give the cell operator an audible and visible indication that above-normal levels of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), etc. have been detected. Advanced systems have inputs tied into the control software that will notify the operator of low levels and will shut the cell down if they exceed a predetermined high level limit. These gases are usually an indication of exhaust leak, inadequate cell ventilation, or excessive blow-by from the crank-case breather.

i. Environmental conditions that affect combustion such as temperature, humidity, and barometric pressure are recorded before, during, and after testing. The optimal test cell has these sensors mounted in locations that are the most representative of the actual environment, away from direct heat sources, air flow, etc. The data from these sensors are usually fed to the control system and recorded in the data stream with the test data. This information is usually recorded and displayed on automated reports and data logs so that accurate assumptions and comparison can be made when analyzing the results.

*** The use of brand names does not constitute endorsement by the Army or any other agency of the Federal Government, nor does it imply that it is best suited for its intended application.

j. Automatic fire-suppression is recommended and may be required by Federal, State, and local fire codes and regulations. Due to the presence of electronics and possible fuel spillage, water deluge systems are not recommended in test cells. The typical agent used for suppressing fires in engine test cells is compressed carbon dioxide (CO_2) gas. It is important to note that CO_2 works by displacing the oxygen source to the fire. If breathed in, it can also displace oxygen in lungs and cause suffocation. The fire suppression systems usually have a waring alarm that sounds 30 seconds prior to discharge. A plan should be in place for all personnel to meet at a designated location. There must be signs posted to warn emergency responders of the presence of CO_2 in the area on every entrance door to the test cell. "Agent Abort" pull stations should be installed by all emergency activation switches so that the system discharge may be delayed if personnel have not evacuated the cell prior to the countdown of the warning alarm. It is also important to note the CO_2 only suppresses the fire if it remains contained in the area. All HVAC systems, exhaust fans, intake louvers, doors, and windows must be closed to the cell. It is recommended to automate the test cell as much as possible to close off air supply in the event of a fire. A compressed CO_2 system is shown in Figure 1.

Figure 1. Automatic CO_2 fire suppression system.

k. The test cell layout may dictate the type handling system that is required to install and maintain the dynamometer, conditioners, and engines to be tested. Some layouts allow for a forklift to set the equipment in place. Some types of engine carts can be pushed around on heavy caster wheels that lock into a fixed receiver. Usually, the test cell has some type of overhead crane or jib crane that can be used to assist in handling the equipment and helping to support the weight of the engine to make fine tune adjustments when mounting. An example of a typical engine test cell is shown in Figure 2.

Figure 2. Typical engine test cell.

2.2 Specialized Equipment and Instrumentation.

a. Climatic. Refer to TOP 02-2-650 Engine Cold Starting and Warm-up Test[2], TOP 02-2-816 High and Low Temperature Test of Vehicles[3], and Military Standard (MIL-STD)-1400C Engines, Gasoline and Diesel, Methods of Test[4].

b. DC power processing equipment may be utilized to place static and dynamic electric loads on the engine's charging system. The relationship between shaft speed, load in amperes, and the amount of torque required at 28 volts direct current (VDC) for a 570 amp (A) Neihoff alternator is shown in Figure 3. The torque required to generate this electric power is a draw on the engine that must be accounted for during testing. Some test scenarios may require that this be taken into account when analyzing the engine test results with no charging system on the engine. Some tests may be designed to specifically target the relationship of the charging system and how the electric load affect engine performance, fuel consumption, or emissions. These relationships can also influence operational procedures such as when a high-idle mode may be required, or when insufficient power is experienced at high altitudes.

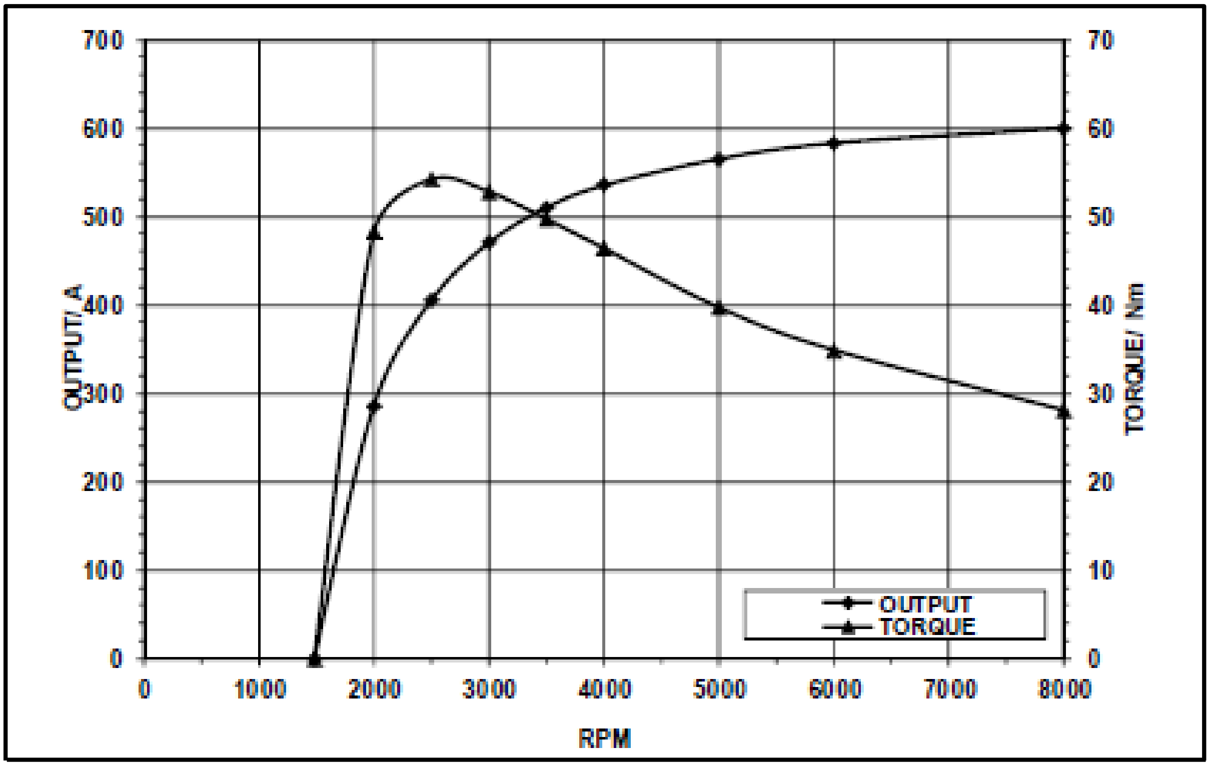

Figure 3. Drive torque in Newton meter (Nm) and output in amperes versus alternator shaft speed in revolutions per minute (rpm) required to produce output curve. Alternator characteristic for 28 V, 570 A, taken at 22 °Celsius (C) (72 °Fahrenheit (F)).

c. The efficiency curve for each specific alternator should be considered when analyzing engine performance in relation to drive profiles or duty cycles. Military vehicles face an ever increasing demand for electric power to supply both the vehicle electronics and Government Furnished Equipment (GFE) such as communications, tracking devices, and electronic countermeasures. An example of a 570 amp Neihoff alternator output and efficiency curve is shown in Figure 4.

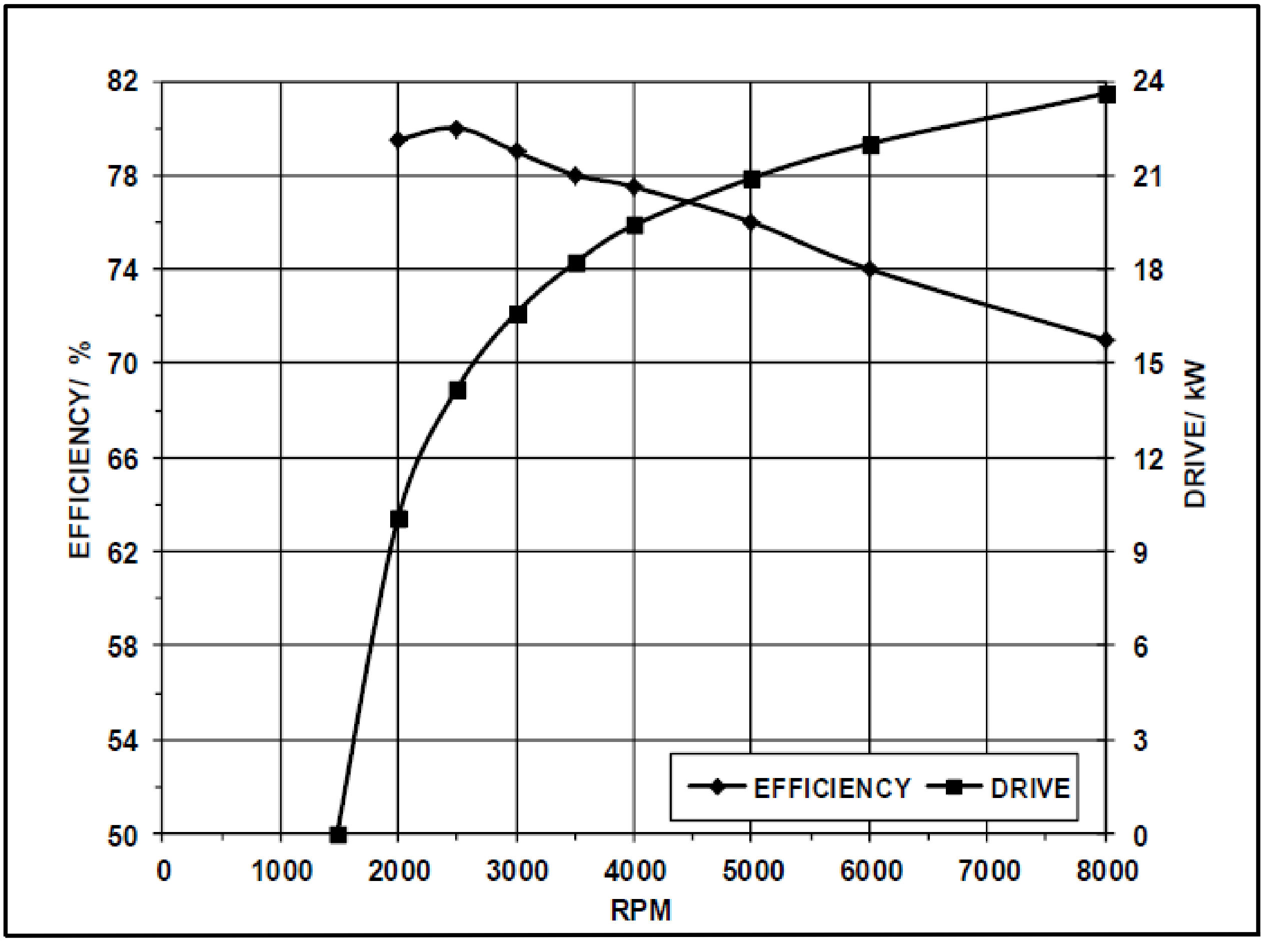

Figure 4. Drive horsepower in kW and efficiency in percentage of output power divided by input power versus alternator shaft speed in rpm required to produce output curve. Alternator characteristic for 28 V, 570 A, taken at 22 °C (72 °F).

d. An emissions analyzer may be required to support testing where accurate measurements of CO, CO_2, oxygen (O_2), NO, and total hydrocarbon emissions (THC) must be made in compliance with the Environmental Protection Agency (EPA) Code of Federal Regulations (CFR) 1065[5]. Most modern analyzers have the capability to interface with On Board Diagnostics (OBD) and record vehicle ECM parameters along with the emission data.

e. Evaporative cooling towers or some other form of heat rejection equipment will be required to conduct engine testing. The cooling capacity, volume, and operation will vary greatly depending on climate, type of dynamometer, type of drive, and other heat rejection loads such as engine coolant, return fuel, engine oil, and charge air. These systems usually have independent controls and make necessary adjustments based on cooling demand. The larger the overall volume of the system, the more resilient it will be to temperature spikes and drops that occur during dynamic testing. An example of an evaporative cooling tower system is shown in Figure 5.

Figure 5. Example of an evaporative cooling tower system.

f. The ECM is a very important component in engine testing. It can affect performance, fuel consumption, emissions, starting, shutdown, and serve to protect the engine. It is recommended that the test cell operator obtain a detailed wiring schematic for the ECM from the manufacturer and fully understand its operation prior to testing. An example of a detailed electrical systems schematic is provided in Caterpillar Schematic, C7 Truck Engine Electrical System, RENR7869[6]. Some basic aspects of the ECM critical to conducting any test are:

(1) ECM Power. The power provided to the ECM is distributed to numerous sensors that return a scaled feedback voltage from whichever parameter they are measuring. The power is also provided to a processor that makes calculations and necessary adjustments required to start, run, and shutdown the engine.

(2) ECM Throttle. Most engine applications use an electronic, Pulse Width Modulated (PWM) voltage to control the amount of fuel being sent to the fuel system. The amount and timing of the fuel is controlled by the ECM, versus manual control of the throttle.

(3) The Controller Area Network (CAN) is a standardized digital interface that allows the communication of information in a vehicle between sensors, electronic control units, and computers. Refer to TOP 01-2-506 Use of Controller Area Network (CAN) Data to Support Performance Testing[7].

(4) Battle Damage. Battle damaged analysis must consider the differences of electronic vs. manual controls, as well as procedures to read, understand, and clear faults identified by the ECM.

(5) There are multiple manufacturers and types of torque transducers used for measuring quasi-static force. Some are very simple and basic, such as dead weights and spring gauges, but most modern systems use hydraulic load cells or strain gauge load cells. Examples of various types of commonly used torque transducers for dynamometer applications can be found at the following link: http://www.hbm.com/en/menu/products/transducers-sensors/.

g. Speed sensors are commonly integrated into the torque transducers, but are also found as encoders on the back side of the shaft of the dynamometer. The engine speed is usually monitored and broadcast over the CAN bus as one of the SAE J1708[8] or J1939[9] channels. Engine speed can also be measured independently, and is usually a direct coupling to the dynamometer shaft, and therefore equal to the dynamometer shaft speed.

h. Coolant, fuel and oil conditioners are often required to maintain desired temperature set points within a very small range. They usually use process water for cooling and an immersion-style heating elements to warm the fluids. Theses conditioners use feedback and control loops that interface with the control software to maintain, display, and record the values. High and low temperature warnings can be established to notify the operator if the conditioners are not able to keep the fluids within desired temperature setting ranges of typically ±3 °C (±5 °F) or less.

i. A Charge Air Cooler (CAC) is usually required to cool the combustion air that heats up due to being compressed by the turbocharger. The CAC operates within a range of the desired set point. Most applications use process water to cool the charged air by means of a liquid cooled heat exchanger.

j. Traditional instrumentation and data acquisition systems are used to measure pressure, temperatures, pulses, and accelerations. Most COTS systems provided by dynamometer manufacturers have provision for all the channels necessary to operate the equipment and take all desired measurements of the test engine.

2.3 Safety Concerns and Equipment.

a. Rotating components such as shafts must be covered by a shaft guard. Care must also be taken to ensure all bolts are torqued properly and inspected periodically. It is also important to stay clear of the engine while it is running and block off areas where belts and pulley are spinning. Loose clothing, jewelry, badge lanyards, etc. are source of potential hazards and do not belong in the test cell.

WARNING

Never, under any circumstances, attempt to occupy test cells when engine is rotating faster than 1000 rpm.

Never, under any circumstances, attempt to make changes or adjustments to the engine, dynamometer, or coupling with the engine running or the dynamometer drive mechanism enabled.

Always use a safety guard around rotating shafts and only view testing above 1000 rpm through shatterproof windows.

b. Toxic fumes are addressed in paragraph 2.1.h. Operators should always use caution to wear the proper Personal Protective Equipment (PPE) when handling fuels, coolants, engine oil, and other automotive related fluids. Additional information is provided in the article “Skin Problems in Motor Vehicle Repair Workers” located at http://www.dermnetnz.org/reactions/mechanics.html[10].

c. Combustible fluids must be stored in approved containers and away from potential heat sources. Automatic fire suppression is addressed is paragraph 2.1.j. Caution should be taken to ensure that power is removed to fuel system pumps, and that residual pressure is carefully bled off prior to disconnecting fuel lines.

d. High temperatures will be present in varying degrees on many components in the test cell. Exhaust gasses, crank-case breather gases, coolant, oil, and fuel may also be very hot. The operator should always wear the proper PPE and allow for adequate time for cooling. Thermal sensors can also be utilized to verify that components have cooled to safe handling temperatures.

e. Exposure to excessive noise levels can cause short- and long-term damage to hearing. Proper PPE should be worn to include double hearing protection. Noise can also make several hours of testing extremely uncomfortable. Many options are available to mitigate noise emitting sources. Ensure that exhaust noise is directed away, driveline vibrations are absorbed and isolated, and not transmitted. Acoustic dampening materials can be installed in the cell and control area. Heavy, well-sealed doors and windows can also help. More in-depth information can be found in SAE Engine Testing - The Design, Building, Modification and Use of Powertrain Test Facilities, 4th Edition[1].

f. High voltage drive cabinets are very common for modern dynamometers. They must be serviced and maintained by qualified personnel. Some regenerative drives may have multiple power sources and require all sources to be properly locked out. Temporary stored power sources must also be given adequate time to discharge.

g. General test cell safety requires the cooperation of all facility related personnel. Strict adherence to Lock Out/Tag Out procedures, shut-down and start-up procedures, equipment maintenance, cleanliness, and use of safety systems can help to mitigate the risk of personal injury. The use of checklist, interlocks, and automation is encouraged to reduce the likelihood of missing a key step during set-up or operation of the cell.

2.4 Calibration.

a. All measuring tools and instrumentation will be calibrated against a higher order standard at periodic intervals not to exceed twelve months. Records, showing the calibration traceability to the National Institute of Standards and Technology (NIST), will be maintained for all measuring and test equipment.

b. All measuring and test equipment and measuring standards will be labeled with the following information:

(1) Date of calibration.

(2) Date of next scheduled calibration.

(3) Name of the organization and technician who calibrated the equipment.

c. A written calibration report will be provided that includes as a minimum the following information for all measurement and test equipment:

(1) Type of equipment, manufacturer, model number, etc.

(2) Measurement range.

(3) Accuracy.

(4) Calibration interval.

(5) Type of standard used to calibrate the equipment (calibration traceability of the standard must be evident).

d. Equipment to be calibrated:

(1) Accelerometers.

(2) Torque transducers.

(3) Fuel systems.

(4) Speed transducers.

(5) Pressure transducers.

(6) Temperature transducers.

(7) Exhaust gas analyzers.

2.5 Preventive Maintenance.

a. Test equipment must be properly maintained to ensure reliable accurate measurements. Preventive Maintenance (PM) can detect abnormal vibrations that indicate an imminent bearing failure, motor problem, set-up issue, etc. Many equipment manufacturers offer PM packages along with calibration services. The level and frequency of PM can vary depending on use and environmental conditions. Budget, workload, personnel, and many factors will determine each specific test cell PM program. Efforts taken to prevent problems almost always tend to be more cost effective than efforts taken to repair problems. Records and reports should be kept and tracked and analyzed to identify trends and predict major repair or maintenance intervals.

b. The test engine should be maintained per manufacturer recommendations. It should also be subjected to daily Preventive Maintenance Checks and Services (PMCS) prior to and post testing. Extreme loading or aggressive testing may dictate frequent periodic inspection intervals. Instrumentation and engine components should also be inspected frequently to ensure mounting and wire routing is not damaged and is clear of rotating parts.

3. REQUIRED TEST CONDITIONS.

3.1 Preparation for Testing.

3.1.1 Initial Inspection.

a. Visually inspect the engine upon arrival for damage. Document any physical damage of the test engine as described in Appendix D of MIL-STD-1400C.

b. Record the physical description of the test engine as described in MIL-STD-1400C.

3.1.2 Mounting.

a. Make all electrical connections necessary to provide power to ECM and charging system if applicable.

b. Plumb in the coolant conditioner feed hose into the engine water pump. If necessary, block the thermostat open before connecting the upper hose from the thermostat housing to the coolant conditioner return hose.

c. Plumb the oil conditioner into the oil filter housing if test requires additional cooling.

d. Plumb in the fuel supply and return (if applicable) to the fuel measurement system.

e. Connect combustion air inlet to air filter housing or facility air supply.

f. Connect the charge air cooler to the turbocharger and air inlet if applicable.

g. Connect the ECM with manufacturer diagnostic software or custom software to monitor engine parameters and view diagnostic codes.

h. Connect any additional instrumentation according to detailed test plan.

3.1.3 Fluids.

a. Fill engine oil, coolant system, and open appropriate valves for oil, coolant, and fuel system. Use only manufacturer approved engine oil, coolant, and fuel.

b. Check for leaks and resolve any issues that are found.

3.1.4 Couple Engine to Dynamometer.

a. Connect the appropriate sized absorber to the crankshaft ensuring all bolts are torqued appropriately.

b. Connect the appropriate sized and balanced driveshaft to the absorber and to the torque flange on the dynamometer shaft. Ensure that all bolts are sized and torqued appropriately.

c. Inspect engine and dynamometer for interference caused by belts, wires, or misalignments. Ensure there are no loose tools or hardware on the engine or inside the crank-case housing. A typical installation is shown in Figure 6.

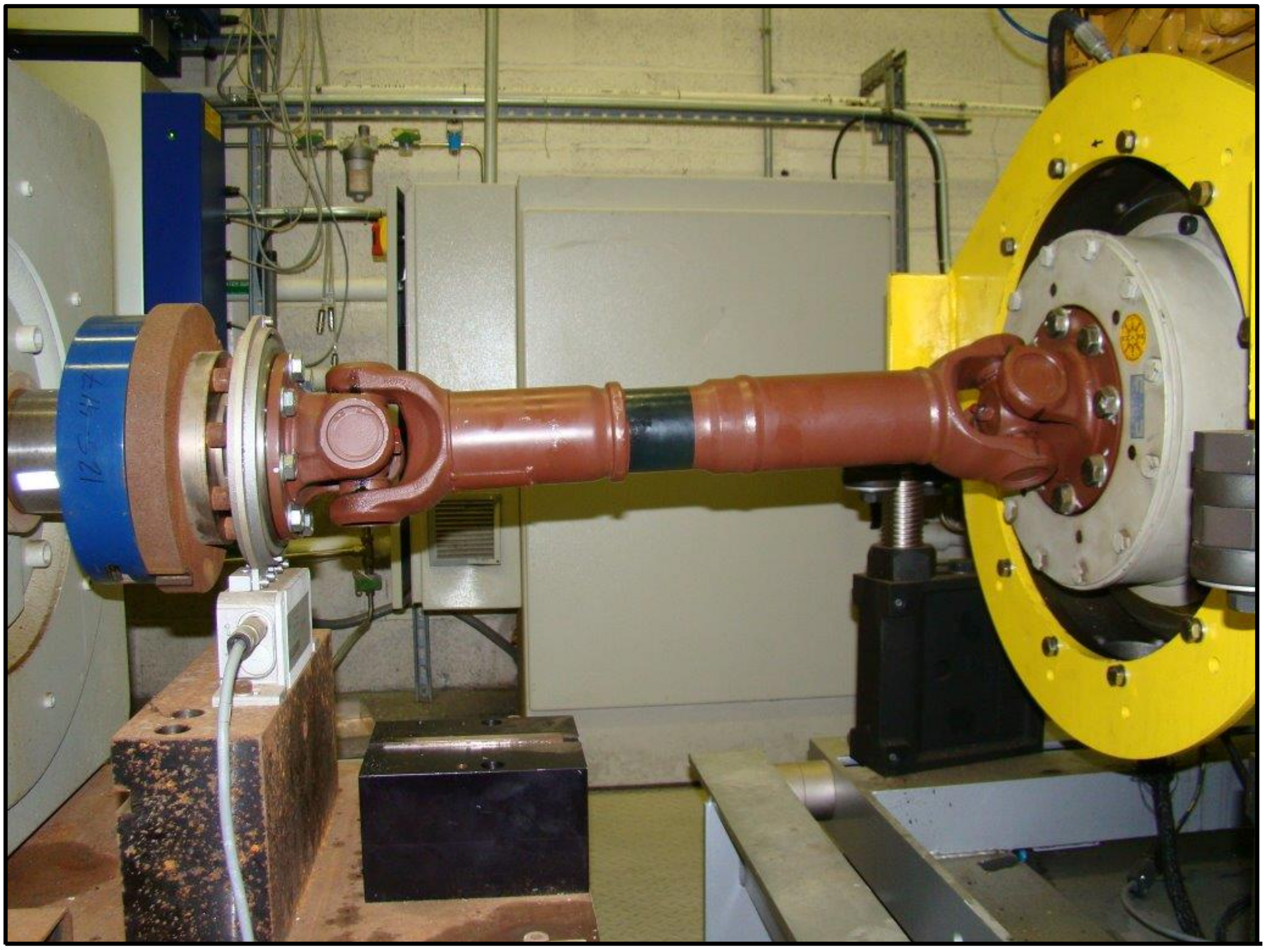

Figure 6. Coupling the engine to the dynamometer.

d. Install the shaft guard. An example of a shaft guard is shown in Figure 7.

Figure 7. Shaft guard installed.

3.1.5. Initial Operation.

a. Follow test cell start-up procedure and enable the dynamometer and supporting equipment. Check for leaks in all fluids, paying particular attention to fuel connections. Select the automated start procedure or manually command the starting mechanism to engage.

b. Start the engine and assure smooth operation. Run engine according to manufacturer's recommended procedures.

3.2 Test Controls.

a. If available, ensure that all software limits for speed, torque, and temperature are set correctly and are active.

b. Utilize manufacturer software to monitor the engine for faults and warnings.

c. Ensure that test cell and engine start-up checklist is complete.

d. Verify all emergency-stops are operational and a normal shutdown procedure is implemented to release load and drop throttle at safe, controlled rates. Ensure that engine components like the turbocharger have time to cool and exhaust gas temperatures (EGT) return to normal no-load operating temperatures prior to shut down.

e. If possible, run a baseline test, such as a power curve, prior to making any changes to the test engine for future reference or diagnostics.

3.3 Required Information.

a. Type of fuel.

b. Type of oil.

c. Type of coolant (when applicable).

d. Calibration identification number from ECM.

e. Any failures or irregularities in operation.

4. TEST PROCEDURES.

4.1 Types of Tests.

Additional information on the types of tests listed in this section can be found in the following reference: SAE Engine Testing - The Design, Building, Modification and Use of Powertrain Test Facilities, 4th Edition[1].

4.1.1 Steady State.

The engine is held at a specified rpm (or series of usually sequential rpms) for a desired amount of time by the variable brake loading as provided by the power absorber unit (PAU). These are performed with brake dynamometers.

4.1.2 Sweep Test.

The engine is tested under a load (i.e., inertia or brake loading), but allowed to sweep up in rpm, in a continuous fashion, from a specified lower starting rpm to a specified ending rpm. These tests can be done with inertia or brake dynamometers.

a. Simple Fixed Load Sweep. A fixed load - of somewhat less than the output of the engine - is applied during the test. The engine is allowed to accelerate from its starting rpm to its ending rpm, varying at its own acceleration rate, depending on power output at any particular rotational speed. Power is calculated using (rotational speed x torque x constant) + the power required to accelerate the dynamometer and engine's rotating mass.

b. Controlled Acceleration Sweep. Similar in basic usage as the Simple Fixed Load Sweep Test, but with the addition of active load control that targets a specific rate of acceleration.

4.1.3 Transient Test.

This test is usually conducted with AC or DC dynamometers, the engine power and speed are varied throughout the test cycle. Aggressive throttle movements, engine speed changes, and engine motoring are characteristics of most transient engine tests.

4.1.4 Common Dynamometer Tests.

a. Net Horsepower. Used to determine maximum horsepower sustained for at least 10 minutes with all nonessential accessories installed on the engine. Additional information is provided in MIL-STD-1400C.

b. Gross Horsepower. Used to determine maximum horsepower sustained for at least 10 minutes without all non-essential accessories. Additional information is provided in MIL-STD-1400C.

c. Accessory Losses. Used to determine maximum horsepower sustained for at least 10 minutes by removing individual nonessential accessories installed on the engine to determine the losses caused by each assessor. Additional information is provided in MIL-STD-1400C.

d. Motoring Friction. Used to determine the power required to overcome engine friction, also known as friction horsepower. Additional information is provided in MIL-STD-1400C.

e. Blow-by. The amount of combustion gases that escape into the crankcase during the combustion cycle. Additional information is provided in MIL-STD-1400C, and is illustrated in Figure 8.

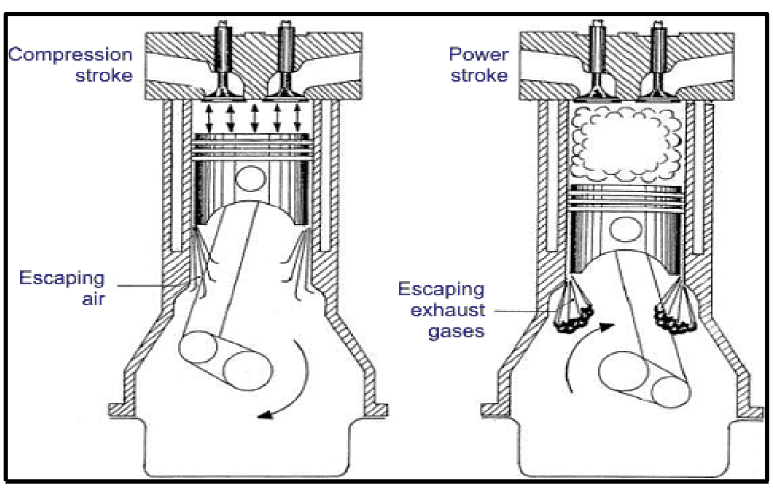

Figure 8. Combustion blow-by.

f. Fuel Consumption. Used to determine the economy of the engine in accordance with TOP 02-2-603A[11].

g. Oil Analysis and Consumption. Used to analyze the rate of oil consumption, health of oil, and condition of internal components in accordance with TOP 02-2-690[12] and where applicable, Alban Advantage Equipment Maintenance Services, Understanding Scheduled Oil Sampling (SOS), Equipment Maintenance Services[13].

h. Cold Starting. Used to determine the amount of torque required to overcome friction horsepower with different viscosity engine oils, optimize fuel/air ratio during cold starts, and various other parameters in accordance with TOP 02-2-650 and MIL-STD-1400C.

i. Performance Test. This test is commonly referred to as the “Power and Torque Curve”. This test provides the tester with an overall view of the engine’s output at different engine speeds and loads. Additional information is provided in MIL-STD-1400C.

j. Endurance Test.

(1) Involves extended operations of one or more test items operating a series of cycles designed to simulate extended field use under controlled, repeatable, proving ground conditions. The endurance test is the principal means of producing data for reliability and maintainability analysis.

(2) A durability test is designed to demonstrate a specified probability and confidence that a vehicle, or a major component, will be able to operate under defined conditions for a specified distance or operating time before needing a major overhaul, replacement, or salvage.

(3) Can be used to analyze the entire engine and accessory package, individual components, electronics, lubrications, fuels, and coolants. Additional information is provided in MIL-STD-1400C.

4.2 Data Recording.

4.2.1 Data Required.

a. The following is a list of the most commonly recorded data for dynamometer testing. This list can be greatly expanded upon depending on the requirements for specific application.

(1) Ambient temperature.

(2) Barometric pressure.

(3) Engine speed.

(4) Torque.

(5) Air intake rate.

(6) Intake air pressure.

(7) Exhaust pressure.

(8) Fuel pressure.

(9) Oil pressure.

(10) Intake air temperature.

(11) Exhaust temperature.

(12) Fuel temperature.

(13) Oil temperature.

(14) Fuel intake rate.

(15) Spark advance (gasoline engines only).

(16) Exhaust smoke analysis.

(17) Turbocharger boost pressure.

(18) Intake air density.

b. There are also several applicable channels that can be recorded from the ECM CAN. Common channels available on the data bus can be referenced, but in many cases must be verified by NIST traceable calibration source. A list of some of these channels follow:

(1) Throttle position.

(2) Percent engine load.

(3) Boost pressure.

(4) Intake manifold temperature.

(5) Barometric pressure.

(6) Engine coolant temperature.

(7) Engine oil temperature.

(8) Injection control pressure.

(9) Battery voltage.

(10) Engine speed.

(11) Fuel rate.

(12) Instantaneous fuel economy.

(13) Total idle hours.

(14) Total fuel consumption.

(15) Vehicle identification number.

(16) Total hours.

(17) Total engine power take off (PTO) hours.

5. PRESENTATION OF DATA.

5.1 General.

Individual test procedures referenced in this TOP should be reviewed and followed carefully. Data requirements, test controls and conditions, data analysis, and presentation should be followed. Appendix A of this TOP provides some of the more commonly used definitions.

5.2 Data Presentation.

Data are presented in various forms, usually only focusing on a few of the many parameters that are recorded. The most typical form of dynamometer test data presentation is the performance curve as shown in Figure 9.

TEST REPORT

A&D Technology, Inc.

Report Version 1.0

1. Test			
Test Date	05-11-2015	Cell Number	C2
Test Time	2:11:35 PM	Air Temperature	-999.0 °F
Test Name	RampPowerCurve	Atmospheric Pressure	-999.0 in Hg
Test Engineer	Administrator	Relative Humidity	-999.0 %
Test Reference	May112015_Run1		

2. Engine Specification			
Engine Description	C7	Engine ID	CAT C7-FMMO5506

3. Test Results					
Max Torque	793.0 lb-ft	1498 RPM	Max Power	303.6 HP	2400 RPM

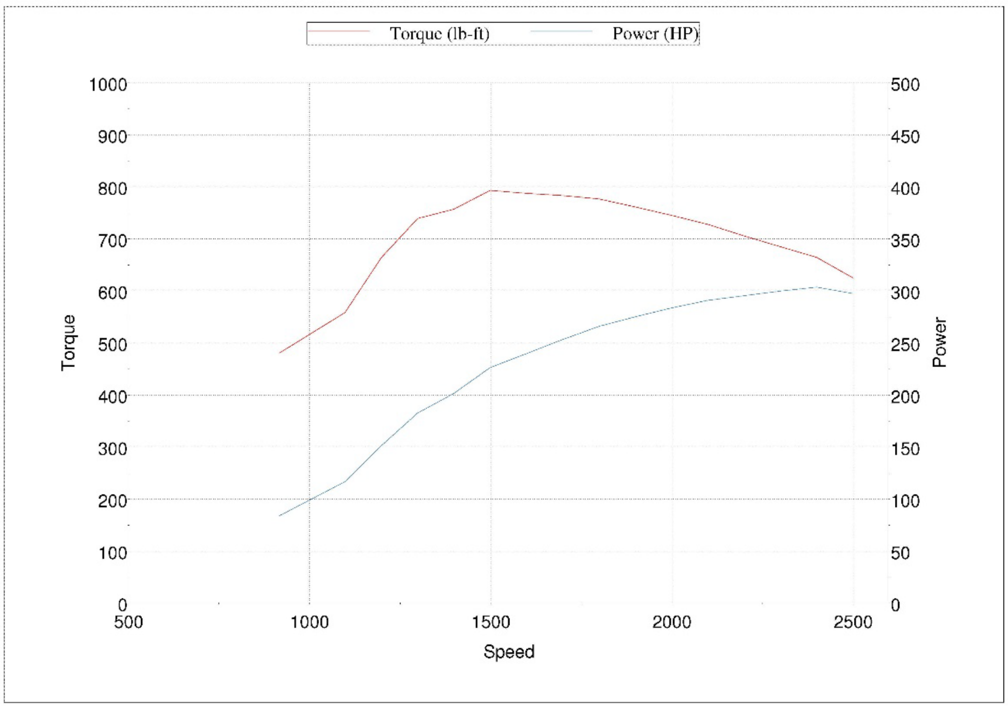

Figure 9. Typical horsepower and torque curve.

APPENDIX A. GLOSSARY.

Term	Definition
Absorber	A tuned spring-mass system which reduces or eliminates the vibration of a harmonically excited system. Rotating machines such as engines, motors, and pumps often incite vibration due to rotational imbalances.
Alternating current (AC) Dynamometer	AC electric motor/generator dynamometer that can be used to absorb the power of the engine and can also drive the engine for measuring friction, pumping losses, and other factors. It can also be configured to regenerate power generated by the test engine and return power to the utility grid.
Air-fuel ratio (AFR)	AFR is the mass ratio of air to fuel present in a combustion process such as in an internal combustion engine or industrial furnace. The AFR is an important measure for anti-pollution and performance-tuning reasons.
Blow-by	Leakage of the air-fuel mixture or of combustion gases between a piston and the cylinder wall into the crankcase of an automobile.
Burn rate	The time required for the air/fuel mixture to burn completely (the speed at which fuel releases its energy) with the piston near top dead center of the stroke. The faster the fuel burns, the more efficient the engine and the more power it will generate and the better fuel economy it will get.
Cam shaft	The camshaft is used to operate poppet valves. It then consists of a cylindrical rod running the length of the cylinder bank with a number of oblong *lobes* protruding from it, one for each valve. The cam lobes force the valves open by pressing on the valve, or on some intermediate mechanism as they rotate.
Cardan shaft	A mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.
Cetane number (CN)	CN is an inverse function of a fuel's ignition delay, and the time period between the start of injection and the first identifiable pressure increase during combustion of the fuel.

APPENDIX A. GLOSSARY.

Term	Definition
Charge air cooler	Used to cool engine air after it has passed through a turbocharger, but before it enters the engine. The idea is to return the air to a lower temperature, for the optimum power for the combustion process within the engine.
Combustion ignition	Ignition in an internal-combustion engine in which the necessary high temperature is produced by compressing air in the cylinder before admission of the fuel (as in a diesel engine).
Compression ratio	In an internal combustion engine is a value that represents the ratio of the volume of its combustion chamber from its largest capacity to its smallest capacity.
Coolant conditioners	Heat exchanger used in place of radiator and cooling fan to maintain desired temperature of engine coolant. The conditioner has an electric heating element to heat and uses process water to cool the engine coolant.
Diesel fuels	Any liquid fuel used in diesel engines, whose fuel ignition takes place, without spark, as a result of compression of the inlet air mixture and then injection of fuel.
Dynamic testing	When change in control instruction and change in force at an AC dynamometer air gap is sensed and occurs in less than 10 milliseconds (ms).
Dynamometer	"Dyno" for short, is a device for measuring force, torque, or power.
Eddy current dynamometer	Uses a varying magnetic field in a coil to generate eddy currents in the end faces of the cooling chambers. These are directed such that the magnetic field they induce creates a torque which opposes the rotor‘s direction of rotation.
Electronic Control Unit (ECU) or Module (ECM)	A type of ECU or ECM that controls a series of actuators on an internal combustion engine to ensure optimal engine performance.
Engine speed	The rotational speed of the engine crank shaft usually described in rpm.

APPENDIX A. GLOSSARY.

Term	Definition
Evaporative cooling tower	Equipment that cools engine coolant, oil, fuel, charged air and electronics by transferring heat away via heat exchangers and then removing the heat by an evaporation process over outside coils.
Exhaust gas	A combination of many different gases: N_2, CO_2, H_2O, and O_2. Though some are harmless, there are few that are harmful and are considered major pollutants. One of the most dangerous of these is CO, carbon monoxide.
Exhaust gar recirculation (EGR)	EGR is a nitrogen oxide (NO_x) emissions reduction technique used in petrol/gasoline and diesel engines. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders.
Fire suppression system	Automatically controls and extinguishes fires without human intervention.
Flexible coupling	Prolongs driveline component life by reducing the magnitude of imposed loads, attenuating vibration in multiple planes, and accommodating misalignments in multiple planes.
Four-quadrant	Dynamometer motor that can load or motor in both directions.
Fuel conditioner	Heats, cools, and removes bubbles from fuel so that constant temperatures can be maintained and fuel density measurements remain accurate.
Harmonics	This condition is caused because every universal-joint (U-joint) that operates at an angle creates a vibration. It creates that vibration because the U-joint cross-rotates with the shaft in a circular motion while also moving from front to rear. That rocking back and forth motion as it rotates causes the cross in the U-joint to accelerate and decelerate.
Heat Exchanger	A device used to transfer heat between one or more fluids. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact.
Horsepower (hp)	One hp is the amount of power it takes to perform 33,000 foot-pounds (ft-lb) of work in 1 minute.

APPENDIX A. GLOSSARY.

Term	Definition
Injector system	The nozzle and valve through which fuel is sprayed into a combustion chamber.
Internal combustion engine	A heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber and the expansion of the high-temperature and high-pressure gases produced apply force to push the piston down, causing the crankshaft to rotate.
Knocking	Occurs in gasoline engines when combustion does not start correctly in response to the ignition by the spark plug and can be damaging to engine. In diesel engines fuel is injected into highly compressed air towards the end of the compression stroke. There is a short lag between the fuel being injected and combustion starting which causes a sudden increase in pressure and temperature that makes the “knocking” sound.
Mean effective pressure	Average pressure acting on a piston during different portions of its cycle.
Motoring tests	Test where electric motor type dynamometers spin the test item.
Oil conditioner	Heat exchanger used in place of oil cooler to maintain desired temperature of engine oil. The conditioner has an electric heating element to heat and uses process water to cool the oil.
Parameter IDs (PIDs)	PIDs are On-Board Diagnostic (OBD) codes used to request data from a vehicle, used as a diagnostic tool. SAE J1979[14] defines many PIDs, but manufacturers also define many more PIDs specific to their vehicles.
Process water	Water that comes in contact with any raw material, product, by-product, or waste during any production or industrial process.
Ramp rate	Rate at which engine accelerates or decelerates.
Shaft couplings	Connects engine to dynamometer taking into account torsional oscillations, vibration of engine and/or dynamometer, whirling of coupling shaft, imposition of axial loads on bearings of engine or dynamometer, damage to engine or dynamometer bearings, and catastrophic failure of coupling shafts.

APPENDIX A. GLOSSARY.

Term	Definition
Shaft whirl	The speed at which a rotating shaft will tend to vibrate violently in the transverse direction if the shaft rotates in horizontal direction.
Spark ignition	Refers to internal combustion engines, generally gasoline/petrol engines, where the combustion process of the air-fuel mixture is ignited by a spark from a spark plug.
Speed mode	Mode in which the dynamometer holds the speed constant while engine controller progressively adjusts throttle.
Starting system	Electric motor dynamometers can spin the engine to get it to start, otherwise you will need an air starter or some other means to crank the engine over. This can be complicated because you also have to overcome the rotational inertia of the coupled dynamometer.
Sweep test	Continuously moving the engine through its operating envelope without dwelling.
Test cell	A facility or designated area of a facility that has the equipment necessary to test engines in a safe and controlled environment.
Throttle	Manual or electronic control that adjusts the amount of fuel flow to the engine.
Torque	Rotational or twisting force around an axis is called torque, which is measured in units of force times distance from the axis of rotation.
Torque mode	Mode in which the dynamometer is required to hold a specific torque during high fluctuations in load while the engine controller progressively adjusts throttle.
Torsional vibrations	Angular vibration along a shaft the can occur during engine testing by crankshaft geometry, discontinuous forces on pistons, geometry of universal joints, clutch engagement, (stick slip), and lash caused by change of rotation direction.
Torsional vibration dampeners	A viscous damper or tuned absorber connected to the crankshaft of an engine to reduce torsional vibration.

APPENDIX A. GLOSSARY.

Term	Definition
Transient testing	Aggressive throttle movements, engine speed changes, and engine motoring are characteristics of most transient engine tests.
Turbocharger	A forced induction device that uses exhaust gases to spin a turbine and create positive combustion air pressure (charged air) into the combustion chamber. The air becomes compressed and contains more oxygen molecules that can burn more fuel, and increases internal combustion engine's efficiency and power output.

APPENDIX B. ABBREVIATIONS.

A	amp
AC	alternating current
AFR	air-fuel ratio
APU	auxiliary power unit
ATC	U.S. Army Aberdeen Test Center
ATEC	U.S. Army Test and Evaluation Command
C	Celsius
CAC	charge air controller
CAN	Controller Area Network
CFR	Code of Federal Regulations
CG	center of gravity
CN	Cetane number
CO	carbon monoxide
CO_2	Carbon dioxide
COTS	commercial off the shelf
DC	direct current
DOD	Department of Defense
ECM	engine control module
ECU	engine control unit
EGR	exhaust gas recirculation
EGT	exhaust gas temperature
EPA	Environmental Protection Agency
F	Fahrenheit
ft	feet
ft-lb	foot pound
GFE	Government Furnished Equipment
hp	horsepower
HVAC	heating, ventilation, and air conditioning
kW	kilowat
lb	pound
MIL-STD	Military Standard
ms	milliseconds

APPENDIX B. ABBREVIATIONS.

NIST	National Institute of Standards and Technology
Nm	Newton meter
NO	nitric oxide
NO_2	nitrogen dioxide
O_2	oxygen
OBD	on board diagnostics
OEM	original equipment manufacturer
PAU	power absorber unit
PID	parameter identification
PM	preventative maintenance
PMCS	preventative maintenance checks and services
PPE	personal protective equipment
PTO	power take off
PWM	pulse width modulation
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SO^2	sulfur dioxide
SOS	scheduled oil sampling
THC	total hydrocarbon emissions
TOP	Test Operations Procedure
VDC	volt direct current

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APPENDIX D. APPROVAL AUTHORITY.

CSTE-TM 4 February 2016

MEMORANDUM FOR

Commanders, All Test Centers
Technical Directors, All Test Centers
Directors, U.S. Army Evaluation Center
Commander, U.S. Army Operational Test Command

SUBJECT: Test Operations Procedure (TOP) 02-2-700A Laboratory Test of Reciprocating Internal Combustion Engines and Powertrain Components, Approved for Publication

1. TOP 02-2-700A Laboratory Test of Reciprocating Internal Combustion Engines and Powertrain Components, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency. The scope of the document is as follows:

This TOP prescribes procedures for analyzing the performance and endurance of reciprocating internal combustion engines. Major factors to be considered when testing for performance include, but are not limited to, differences in fuels, lubrication, temperatures, engine control module parameters, component wear, exhaust, and air intake systems. Power train component such as transmissions and transmission steering devices are not covered in this TOP.

2. This document is approved for publication and will be posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 2202 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Range Infrastructure Division (CSTE-TM), US Army Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: Automotive Directorate (TEDT-AT-AD), U.S. Army Aberdeen Test Center, 400 Colleran Road, Aberdeen Proving Ground, MD 21005. Additional copies can be requested through the following website: http://www.atec.army.mil/publications/topsindex.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.