

ONLINE ENGINE EMISSION CALIBRATION AND ESTIMATION**TECHNICAL FIELD**

[0001] The present disclosure is related to internal combustion engines. In particular, the present disclosure is related to online estimation of internal combustion engine emissions.

BACKGROUND

[0002] Engine systems including internal combustion engines are often required to perform well in several areas that involve tradeoffs. Such areas of performance include power delivery, efficiency in terms of resource consumption (e.g., fuel consumption), and emission requirements, such as sociability requirements and/or regulatory requirements for emissions, such as smoke. For example, typically to deliver required power at a specific fuel consumption requires the trade-off of different engine-out emissions.

[0003] Engine systems often include a processing subsystem configured to control the engine. In order to meet these performance criteria, the processing subsystem may attempt to predict engine emissions in order to prevent emission transient events that would violate an emission requirement. To predict emission transient events, transient calibration data is often required, which results in extended engine calibration cycles. Furthermore, many predictive models used suffer from having limited fidelity or robustness under transient conditions (e.g., heavy transients), being computationally intensive, having limited transient applicability, and being dependent on in-cylinder sensors that are costly to implement or maintain. There remains the continuing need for more robust and accurate online prediction of engine emissions, particularly in heavy transient engine conditions.

SUMMARY

[0004] Aspects of various embodiments relate to a method for calibrating a predictive emission event model, comprising: subjecting an engine to a plurality of steady state engine conditions; interpreting, for each steady state engine condition, values of a key basis variable set; interpreting, for each steady state engine condition, an emission value; calibrating an emission predictive module to provide a predicted emission value in response to the values of the key basis variable set and the emission values for the plurality of steady state engine conditions; and calibrating a command generation module to predict an emission transient event in response to the predicted emission value. The predictive model is optionally a statistical model, such as a multivariate local regression model.

[0005] Further embodiments relate to a method for predicting an emission value transient event, comprising: determining a basis value set including at least one of an engine torque value, an engine speed value, a total fueling quantity value, a rail pressure value, a start-of-injection (SOI) value, in-cylinder [O₂] before SOI value, and an in-cylinder oxygen-to-fuel ratio (OFR) before SOI value; determining a predictive model output in response to the basis value set, the predictive model output being calibrated in response to a plurality of steady state engine conditions; and predicting a emission value transient event in response to the predictive model output.

[0006] The method optionally modifies an engine command in response to predicting the emission value transient event, such as a reduced fueling command. Further still, the method optionally determines an in-cylinder oxygen concentration before start of injection value in response to a virtual sensor.

[0007] Additional embodiments relate to a controller. The controller comprises a hardware description module (HDM) structured to interpret a basis value set including one or more of an engine torque value, a total fueling quantity value, an engine speed value, a rail pressure value, a start-of-injection (SOI) value, in-cylinder [O₂] before SOI value, and an in-cylinder oxygen-to-fuel ratio (OFR) before SOI value; an emission predictive module (EPM) structured to determine an EPM output in response to the basis value set, the EPM output being calibrated in response to a plurality of steady state engine conditions; and a command generation module (CGM). The CGM is structured to: predict an emission transient event in response to the EPM output; and determine a modified engine command set in response to the predicted emission transient event.

[0008] The CGM optionally provides a reduced fueling command. Further still, the method optionally determines an in-cylinder oxygen concentration before start of injection value free of an in-cylinder oxygen sensor.

[0009] While multiple embodiments are disclosed, still other embodiments of the present invention will become apparent to those skilled in the art from the following detailed description, which shows and describes illustrative embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a schematic illustration of an engine system utilizing a controller for predicting an emission transient event, according to some embodiments of the disclosure.

[0011] FIG. 2 is a schematic illustration of a processing subsystem including the controller of FIG. 1 to perform certain operations to predict an emission transient event, according to some embodiments.

[0012] FIG. 3 is a schematic flow chart diagram of an example procedure for calibrating the engine system of FIG. 1, according to some embodiments.

[0013] FIG. 4 is a schematic flow chart diagram of an example procedure for operating the system of FIG. 1, according to some embodiments.

[0014] FIG. 5 is a graph of an example result set including a predicted emission value and an actual emission value over time during operation of the engine system of FIG. 1, according to some embodiments.

[0015] While the invention is amenable to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and are described in detail below. The intention, however, is not to limit the invention to the particular embodiments described. On the contrary, the invention is intended to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

[0016] FIG. 1 is a schematic illustration of an engine system 100 utilizing a controller 125 for predicting an emission transient event, according to some embodiments of the disclosure. As shown, the system 100 includes an engine 105 and various subsystems, such as a fuel system 110, an air handling system 115, and an aftertreatment system 120. An example system 100 includes a controller 125 (e.g., ECM) coupled to the engine 105, which provides and receives signals related to various engine components, such as receiving measurement signals from sensors disposed in the engine 105 and providing control signals or commands to the subsystems. Although not explicitly illustrated, the example controller 125 is also operatively coupled to other components of the system 100, such as the subsystems 110, 115, 120, so that the controller is in similar communication with those subsystems.

[0017] The system 100 decouples the generation of target values from the generation of command values. For example, the system 100 generates one or more engine commands in response to one or more basis variables. Though many variables can affect emissions performance of the system 100, one or more key basis variables are selected to characterize a majority of effects for an engine emission whether the engine is in a steady state or transient state condition, which may include heavy transient conditions. In some embodiments, additional key basis variables are included to facilitate characterizing other engine conditions, such as a cold

start. In response to the one or more key basis variables, the system 100 predicts an emission transient event. For example, the emission transient event may be a heavy-transient smoke spike that would violate jurisdictional emissions requirements or sociability requirements. In response to predicting the emission transient event, the system 100 provides or modifies one or more engine commands to then modify, mitigate, or prevent unwanted effects of the predicted emission transient event. The example system 100 modifies a nominal fueling amount to provide a reduced a fueling amount, or change in commanded rail pressure, to prevent the continued production of smoke. By limiting the continued production of smoke, the effect of a predicted smoke spike is mitigated.

[0018] The present disclosure contemplates control of emissions not limited to smoke. Non-limiting examples of emissions contemplated in this disclosure include smoke, hydrocarbon, carbon monoxide and/or dioxide, particulate matter, non-NOX emissions, any related quantities, and/or combinations thereof.

[0019] The level of emissions produced by an internal combustion engine is the result of conditions within the cylinder after intake valve closing and during combustion. Fuel, air, and recirculated exhaust (EGR) are major components of combustion. An example EGR component includes internal and/or external components and is to attain a particular concentration of the components of the trapped charge, for example, O₂ and N₂. System 100 includes fuel system 110 and air handling system 115 to provide fuel, air and, EGR and air for combustion.

[0020] In particular, the example fuel system 110 delivers a total fueling amount at one or more specific times to one or more cylinders during each combustion cycle. The one or more specific times are, for example, defined by a start-of-injection (SOI) time in response to an SOI command. The example fuel system 110 includes a fuel injector valve, which responds to the one or more SOI commands. The example fuel system 110 optionally provides fuel at a specific pressure, for example, a rail pressure for a common rail fuel system. In some embodiments, the rail pressure is set in response to a rail pressure value, which includes a rail pressure command or a default rail pressure value. The example fuel system 110 includes a fuel pump, which responds to the rail pressure value.

[0021] As illustrated, the air handling system 115 includes an optional turbocharging system 128 including at least one turbocharger, shown schematically as a compressor 130 and a turbine 135. The turbocharging system 128 receives exhaust and provides compressed air. In some embodiments, the compressor 130 is driven by the turbine 135 in a turbocharging configuration, wherein the compressor 130 is the air intake side of a turbocharger and the turbine 135 is the exhaust side of the turbocharger. In various embodiments, the turbocharging system 128 includes a waste gate 137 for bypassing the turbine 135 to control the speed of the turbine

135 and compressor 130, for example, to avoid excessive speed. The example air handling system 115 includes a wastegate turbocharger. However, the example air handling system 115 includes, without limitation, one or more of a naturally aspirated system, a fixed geometry turbocharger, a variable geometry turbocharger, a compressor bypass turbocharger, a dual turbocharger (series or parallel), and combinations thereof. Because the air handling system 115 affects the amount of air being delivered into the cylinders of the engine, the air handling system 115 affects the amount of emissions to be produced by the engine.

[0022] The illustrated system 100 includes a system air intake 140 into which air enters from the ambient environment. The air then flows into and out of the air compressor 130 to engine air intake 145. The example engine 105 includes an intake manifold coupled to the engine air intake 145 to deliver the air to the intake ports of the cylinders. The example system 100 includes one or more of an intercooler, charger air cooler, and/or bypass systems therefore (not shown). After combustion, exhaust flows from the engine 105 to engine exhaust 150. The example engine 105 includes an exhaust manifold coupled to the exhaust ports of the cylinders to collect the exhaust and direct the exhaust to the engine exhaust 150.

[0023] The air handling system 115 includes one or more sensors to measure characteristics of intake air, such as temperature, pressure, or humidity. An example sensor is humidity sensor 140, which measures the humidity of air being delivered into the engine 105. In embodiments of the air handling system 115 including an exhaust gas recirculation (EGR) system 152, the one or more sensors optionally capture the effect of the recirculated EGR gases on the air being delivered to the cylinder. Non-limiting examples of types of EGR system 152 include a low-pressure EGR, a high-pressure EGR, and a dual-loop EGR. The one or more sensors may be physical or virtual. Virtual sensors are determined in response to sensor measurements and/or data structures in the controller 125. Example sensors include, but are not limited to, one or more of an EGR flow measurement sensor and an O₂ content sensor.

[0024] The illustrated system 100 includes optional aftertreatment system 120 receives the exhaust from aftertreatment inlet 155 and at least a portion of the exhaust is expelled at the aftertreatment outlet 160, which may also be referred to as the system outlet or tailpipe. The aftertreatment system 120 includes devices that cooperate to treat emissions before exiting the tailpipe, such as one or more of a particulate filter or diesel particulate filter (DPF), a selective catalytic reduction (SCR) system, a NO_x reductant fluid system, and an oxidation catalyst. The components of the aftertreatment system 120 have limits to their ability to treat emissions. Heavy transient events, such as a smoke spike, may overwhelm the capabilities of the aftertreatment system 120 and violate jurisdictional or sociability requirements. The ability to predict emission transient events helps to modify, mitigate, or prevent such events.

[0025] The controller 125 performs certain operations to control one or more subsystems of an internal combustion engine, such as one or more of the fuel system 110, the air handling system 115, and the aftertreatment system 120. In certain embodiments, the controller 125 forms a portion of a processing subsystem including one or more computing devices having memory, processing, and communication hardware. The example controller 125 is a single device or optionally a distributed device, and the functions of the controller are performed by hardware and/or as computer instructions on a non-transient computer readable storage medium.

[0026] In certain embodiments, the controller 125 includes one or more modules that functionally execute the operations of the controller. The description herein including modules emphasizes the structural independence of certain aspects of the controller 125, and illustrates one grouping of operations and responsibilities of the controller. Other groupings that execute similar overall operations are understood within the scope of the present application. Modules are optionally implemented in hardware and/or as computer instructions on a non-transient computer readable storage medium, and modules are optionally distributed across various hardware or computer based components.

[0027] Example and non-limiting module implementation elements include sensors providing any value determined herein, sensors providing any value that is a precursor to a value determined herein, datalink and/or network hardware including communication chips, oscillating crystals, communication links, cables, twisted pair wiring, coaxial wiring, shielded wiring, transmitters, receivers, and/or transceivers, logic circuits, hard-wired logic circuits, reconfigurable logic circuits in a particular non-transient state configured according to the module specification, any actuator including at least an electrical, hydraulic, or pneumatic actuator, a solenoid, an op-amp, analog control elements (springs, filters, integrators, adders, dividers, gain elements), and/or digital control elements.

[0028] FIG. 2 is a schematic illustration of a processing subsystem 200 including controller 125 to perform certain operations to predict an emission transient event, according to some embodiments. An example controller 125 includes a hardware description module 202, an emission predictive module 204, and a command generation module 206. Other modules are optionally included, but are not shown here. The modules 202, 204, and 206 cooperatively predict an emission transient event in response to various parameters.

[0029] Certain operations described herein include operations to interpret and/or to determine one or more parameters or data structures. Interpreting or determining, as utilized herein, includes receiving values by any method known in the art, including at least receiving values from a datalink or network communication, receiving an electronic signal (e.g., a voltage, frequency, current, or PWM signal) indicative of the value, receiving a computer generated

parameter indicative of the value, reading the value from a memory location on a non-transient computer readable storage medium, receiving the value as a run-time parameter by any means known in the art, and/or by receiving a value by which the interpreted parameter can be calculated, and/or by referencing a default value that is interpreted to be the parameter value.

[0030] In addition to the modules, the controller 125 typically includes one or more parameters or data structures, such as values, variables, commands, and sets thereof. These parameters or data structures are optionally provided to, provided by, and used by any of the modules in the controller 125. Further, some parameters or data structures are received by the controller 125 from a module external to the controller 125 or other source, which are optionally provided to and used by any of the modules. Some parameters or data structures are also optionally provided by the controller 125 to a module external to the controller 125 or other destination. Data structures are optionally provided to the controller 125 as sensor measurements, which are physical measurements or virtual measurements. In some cases, virtual sensor measurements are the output of a module, such as a virtual sensor module or other module.

[0031] In the illustrated embodiment, for example, the controller 125 receives inputs to the module, such as the engine speed 212 and/or an requested torque value 214, which is optionally derived from operator input. Further, the controller 125 provides one or more parameters as outputs, such as the engine command set 236 for controlling an engine component.

[0032] The hardware description module (HDM) 202 interprets parameters for use in the controller 125. An example HDM 202 interprets the key basis variable set 210. The key basis variable set 210 includes one or more of an engine speed 212, a requested torque value 214, an in-cylinder oxygen concentration ($[O_2]$) before SOI value 216, a rail pressure value 218, an SOI value 220, an in-cylinder oxygen-to-fuel ratio (OFR) value 222, an intake manifold temperature (IMT) value 224, a temperature at intake valve closing (IVC) value 226, and a temperature before first SOI value 228. As an alternative, or in addition, to direct measurement by an in-cylinder sensor, the in-cylinder OFR value 222 is determined in response to one or more of an air-to-fuel ratio (AFR) value, an intake manifold oxygen-to-fuel ratio (IMOFR) value, and a charge to fuel ratio (CFR) value (e.g., virtually or derivatively).

[0033] An example key basis variable set 210 for a smoke value transient event prediction, for steady state and transient state, includes one or more of the engine speed 212, the requested torque value 214, the in-cylinder $[O_2]$ before SOI value 216, the rail pressure value 218, the SOI value 220, and the in-cylinder OFR value 222. This example key basis variable set is utilized in response to a nominal operating temperature of the engine 105 to characterize a

majority of effects on the production of an emission whether at steady state or transient state. A further example key basis variable set 210 includes each of these parameters.

[0034] In some embodiments, the requested torque value 214 corresponds to a combustion-relevant fueling value. The combustion-relevant fueling value is the amount of fuel that is intended to generate torque within a cylinder. An example combustion-relevant fueling value excludes a very late post injection for the aftertreatment system 120. Alternatively, or in addition, to the requested torque value 214, a total fueling quantity value 215 is utilized as a key basis variable. Under certain circumstances, the requested torque value 214 has a direct relationship to the combustion-relevant fueling value and/or the total fueling quantity value 215.

[0035] Yet another example key basis variable set 210 for a smoke value transient event prediction, for a cold start, further includes one or more of the intake manifold temperature (IMT) value 224, the temperature at intake valve closing (IVC) value 226, and the temperature before first SOI value 228. The further included one or more key basis variables for a cold start prediction capture the effect when a temperature in the engine 105 is sufficiently low in temperature such that combustion characteristics deviate from the combustion characteristics at the nominal operating temperature. Typically, when the ambient temperature is less than a range from 10 degrees Celsius to -20 degrees Celsius, the combustion characteristics are atypical. The example system 100 is recalibrated or retuned from a nominal operating mode to attain the correct behavior in a cold-start operating mode.

[0036] Using the key basis variable set 210 as an input, the example emission predictive model (EPM) 204 determines an output 230 indicative of a predicted emission value. The example EPM output 230 includes one or more of a dry particulate matter (DPM) value 232 and a brake-specific dry particulate matter (bsDPM) value 234 for determining a predicted smoke value. The example EPM 204 determines the output 230 using a model, such as a statistical model. An example optional statistical model is a multivariate local regression (MLR) model. A person having skill in the art and the benefit of the present disclosure would be able to select an appropriate predictive model.

[0037] For purposes of calibration, various embodiments of the EPM 204 are calibrated in response to key basis variables and dry particulate matter values (e.g., DPM and/or bsDPM), which are measured at steady state engine conditions at various operating points (e.g., engine speed and engine torque). Proper selection of the key basis variables allow for the calibration of the EPM 204 to robustly predict emission transient events at steady state and transient state engine conditions without the need to additionally perform calibration at transient state conditions. However, the example EPM 204 is optionally calibrated at transient state conditions to test the EPM 204 and/or for further the robustness of the EPM output 230.

[0038] In response to the EPM output 230, the example command generation module 206 determines an engine command set 236. The engine command set 236 is provided from the controller 125 to an engine component, such as the fuel system 110 or the air handling system 115 (e.g., to control a VGT turbocharger). An example engine command set 236 includes a fueling command 238 and/or a VGT command 240.

[0039] The example command generation module 206 is capable of predicting an emission transient event in response to the key basis variable set 210 and the EPM output 230. The example command generation module 206 determines that the EPM output 230, which is a modeled prediction, exceeds a predetermined threshold value for an emission. This determination indicates a spike in emission (e.g., a smoke spike), which is one type of emission transient event. Other manners of detecting an emission transient event include, without limitation, exceeding a predetermined emission slope value and exceeding an emission trajectory threshold. A person having ordinary skill in the art and the benefit of the disclosure would be able to select an appropriate manner of detecting an emission transient event.

[0040] In response to the predicted emission transient event, the example command generation module 206 provides a modified engine command set 236, which is modified from a nominal engine command set. An example nominal engine command set 242 is determined in the controller 125 by the command generation module 206 or another module (not shown). In some cases, the example command generation module 206 determines that in response to the nominal engine command set 242, the system 100 would produce an emission in violation of emission requirements. Thus, in response, the example command generation module 206 provides a modified engine command set 236 in order to modify, mitigate, or prevent such emission production. A person having skill in the art and the benefit of the disclosure would be able to appropriately modify the nominal engine command set 242 to modify, mitigate, or prevent unwanted emission production.

[0041] The example controller 125 also includes optional in-cylinder oxygen determination module 208. The in-cylinder oxygen determination module 208 determines an in-cylinder $[O_2]$ before SOI value 216, which is an estimation, prediction, or measurement made in response to fundamental physical principles. For example, the in-cylinder oxygen determination module 208 determines the in-cylinder $[O_2]$ before SOI value 216 without information provided by an in-cylinder oxygen sensor. In some embodiments, the in-cylinder oxygen determination module 208 includes an intake oxygen model and an in-cylinder residual gas model, for example, also providing outputs in response to fundamental physical principles. The example in-cylinder oxygen determination module 208 optionally includes one or more intake oxygen sensors. The example in-cylinder oxygen determination module 208 determines the in-cylinder

[O₂] before SOI value 216 in response to one or more of a mass charge flow (MCF) value 244, an EGR fraction value 246, an exhaust manifold pressure (EMP) value 248, an exhaust manifold temperature value (EMT) 250, a humidity value 252, and an in-cylinder residual gas value 252. An example humidity value 252 is an ambient value or a value measured within an engine component, such as the intake manifold. Some embodiments of the in-cylinder oxygen determination module 208 utilize all of these parameters. Various embodiments of the in-cylinder [O₂] before SOI value 216 are determined in response to the measurement from one or more optional in-cylinder sensors (not shown), such as an in-cylinder oxygen sensor, an in-cylinder pressure sensor, or an in-cylinder temperature sensor.

[0042] In this manner, the processing subsystem 200 is capable of controlling the system 100 to modify, prevent, or mitigate the effects of an emission transient event by predicting the emission transient event in response to one or more key basis variables. Advantageously, this method of control does not require intrusive testing or substantial disruptions to engine operation or engine parameters to retrieve the key basis variables and/or to estimate the transient event.

[0043] One of skill in the art, having the benefit of the disclosures herein, will recognize that the processing subsystem 200 and the controller 125 perform operations that improve various technologies and provide improvements in various technological fields. Without limitation, example and non-limiting technology improvements include improvements in combustion performance of internal combustion engines, improvements in emissions performance, aftertreatment system regeneration, engine torque generation and torque control, engine fuel economy performance, improved durability of exhaust system components for internal combustion engines, and engine noise and vibration control. Without limitation, example and non-limiting technological fields that are improved include the technological fields of internal combustion engines, fuel systems therefore, aftertreatment systems therefore, air handling devices therefore, and intake and exhaust devices therefore.

[0044] The schematic flow diagram and related description which follows provides an illustrative embodiment of performing procedures for calibrating and controlling an engine system 100 including an internal combustion engine 105. Operations illustrated are understood to be exemplary only, and operations are optionally combined or divided, and added or removed, as well as re-ordered in whole or part, unless stated explicitly to the contrary herein. Certain operations illustrated are optionally implemented by a computer executing a computer program product on a non-transient computer readable storage medium, where the computer program product comprises instructions causing the computer to execute one or more of the operations, or to issue commands to other devices to execute one or more of the operations.

[0045] FIG. 3 is a schematic flow chart diagram of an example procedure 300 for calibrating the system 100, according to some embodiments. A calibration test is performed on system 100, for example, to calibrate the emission predictive model 204 or other modules in the processing subsystem 200, which form an example online emission estimator. An example calibration test subjects an engine 105 to a plurality of steady state engine conditions. Further example calibration tests include one or more of a plurality of transient state engine conditions, a plurality of engine conditions at various altitudes, a cold-start engine condition, and a regeneration engine condition. Generally, an example online emission estimator is responsive enough and capable of providing control outputs utilized by the system 100 during run-time operations to control emissions.

[0046] In operation 305, key basis variables for at least one emission are identified. An example emission is selected, such as smoke, produced by the operation of the internal combustion engine 105. A key basis variable set is selected to characterize the major effects occurring in the engine 105 to produce the selected emission(s) so that the engine can be robustly controlled whether the engine condition is steady state or transient state. Additional or alternative key basis variable sets are included for specific engine conditions, such as a cold start engine condition. The selection of the key basis variables is made in response to strong correlations with the physics of the combustion process. For example, the key drivers for smoke are utilized in the development of an online emission estimator for predicting smoke (e.g., CFR, O₂ content, etc.). In addition, the transient behavior of the engine implies that certain input variables with long time constants cannot be utilized for the transient emission estimation. Hence, the need to find key variables that can predict the transient behavior by utilizing steady-state engine data.

[0047] An example calibration test includes a plurality of operating points in a steady state engine condition. Because key basis variables are capable of characterizing effects in the engine that produce the emission for both steady state and transient state engine conditions, the calibration test need not be performed at operating points in a transient state condition. Though not necessary, further calibration tests are optionally performed on a plurality of operating points in a transient state engine condition for further robustness of the online emission estimator.

[0048] In operation 310, key basis variables are interpreted for each of a plurality of operating points. An example calibration test operates a system 100 at a plurality of engine speed and engine torque value points, and the key basis variables are interpreted. Also, during the calibration test, actual emission values for each the plurality of operating points are interpreted for operation 315.

[0049] In operation 320, a predictive model is calibrated for the plurality of operating points in response to the key basis variables and the actual emission values. Using the interpreted

key basis variables and the actual emission values, a predictive model is calibrated or developed. An example predictive model is a statistical, multi-variate local regression model that accepts inputs, such as key basis variables, and outputs, such as predicted emission values. Once calibrated, the predictive model provides predicted emission values in response to one or more key basis variables to provide information to operate the system 100 at steady state and transient state engine conditions. An example predictive model is implemented in a module of a controller. The module is optionally configured further to provide a predicted emission transient event indication in response to the key basis variables.

[0050] FIG. 4 is a schematic flow chart diagram of an example procedure 400 for operating the system 100, according to some embodiments. The example procedure 400 optionally utilizes an example predictive model calibrated by procedure 300.

[0051] Operation 405 includes interpreting an operating point of the engine system, such as system 100. In operation 410, key basis variables are interpreted for the engine system associated with the operating point. A predicted emission value is determined in response to the key basis variables and the operating point in operation 415. Operation 420 includes controlling the engine system in response to the predicted emission value. In some embodiments, controlling the engine system includes determining a predicted emission transient event in response to the key basis variables and modifying an engine command set.

[0052] FIG. 5 is a graph of an example result set 500 including a predicted emission value 505 and an actual emission value 510 over time during operation of an example engine system 100, according to some embodiments. The Y-axis is measured in units of an emission value, and the X-axis is measured in units of time, such as seconds. In the illustrated result set 500, the emission was smoke. The result set 500 was generated by determining the predicted emission value 505 and measuring actual emission value 510. In some embodiments, the predicted emission value 505 is determined or generated in response to an emission predictive module, such as module 204.

[0053] The result set 500 shows four predicted emission transient events 515 and four actual emission transient events 520. The transient events 515, 520 are shown as spikes, occurring near the 1980, 2010, 2040, and 2070 time marks. An example spike is defined as a sharp increase, which is optionally followed by a sharp decrease in an emission value. An emission transient event results in substantially greater emission production than nominal emission production (e.g., during steady state).

[0054] As can be seen, the predicted emission transient event 505 closely tracks the actual emission value 510. In particular, each predicted emission transient event 515 closely tracks each actual emission transient event 520. The close tracking facilitates modifying

operation of an engine system 100 to proactively in response to one or more predicted emission transient events 515, before one or more actual emission transient events 520 occurs.

Modifications during and after the actual emission transient events 520 is also contemplated. In this manner, the engine system 100 is positioned to modify, mitigate, or prevent effects of potential emission transient events 520.

[0055] It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reading and understanding the above description. For example, it is contemplated that features described in association with one embodiment are optionally employed in addition or as an alternative to features described in association with another embodiment. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

CLAIMS

The following is claimed:

1. A method for calibrating a predictive emission event model, comprising:
 - subjecting an engine to a plurality of steady state engine conditions;
 - interpreting, for each steady state engine condition, values of a key basis variable set;
 - interpreting, for each steady state engine condition, an emission value;
 - calibrating an emission predictive module to provide a predicted emission value in response to the values of the key basis variable set and the emission values for the plurality of steady state engine conditions;
 - calibrating a command generation module to predict an emission transient event in response to the predicted emission value.
2. The method of claim 1, wherein the key basis variable set includes at least one of an engine torque value, a total fueling quantity value, an engine speed value, a rail pressure value, a start-of-injection (SOI) value, in-cylinder [O₂] before SOI value, and an in-cylinder oxygen-to-fuel ratio (OFR) before SOI value.
3. The method of claim 1, wherein the predictive model comprises a statistical model.
4. The method of claim 3, wherein the statistical model comprises a multivariate local regression model.
5. A method for predicting an emission value transient event, comprising:
 - determining a basis value set including at least one of an engine torque value, an engine speed value, a total fueling quantity value, a rail pressure value, a start-of-injection (SOI) value, in-cylinder [O₂] before SOI value, and an in-cylinder oxygen-to-fuel ratio (OFR) before SOI value;
 - determining a predictive model output in response to the basis value set, the predictive model output being calibrated in response to a plurality of steady state engine conditions; and
 - predicting a emission value transient event in response to the predictive model output.

6. The method of claim 5, further comprising providing a modified engine command in response to predicting the emission value transient event.

7. The method of claim 6, further comprising providing a reduced fueling command in response to predicting the emission value transient event.

8. The method of claim 6, further comprising providing a modified variable geometry turbocharger (VGT) command in response to predicting the emission value transient event.

9. The method of claim 6, further comprising providing one or more of a modified rail pressure and a modified exhaust gas recirculation (EGR) fraction in response to predicting the emission value transient event, the emission value transient event being a mild-type.

10. The method of claim 5, further comprising predicting the emission value transient event in response to one of a dry particulate matter (DPM) value and a brake specific dry particulate matter (bsDPM) value as the predictive model output.

11. The method of claim 5, further comprising predicting the emission value transient event in response to a transient state engine condition.

12. The method of claim 5, further comprising determining the in-cylinder $[O_2]$ before SOI value in response to a virtual sensor.

13. The method of claim 12, further comprising determining the in-cylinder $[O_2]$ before SOI value in response to an intake $[O_2]$ model and an in-cylinder residual gas model.

14. The method of claim 13, further comprising determining the in-cylinder $[O_2]$ before SOI value in response to a humidity value.

15. The method of claim 5, further comprising determining the in-cylinder OFR before SOI value in response to one or more of an air-to-fuel ratio (AFR) value, an intake manifold oxygen fuel ratio (IMOFR), and a charge fuel ratio (CFR).

16. The method of claim 5, further comprising determining the basis value set in response to a cold start engine condition, wherein the basis value set further includes one or more of an intake manifold temperature (IMT) value, a temperature at intake valve closure (IVC) value, and a temperature before first SOI value.

17. A controller, comprising:

a hardware description module (HDM) structured to interpret a basis value set including one or more of an engine torque value, a total fueling quantity value, an engine

speed value, a rail pressure value, a start-of-injection (SOI) value, in-cylinder [O₂] before SOI value, and an in-cylinder oxygen-to-fuel ratio (OFR) before SOI value;

an emission predictive module (EPM) structured to determine an EPM output in response to the basis value set, the EPM output being calibrated in response to a plurality of steady state engine conditions; and

a command generation module (CGM) structured to:

predict an emission transient event in response to the EPM output; and

determine a modified engine command set in response to the predicted emission transient event.

18. The controller of claim 17, wherein the CGM is further structured to predict an emission transient event in response to the EPM output exceeding a predetermined threshold.

19. The controller of claim 17, wherein the modified engine command set includes a reduced fueling command.

20. The controller of claim 17, wherein the modified engine command set includes a modified variable geometry turbocharger (VGT) command.

21. The controller of claim 17, wherein the CGM is further structured to predict the emission transient event in response to one of a dry particulate matter (DPM) value and a brake specific dry particulate matter (bsDPM) value as the EPM output.

22. The controller of claim 17, wherein the CGM is further structured to predict the emission transient event in response to a transient state engine condition.

23. The controller of claim 17, further including a virtual sensor module structured to determine the in-cylinder [O₂] before SOI value free of an in-cylinder [O₂] sensor.

24. The controller of claim 17, further including a virtual sensor module configured to determine the in-cylinder OFR before SOI value in response to one or more of an air-to-fuel ratio (AFR) value, an intake manifold oxygen fuel ratio (IMOFR), and a charge fuel ratio (CFR).

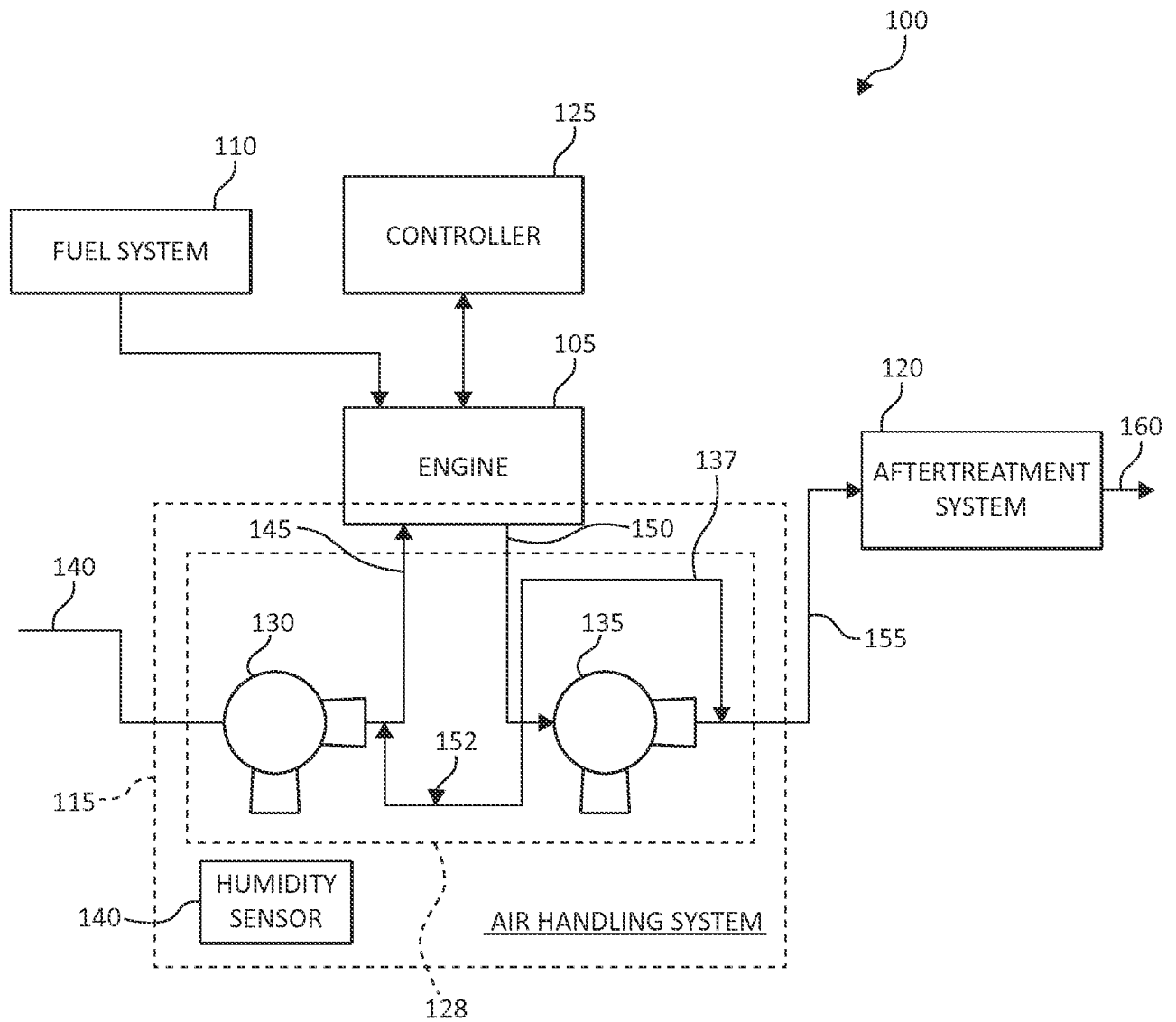


FIG. 1

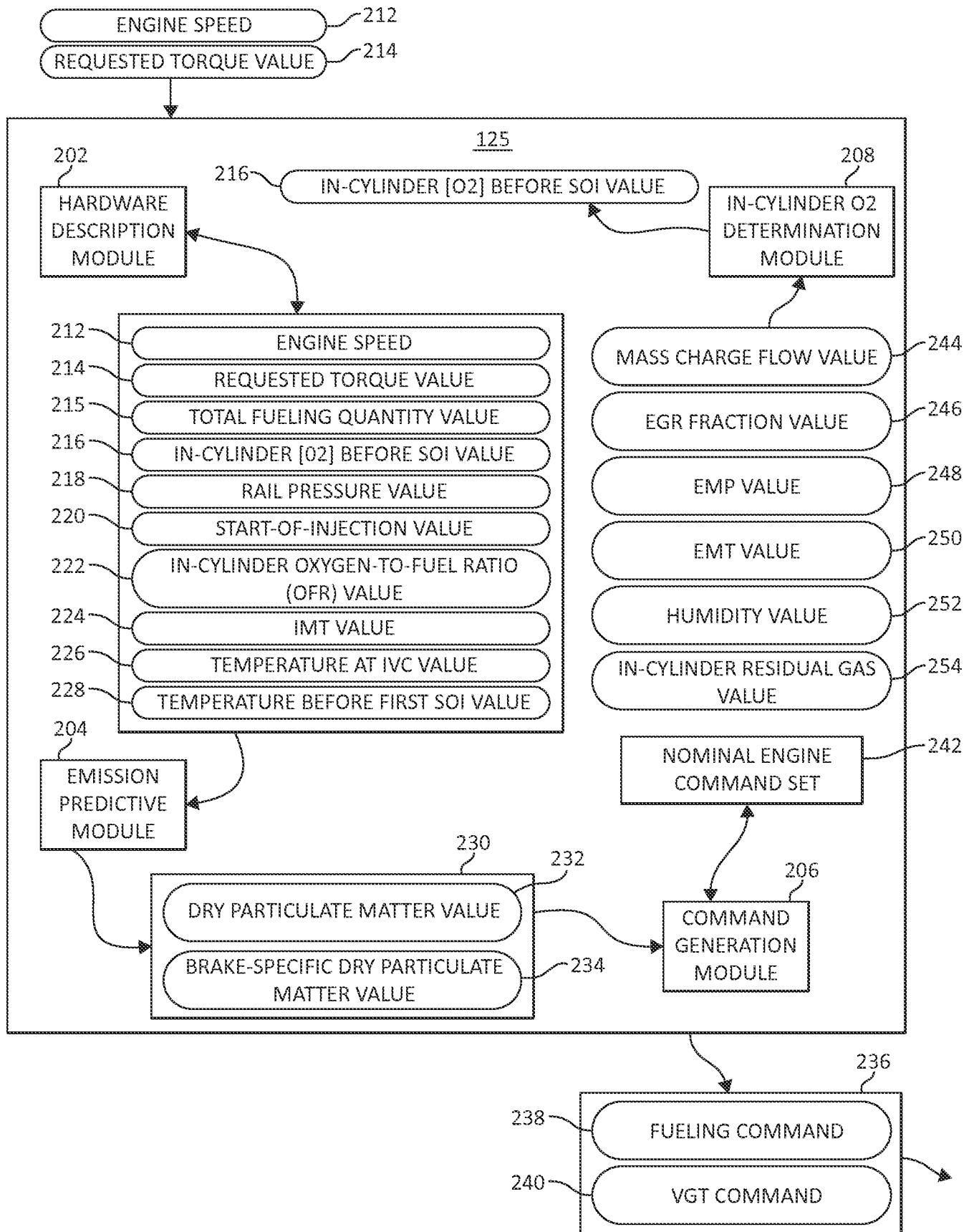
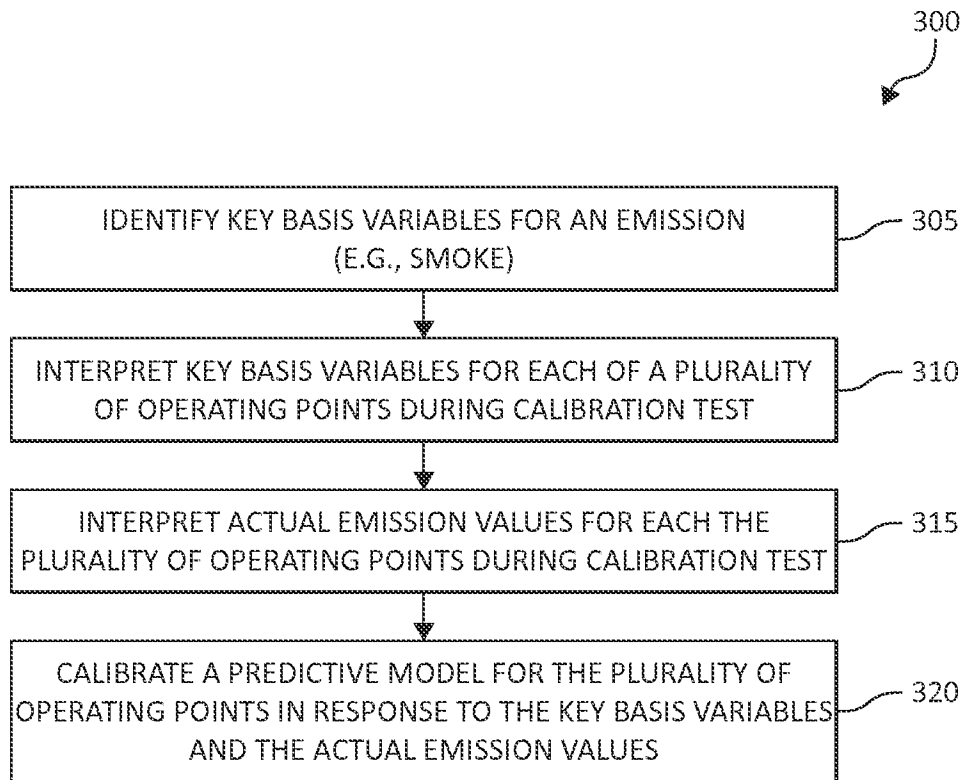
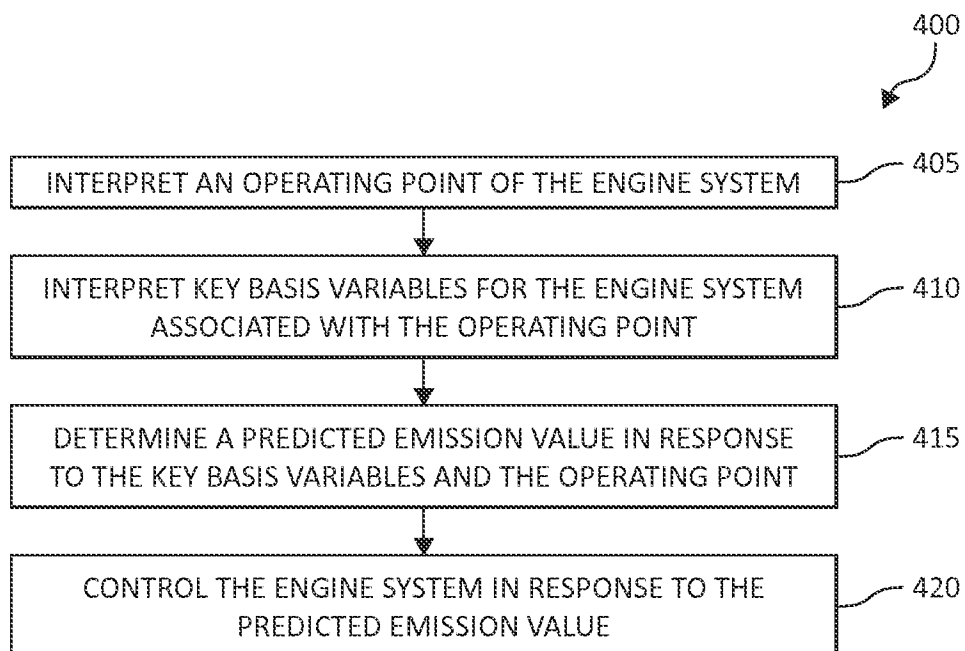


FIG. 2

**FIG. 3****FIG. 4**

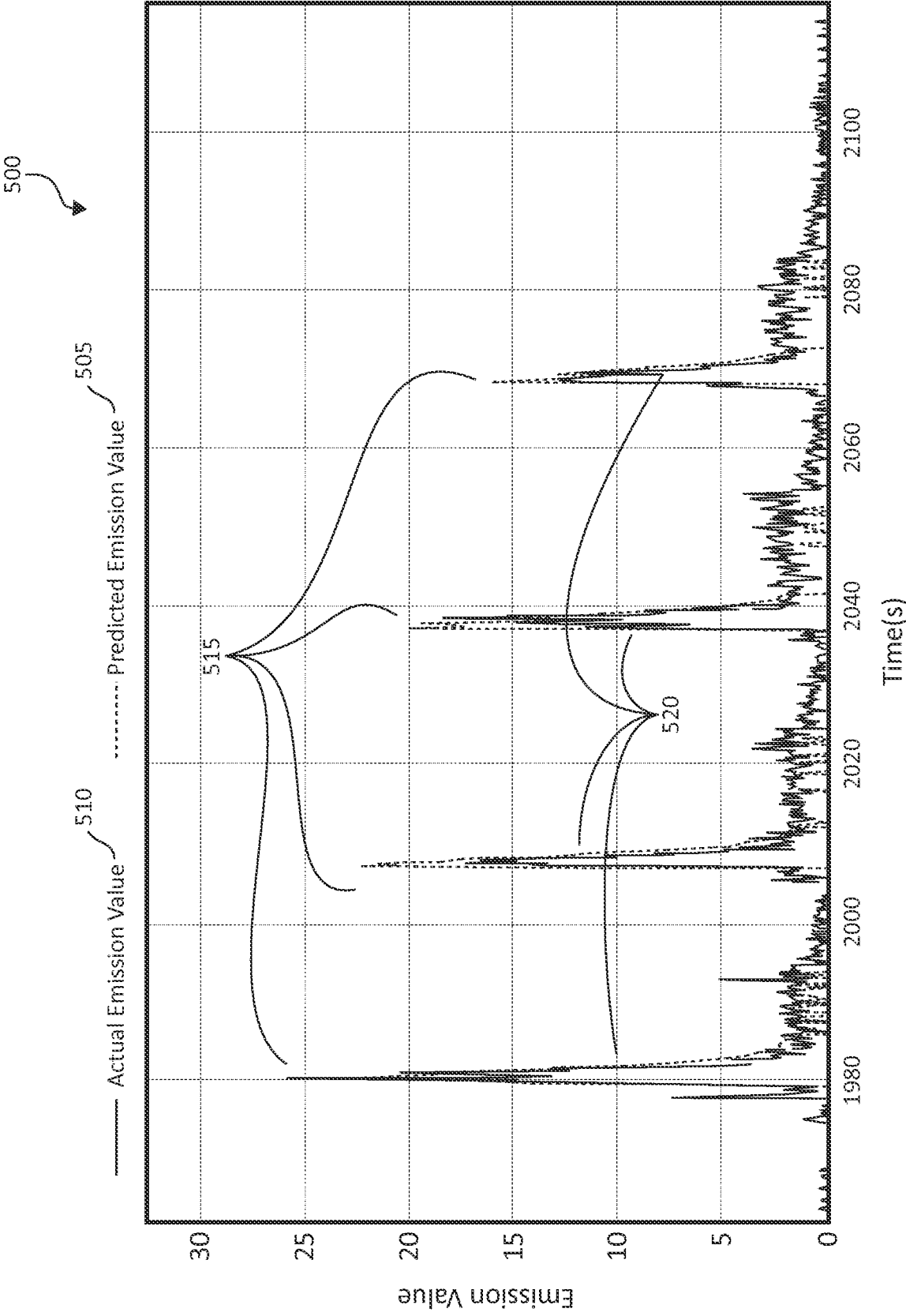


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/28400

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01N 31/00 (2015.01)

CPC - G01N 30/8641

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): G01N 31/00 (2015.01); CPC: G01N 30/8641

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC: 702/32, 702/22, 700/32

IPC(8): G01N 31/00 (2015.01); CPC: G01N30/8641, G01N30/8624, G01N21/274, G01N30/8631, G01N30/8651

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatBase, ProQuest Dialog, Google Web, Google Patents (Search terms: predict, emission, model, start of injection, oxygen, O2, oxygen to fuel ratio, variable geometry turbocharger, cold start, dry particulate matter, exhaust gas recirculation, fraction, incylinder, oxygen intake model, residual gas model, estimate, humidity, etc.)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,682,317 A (Keeler et al.) 28 October 1997 (28.10.1997), col. 3, ln. 34-35, 47-51, and 55-60, col. 4, ln. 1-5 and 19-21, col. 5, ln. 14-28, col. 6, ln. 31-38, col. 7, ln. 15-23, col. 10, ln. 60 to col. 11, ln. 49, col. 12, ln. 25-27 and 59-60, col. 13, ln. 5-16, col. 14, ln. 13-14 and 39-55, col. 15, ln. 12-38 and 60-66, and col. 18, ln. 1-20, and Figs. 1-2, 5a, 11, 13-14, and 19.	1-7, 11, 17-19, 22 ----- 8-10, 12-16, 20-21, 23-24
Y	US 6,935,100 B2 (Miura) 30 August 2005 (30.08.2005), col. 3, ln. 50-53 and ln. 66 to col. 4, ln. 6, col. 6, ln. 13-15, col. 10, ln. 37-39, and col. 17, ln. 66 to col. 18, ln. 1.	8-9, 16, 20
Y	US 7,725,199 B2 (Brackney) 25 May 2010 (25.05.2010), col. 7, ln. 30-45, and col. 14, ln. 25.	10, 21
Y	US 7,275,426 B2 (Lahti et al.) 02 October 2007 (02.10.2007), col. 5, ln. 35-37, col. 6, ln. 7-10 and 15-18, and col. 7, ln. 38-40 and 57-60.	12-14, 23
Y	US 2015/0089940 A1 (Sivasubramaniam et al.) 02 April 2015 (02.04.2015), para. [0037], [0061], [0100], and [0104]-[0105].	15, 24

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

16 July 2015 (16.07.2015)

Date of mailing of the international search report

14 AUG 2015

Name and mailing address of the ISA/US

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