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(54) **SYSTEMS AND METHODS FOR MODEL BASED CONTROL OF CATALYTIC CONVERTER SYSTEMS**

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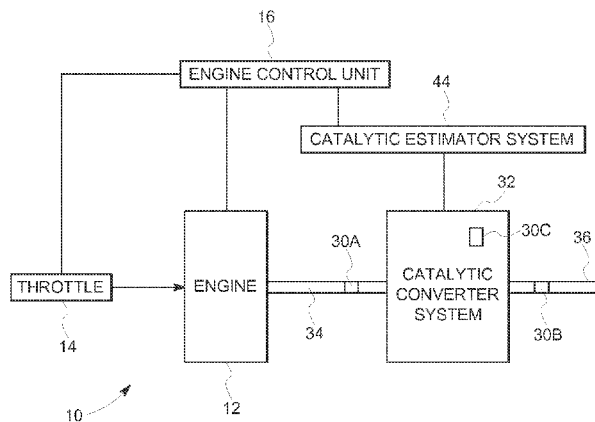*F01N 3/00*   (2006.01)
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(57)   **ABSTRACT**

A system includes a controller that has a processor configured to receive a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system; and to receive a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein the second oxygen sensor is disposed downstream of the catalytic converter system; and to execute a catalyst estimator system, wherein the catalyst estimator system is configured to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model. The processor is configured to derive a system oxygen
(Continued)

storage setpoint for the catalytic converter system based on the catalytic converter model and the oxygen storage estimate.

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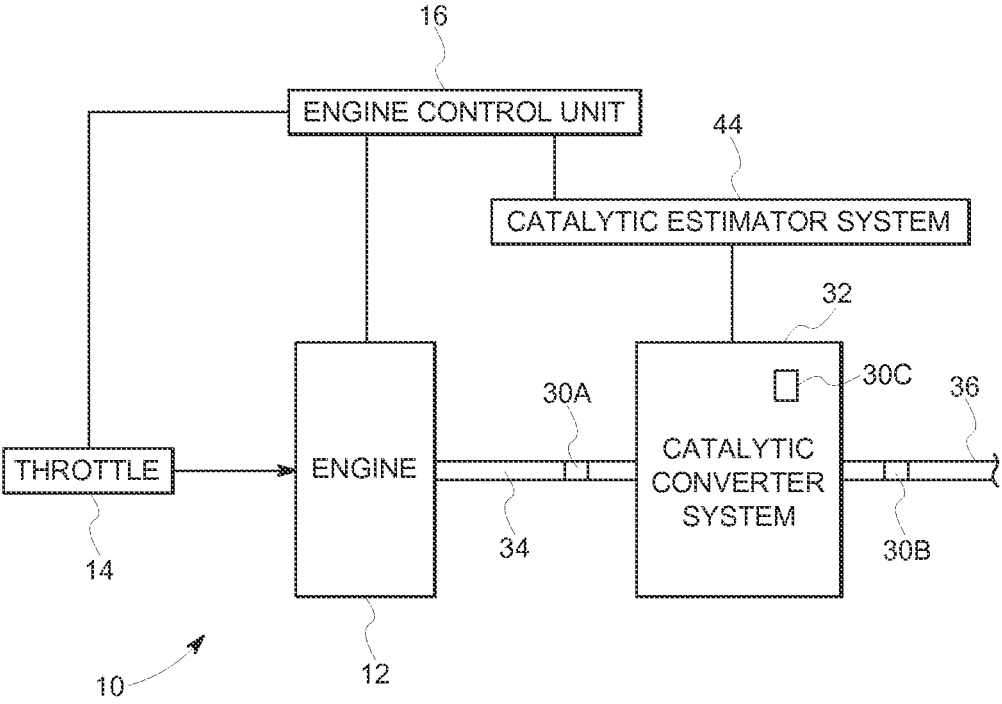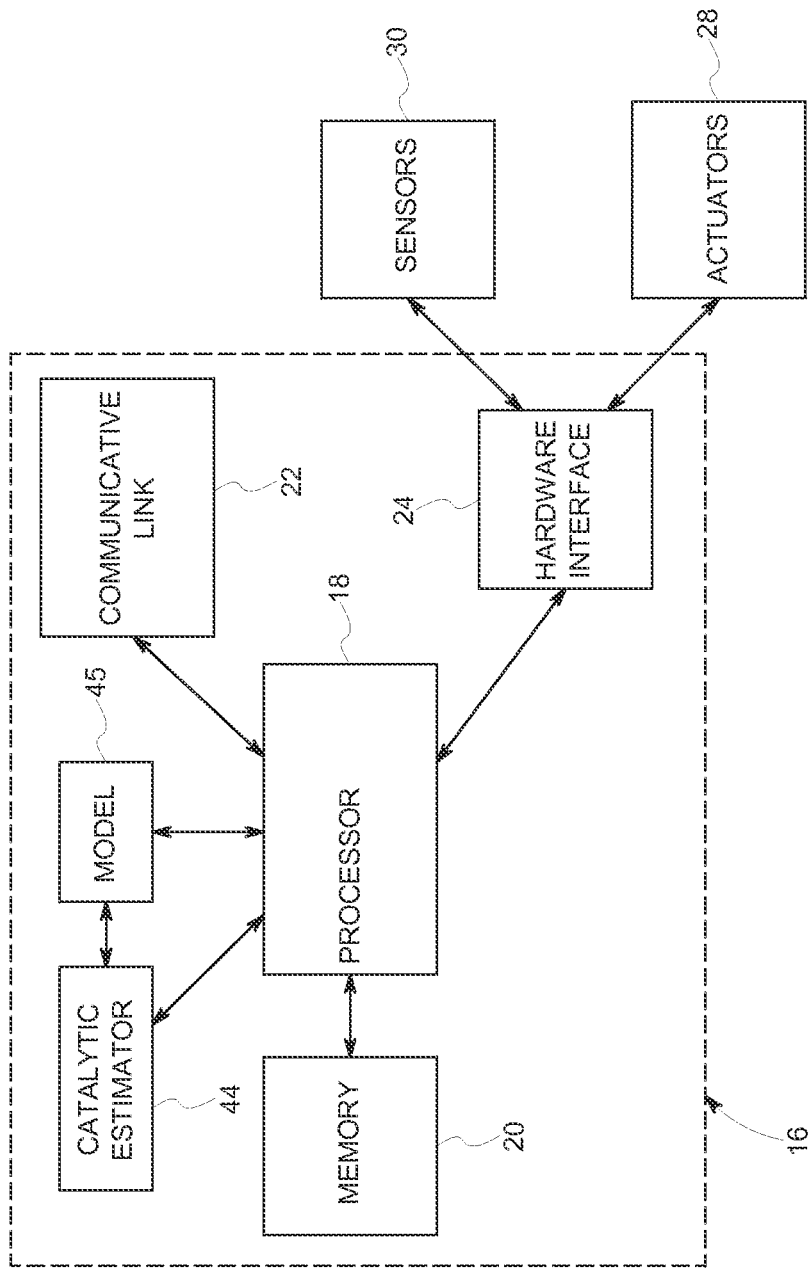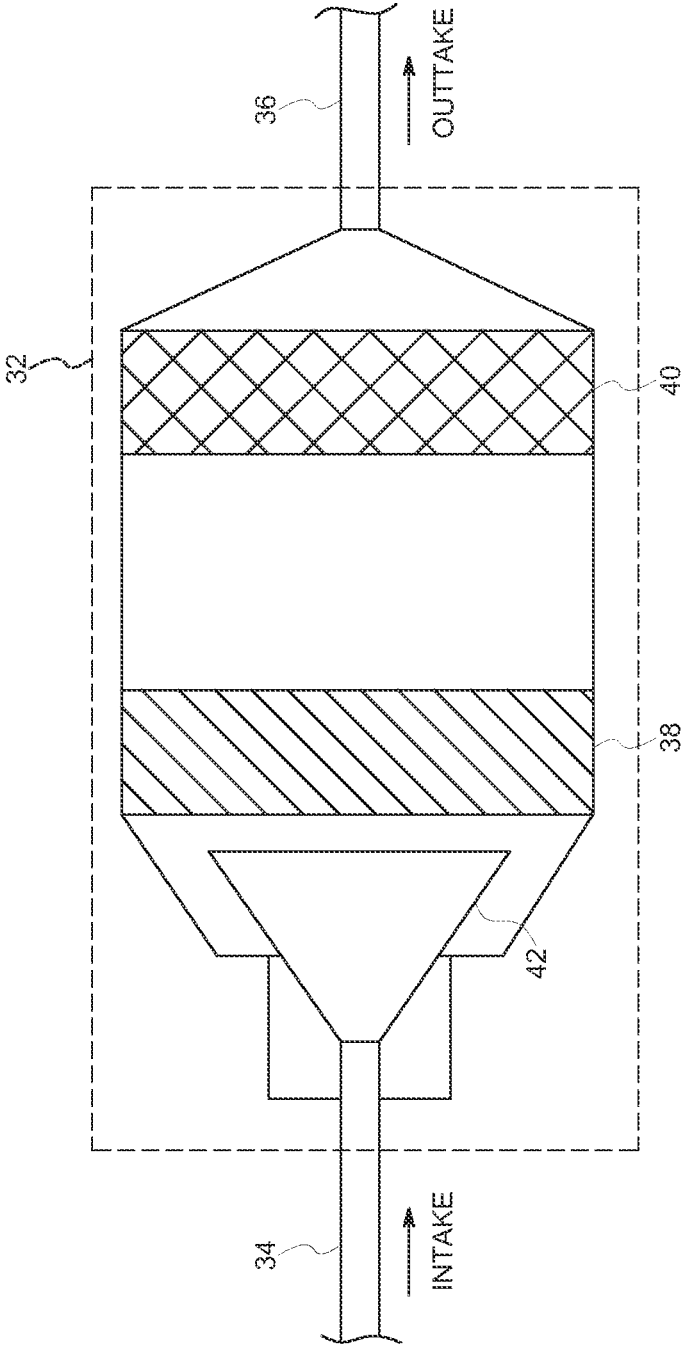
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16

ENGINE CONTROL UNIT

44

CATALYTIC ESTIMATOR SYSTEM

32

30C

36

30A

THROTTLE → ENGINE

CATALYTIC
CONVERTER
SYSTEM

34

14

30B

10

12

FIG. 1

FIG. 2

32

36

OUTTAKE

40

38

42

34

INTAKE

FIG. 3

FIG. 4

60

Create
Catalytic Converter
Models — 62

Models — 64

Create Catalytic
Estimators — 66

Estimators — 68

Save Selected Inputs,
Model, And Estimates — 90

Analyze Saved Data — 92

Perform Diagnostic — 94

Health State — 96

Control Actuators To
Achieve Setpoint — 88

AFR Setpoint — 86

Receive State Inputs — 70

Select Models Of
Estimators — 72

Estimate System
Dynamics — 74

Estimates — 76

Derive Oxygen
Storage Setpoints — 78

Oxygen
Storage Setpoints — 80

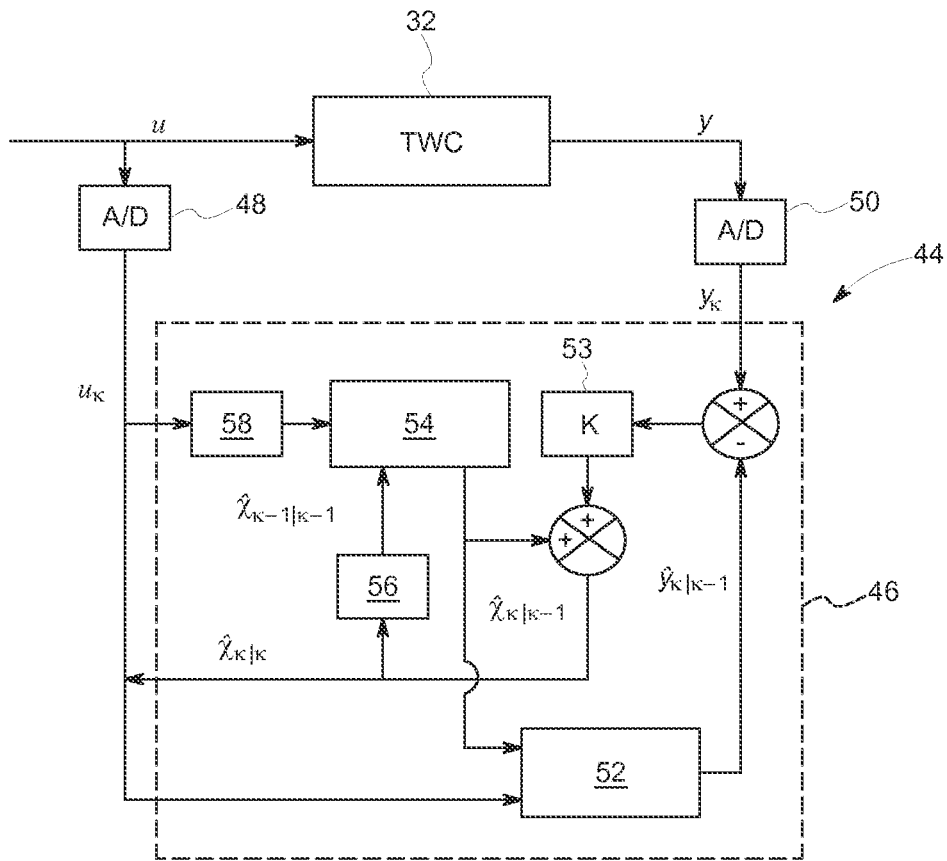Compare Estimates
And Setpoints — 82
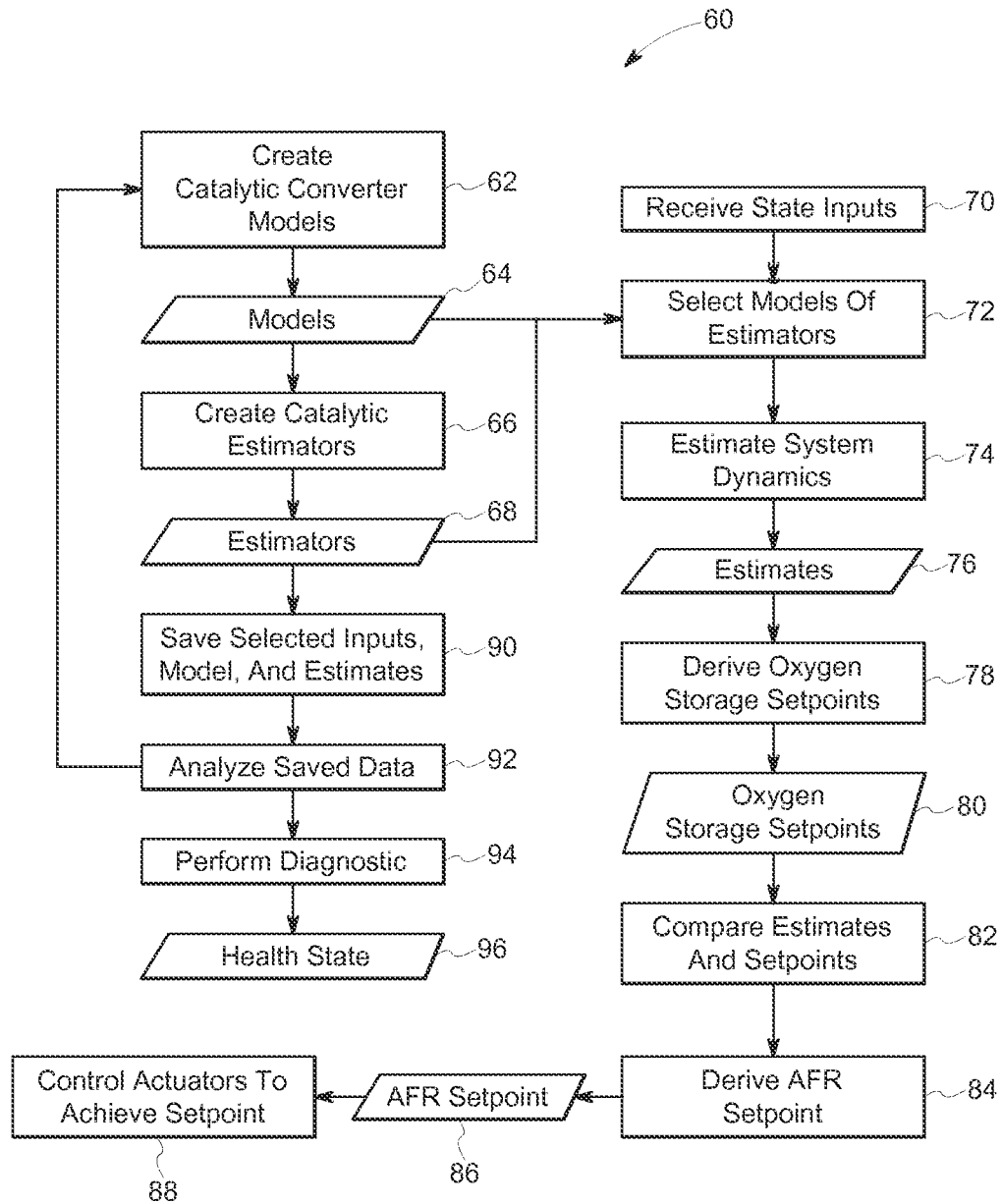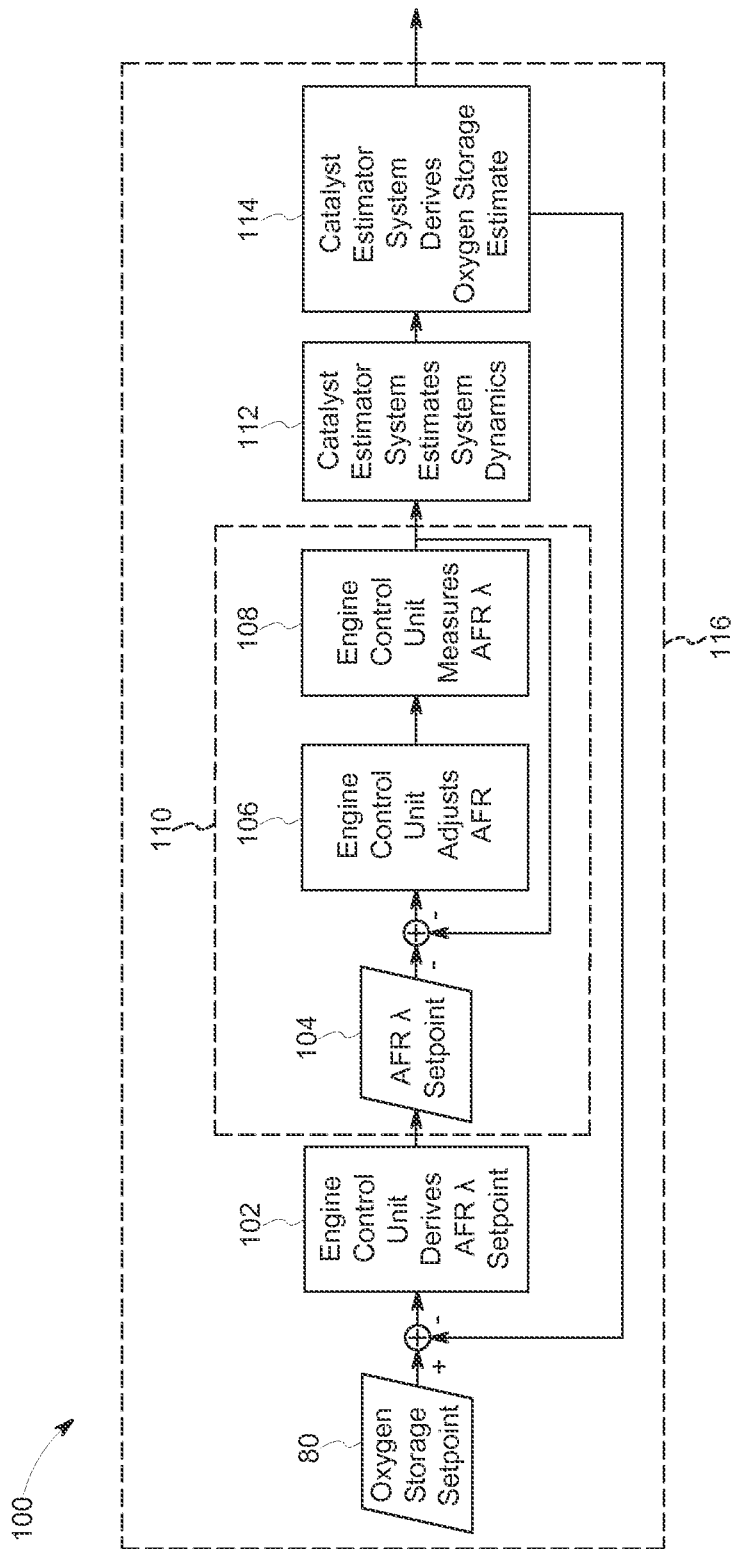
Derive AFR
Setpoint — 84

FIG. 5

FIG. 6

SYSTEMS AND METHODS FOR MODEL BASED CONTROL OF CATALYTIC CONVERTER SYSTEMS

BACKGROUND

The subject matter disclosed herein relates to model based control of catalytic converter systems. Specifically, the subject matter described below relates to systems and methods for controlling certain parameters of a catalytic converter system.

Gas turbine and engine systems provide power for a variety of applications, such as oil and gas processing systems, commercial and industrial buildings, and vehicles. The turbine and gas engine systems may be fluidly coupled to a catalytic converter system, such as three-way catalytic converters suitable for controlling emissions of certain oxides, such as nitrogen oxides. The engine systems include or are coupled to a control system that oversees the operation of the engine system. The control system may improve efficiency of the engine system, and provide other functionality. For example, the control system may improve the efficiency of internal combustion engine systems by controlling the air-to-fuel ratio of the engine, which represents the amount of air provided to the engine relative to the amount of fuel provided to the engine. Depending on desired applications, the control system may try to keep the air-to-fuel ratio near stoichiometry. Other applications may keep the air-to-fuel ratio in a range between rich (i.e., excess fuel) and lean (i.e., excess air).

As will be appreciated, engine systems produce exhaust gases as a result of burning fuel; and the type of exhaust gases emitted may depend in part on the type and amount of fuel provided to the engine system. Many industries and jurisdictions (e.g., coal-burning plants, federal and state governments, etc.) may have regulations and restrictions specifying the types and amounts of exhaust gases that different gas engine systems are permitted to emit.

To comply with regulations and restrictions, the gas engine system may use the catalytic converter system to control emissions. The catalytic converter system receives the exhaust gases and substantially converts the exhaust gases into other types of gases permitted by regulations and restrictions. The performance of the catalytic converter system may impact the performance of the gas engine, and vice versa. It would be beneficial to improve the performance of the gas engine and catalytic convertor systems via the control system.

BRIEF DESCRIPTION

Certain embodiments commensurate in scope with the originally claimed invention are summarized below. These embodiments are not intended to limit the scope of the claimed invention, but rather these embodiments are intended only to provide a brief summary of possible forms of the invention. Indeed, the invention may encompass a variety of forms that may be similar to or different from the embodiments set forth below.

In a first embodiment, a system includes a controller that has a processor. The processor is configured to receive a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system. The processor is additionally configured to receive a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein the second oxygen sensor is disposed

downstream of the catalytic converter system. The processor is further configured to execute a catalyst estimator system, wherein the catalyst estimator system is configured to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model. The processor is also configured to derive a system oxygen storage setpoint for the catalytic converter system based on the catalytic converter model and the oxygen storage estimate, and to compare the oxygen storage estimate with the system oxygen storage setpoint, wherein the processor is configured to apply the comparison during control of a gas engine.

In a second embodiment, a system includes a gas engine system that has a gas engine fluidly coupled to a catalytic converter system and a catalytic controller operatively coupled to the gas engine and communicatively coupled to the catalytic converter. The catalytic controller has a processor configured to receive a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system. The processor is additionally configured to receive a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein the second oxygen sensor is disposed downstream of the catalytic converter system. The processor is further configured to execute a catalyst estimator system, wherein the catalyst estimator system is configured to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model. The processor is also configured to derive a system oxygen storage setpoint for the catalytic converter system based on the catalytic converter model and the oxygen storage estimate, and to compare the oxygen storage estimate with the system oxygen storage setpoint, wherein the processor is configured to apply the comparison during control of a gas engine. The processor is additionally configured to derive an air-to-fuel ratio (AFR) setpoint based on the comparison, wherein the AFR setpoint is applied to control the gas engine.

In a third embodiment, a method includes receiving a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system. The method additionally includes receiving a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein the second oxygen sensor is disposed downstream of the catalytic converter system. The method further includes executing a catalyst estimator system, wherein the catalyst estimator system is configured to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model. The method also includes deriving a system oxygen storage setpoint for the catalytic converter system based on the catalytic converter model and the oxygen storage estimate, and comparing the oxygen storage estimate with the system oxygen storage setpoint to apply the comparison during control of a gas engine.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a block diagram of a gas engine system including a catalytic estimator system, in accordance with an embodiment;

FIG. **2** is a block diagram of an engine control unit and catalytic estimator system for the gas engine system of FIG. **1**, in accordance with an embodiment;

FIG. **3** is a cross-sectional of a catalytic converter system included in the gas engine system of FIG. **1**, in accordance with an embodiment;

FIG. **4** is a block diagram of an Adaptive Extended Kalman Filter (AEKF) system included in the catalytic estimator system of FIG. **1**, in accordance with an embodiment;

FIG. **5** is a flow chart depicting a method of operation for the catalytic estimator system of FIG. **1**, in accordance with an embodiment; and

FIG. **6** is a flow chart depicting a control process derived from the method of FIG. **5**, in accordance with an embodiment.

DETAILED DESCRIPTION

One or more specific embodiments of the present invention will be described below. In an effort to provide a concise description of these embodiments, all features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

When introducing elements of various embodiments of the present invention, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

Various embodiments relate to controlling the catalytic converter system fluidly coupled to, for example, a turbine or a gas engine. In one embodiment, a catalytic estimator may be provided, suitable for estimating, as an example, an oxygen storage state of a three-way catalyst. The catalytic estimator may be provided as an Adaptive Extended Kalman filter (AEKF), and the AEKF may use a calibrated kinetic model of the three-way catalyst, as further described below. During operations, the catalytic estimator may receive sensor inputs from various locations, such as locations at the inlet of the three-way catalyst, the outlet of the three-way catalyst, and/or at intermediate points in the three-way catalyst. The sensor inputs may include lambda sensor inputs measuring a proportion of oxygen (O2) at the lambda sensor's location, as well as temperature sensors, nitrogen oxides (NOx) sensors, carbon oxides (COx) sensors, mass flow sensors, pressure sensors, and the like. Engine-out emissions and corresponding emission species concentrations may also be predicted, based on current engine conditions. The catalytic estimator may use the sensor data to increase estimation accuracy of the behavior of the three-way catalyst, for example, by adaptively modifying itself or the underlying kinetic model to capture catalyst degradation or ageing, variations among individual catalysts, and so on. A model based control (MBC) system that oversees the operation of the engine system may then be used to control certain aspects of the catalytic system, such as an amount of

oxygen stored, and provide more fine control of emissions species and amounts exiting the catalyst system. The MBC controller may, for example, determine a setpoint for the AFR based on the estimator's derivations of the catalyst system. The MBC controller may then adjust the AFR accordingly. By controlling the AFR, the engine may combust fuel to result, for example, in a desired catalytic O2 storage, exit flow, and so on, thus controlling the catalytic system. The control system may also use the estimated behavior of the catalytic converter for diagnostic purposes.

Turning now to FIG. **1**, a gas engine system **10** is depicted, suitable for combusting fuel to produce power for a variety of applications, such as power generation systems, oil and gas systems, commercial and industrial buildings, vehicles, landfills, and wastewater treatment. The gas engine **10** system includes a gas engine **12**, such as a Waukesha™ gas engine available from the General Electric Company. The gas engine system **10** also includes a throttle **14** coupled to the gas engine **12**. The throttle **14** may be a valve whose position controls the amount of fuel or air provided to the gas engine **12**. As such, the position of the throttle **14** partly determines an air-to-fuel ratio (AFR) of the gas engine **12**. The AFR represents the ratio between an amount of oxidant (e.g., oxygen) available to combust an amount of fuel provided to the gas engine **12**.

The gas engine system **10** further includes an engine control unit **16**, which may control the operation of the gas engine system **10**, which is described in further detail below. To that end, the gas engine system **10** also includes sensors and actuators that may be used by the engine control unit **16** to perform various tasks. For example, as shown in FIG. **1**, the gas engine system **10** may include sensors **30A**, **30B**, **30C** that are disposed at different locations in the gas engine system **10**. The sensors **30A**, **30B**, **30C** may include lambda sensors (e.g., oxygen sensors), temperature sensors, mass flow sensors, pressure sensors, NOx sensors, CO sensors, and the like, that provide signals correlative to measurements for that particular location. The gas engine **12** may emit certain types and amounts of exhaust gases based on the type of fuel used. Certain industries and organizations (e.g., the oil and gas industry, coal-burning plants, federal and state governments, etc.) may have restrictions and regulations that specify the types and amounts of exhaust gases gas engines are permitted to emit.

To comply with these restrictions and regulations, the gas engine system **10** includes a catalytic converter system **32** coupled to an exhaust conduit **34** of the gas engine **12**. The catalytic converter system **32** receives the exhaust gases from the gas engine **12** and captures the exhaust gas and/or converts the exhaust gases into other types of emissions permitted by restrictions and regulations. For example, the catalytic converter system **30** depicted in FIG. **1** may perform three conversions: 1.) converting nitrogen oxides to nitrogen and oxygen, 2.) converting carbon monoxide to carbon dioxide, and 3.) converting unburned hydrocarbons to carbon dioxide and water. That is, the catalytic converter system **32** depicted in FIG. **1** is a three-way catalyst. Other embodiments may use other types of catalytic converters. The converted gases may then exit the catalytic converter system **32** via an output conduit **36**, which may lead to another component of the gas engine system **10** (e.g., another catalytic converter **32**, a heat recovery system) or to a vent.

To oversee the catalytic converter system **32**, the gas engine system **10** includes a catalytic estimator system **44**, as shown in FIG. **1** and described in further detail below. The catalyst estimator system **44** may be part of the engine

control unit **16** or may be a separate system that communicates with the engine control unit **16**.

Turning now to FIG. **2**, the engine control unit **16** includes a processor **18**; a memory **20**, a communicative link **22** to other systems, components, and devices; and a hardware interface **24** suitable for interfacing with sensors **30** (e.g., sensors **30A**, **30B**, **30C**) and actuators **28**. The processor **18** may include, for example, general-purpose single- or multichip processors. In addition, the processor **18** may be any conventional special-purpose processor, such as an application-specific processor or circuitry. The processor **18** and/or other data processing circuitry may be operably coupled to the memory **20** to execute instructions for running the engine control unit **16**. These instructions may be encoded in programs that are stored in the memory **20**. The memory **20** may be an example of a tangible, non-transitory computer-readable medium, and may be accessed and used to execute instructions via the processor **18**.

The memory **20** may be a mass storage device (e.g., hard drive), a FLASH memory device, a removable memory, or any other non-transitory computer-readable medium. Additionally or alternatively, the instructions may be stored in an additional suitable article of manufacture that includes at least one tangible, non-transitory computer-readable medium that at least collectively stores these instructions or routines in a manner similar to the memory **20** as described above. The communicative link **22** may be a wired link (e.g., a wired telecommunication infrastructure or a local area network employing Ethernet) and/or wireless link (e.g., a cellular network or an 802.11x Wi-Fi network) between the engine control unit **16** and other systems, components, and devices. For example, the link **22** may be a controller area network (CAN) link, an on-board diagnostics (OBD) link, a Modbus link, and so on.

The sensors **30** may provide various signals to the engine control unit **16**. For example, as mentioned above, the sensors **30** may include oxygen, temperature, mass flow, and/or pressure sensors **30A**, **30B**, **30C**, disposed at different locations in the gas engine system **10** to provide signals correlative to oxygen, temperature, flow, and/or pressure measurements for that particular location. The actuators **28** may include valves, pumps, positioners, inlet guide vanes, switches, and the like, useful in performing control actions. For instance, the throttle **14** is a specific type of actuator **28**.

Based on signals received from the sensors **30**, the engine control unit **16** may determine if one or more control aspects of the gas engine system **10** should be changed and adjusts the control aspect accordingly using an actuator **28**. For instance, the engine control unit **16** may endeavor to improve the efficiency of the gas engine **12** by controlling the AFR of the gas engine **12**. In particular, the engine control unit **16** may attempt to keep the AFR of the gas engine **12** at a desired ratio, such as near stoichiometry. In other embodiments, the engine control unit **16** may attempt to keep the AFR of the gas engine **12** within a narrow band of acceptable values, including values where the AFR includes rich (i.e., excess fuel) burns and lean (i.e., excess air) burns, depending on desired engine **12** applications.

The engine control unit **16** may also include the catalytic estimator system **44**. During engine **12** operations, the catalytic estimator system **44** may be continuously providing various estimates of the state of the catalytic system **32**, such as an amount of O2 that is being stored by the catalytic system **32**, as well as amounts of certain species of interest, such as NOx and COx that may be emitted into the environment. The engine control unit **16** may use this information to more efficiently operate the engine **12** as well as to

better maintain regulatory emissions compliance. The catalytic estimator system **44** may use or include a model **45**, such as a kinetic first principle chemical model of the catalytic converter **32** suitable for modeling the chemical reactions taking place in the catalytic converter and including appropriate calibrations for mass transfer and energy transfer. It is to be noted that the engine control unit **16** may be thus be a controller, such as a catalytic controller, suitable for controlling the catalytic system **32**. It is also to be noted that, while the estimator **44** is depicted as included in the control unit **16**, the estimator **44** may be separate from the controller **44** and may thus be a controller as well, such as a catalytic controller, suitable for controlling the catalytic system **32**.

The model **45** may include sub models, such as additional kinetic models, reactor models, and the like. Kinetic models may include models describing carbon monoxide oxidation, ethylene oxidation, acetylene oxidation, methane oxidation, and/or the reduction of nitrogen oxides. For example, the models may be based on the adsorption rate of a component i on noble metal, which may be given by Equation 1.

$$r_{a,i} = k_{a,i} L_{N,M} C_{s,i} \theta^* \qquad \text{Equation (1):}$$

For Equation 1, k is an adsorption rate coefficient, L is a capacity of catalyst phase, C is a concentration (e.g., molar), and θ^* determines a fraction of empty ceria surface. The adsorption rate coefficient can be found via first principles, e.g., kinetic gas theory. The reactor models may model a one or more dimensional adiabatic reactor based on the geometry of the catalytic converter system **32**, including channels, axial gradients, and heat and mass transfer coefficients based on laminar flow from bulk gas to catalyst washcoat. The kinetic model **45** may be calibrated for a specific catalytic converter system **32**, for example, by running the system **32** in various conditions, including lean burn and rich burn conditions. Accordingly, it may be useful to describe an embodiment of the catalytic converter system **32** in more detail.

Turning now to FIG. **3**, an embodiment of the catalytic converter system **32** may include at least two catalytic structures, a reduction catalyst **38** and an oxidation catalyst **40**. Both of the catalytic structures may comprise ceramic structures coated with a noble metal catalyst, such as platinum, rhodium, and palladium. The catalytic structures may comprise honeycomb shaped or ceramic beads, and may be divided into cells, which are measured per square inch.

As depicted in FIG. **3**, the exhaust gases, coming from the exhaust conduit **34**, first encounter the reduction catalyst **38**. The reduction catalyst **38** may be coated with one or more of a platinum group metal (PGM) coating, including ruthenium, rhodium, palladium, osmium, iridium, and/or platinum, and reduces the nitrogen oxides in the exhaust gases to nitrogen and oxygen. Next, the gases encounter the oxidation catalyst **40**, which may be coated with one or more PGM coating. The oxidation catalyst **38** oxidizes the unburned hydrocarbons in the exhaust gases to carbon dioxide and water, and the carbon monoxide in the exhaust gases to carbon dioxide. Finally, the converted gases exit the catalytic converter system via the output conduit **36**.

In certain embodiments, the catalytic converter system **32** may include a diffuser **42** positioned between the exhaust shaft **34** and the reduction catalyst **38**. The diffuser **42** scatters the exhaust gases evenly across the width of the catalytic structures in the catalytic converter system **32**. As a result, a larger amount of the exhaust gases may come into contact with the front end of the catalytic structures, allowing them to convert a large amount of the exhaust gases

within a shorter distance. Further, scattering the exhaust gases using the diffuser **34** may also reduce the likelihood that different areas of the catalytic structures age at varying rates due to different concentration of the exhaust gases in particular areas.

As mentioned above, the engine control unit **16** may control the AFR of the gas engine **12** so as to control the catalytic converter system **32** and improve the efficiency of the gas engine **12**. To do so, the engine control unit **16** may monitor a number of factors, such as the exhaust gas composition entering and/or exiting the catalytic converter system **32**, in order to determine any adjustments to the AFR of the gas engine **12**. In many situations, the performance of the catalytic converter system **32** may also provide an indication of whether and how the AFR of the gas engine **12** should be adjusted. For example, if the amount of oxidation of exhaust gases is below a certain threshold, it may be an indication that the gas engine is not receiving enough oxygen and the air-to-fuel ratio should be adjusted to become leaner.

To improve the control of the AFR of the gas engine **12**, the engine control unit **16** may work in conjunction with the catalyst estimator system **44**. That is, the engine control unit **16** may control the AFR of the gas engine **12** based on feedback from the catalyst estimator system **44**. As depicted in FIG. **4**, an embodiment of the catalyst estimator system **44** may include an Adaptive Extended Kalman Filter (AEKF) system **46** suitable for estimating, for example, the oxygen storage and release of the catalytic converter system **32**. The "extended" portion of the AEKF may be more suitable for analyzing non-linear data, unlike traditional Kalman filter techniques.

The catalyst estimator system **44** may estimate and monitor the operation of the catalytic converter system **32**. In particular, the catalyst estimator system **44** may estimate and monitor the oxygen storage dynamics of the catalytic converter system **32**. Ideally, the catalytic converter system **32** receives suitable oxygen from the fuel or the oxidation structure **40** to oxidize the unburned hydrocarbons and/or the carbon monoxide. That is, the amount of oxygen received from fuel or stored in the oxidation structure **40** may then determine the performance of the catalytic converter system **32** for two of its main functions, converting unburned hydrocarbons to carbon dioxide and water and carbon monoxide to carbon dioxide. As such, the oxygen storage dynamics of the catalytic converter system **32** may be a suitable indicator of the performance of the catalytic converter system **32**. However, it should be appreciated that the catalyst estimator system **44** may be used to estimate and monitor other performance indicators for the catalytic converter system **32**, such as temperature, mass flow, concentration of species of interest (e.g., COx, NOx, methane), pressure, and so on.

To that end, a measurement u representative of signals received from the sensors **30** upstream (or inside the catalytic converter system **32**) may be processed by an analog-to-digital (A/D) converter **48** into values u_k. Likewise, output signals y representative of sensors **30** downstream (or inside the catalytic converter system **32**) may be processed by an A/D converter **50** into values y_k may be used to as feedback to improve the AEKF system **46**. For example, y_k may be summed while an output of observation h block **52** (e.g., output of $h(\hat{X}_{k|k-1}, u_k)$) may be subtracted to arrive at a value K (shown via element number **53**), e.g., optimal Kalman gain with updates. $\hat{X}$ may represent an estimated value (e.g., oxygen storage, temperature, mass flow, pressure, species concentration) arrived at via the kinetic model

45. The value K may then be summed with an output of an f_d block **54** (e.g., $f_d(\hat{X}_{k-1|k-1}, u_{k-1})$), the sum which may then be used an input to block **56** (e.g., z^{-1}, representative of the square root of an observation of the true state), as well as to the block **52**. u_k may also be used as input to a block **58** (e.g., z^{-1}) which may provide its output to block **54**.

In one embodiment, an augmented state-parameter model for the AEKF system **46** may include:

$$\begin{bmatrix} X_k \\ \theta_k \end{bmatrix} = \begin{bmatrix} f_d(x_{k-1}, u_{k-1} \cdot \theta_{k-1}) \\ \theta_{k-1} \end{bmatrix} + \begin{bmatrix} w_{k-1}^x \\ w_{k-1}^\theta \end{bmatrix} \qquad \text{Equation (2)}$$

where $y_k = h(x_k, u_k, \theta_{k-1}) + v_k$, and $\theta_L \le \theta_k < \theta_U$ and a weight matrix w is a two element matrix as shown.

An augmented state-parameter vector may include:

$$x_k = [x_k \theta_k]^T \qquad \text{Equation (3):}$$

Where θ is representative of a fractional surface ceria coverage, and T is temperature. It is to be note that other Kalman filter systems may be used, as well as or in addition to the system **46**. It is also to be noted that other techniques, such as neural networks, genetic algorithms, expert systems, and the like, may be used in addition to or alternative to the system **46**.

To evaluate the oxygen storage dynamics of the catalytic converter system **32**, the catalyst estimator system **44** estimates, via the AEKF system **46** the oxygen storage dynamics of the catalytic converter system **32**. The control system **16** also determines a system oxygen storage setpoint for the catalytic converter system based on desired operating conditions (e.g., lean burn, rich burn), desired emissions levels (e.g. levels suitable for maintaining regulatory emissions compliance), catalytic degradation (e.g., degradation determined via the estimator **44**), and so on. The engine control unit **16** then determines a setpoint for the AFR of the gas engine **12** based on the comparison between the oxygen storage estimates and the oxygen storage setpoints and adjusts the AFR accordingly. In certain embodiments, the catalyst estimator system **44** may determine the AFR setpoint instead of the engine control unit **16**. Further, the catalyst estimator system **44** may adjust the AFR in certain embodiments. Regardless, the AFR setpoint may then be used by the engine control unit **16** to provide for control of various actuators, including fuel delivery actuators, and so on.

FIG. **5** depicts an embodiment of a process **60** suitable for defining and applying the catalyst estimator system **44**. Although the process **60** is described below in detail, the process **60** may include other steps not shown in FIG. **5**. Additionally, the steps illustrated may be performed concurrently or in a different order. Further, as will be appreciated, a portion of the steps of process **60** may be performed while the gas engine system **10** is offline (i.e., not in operation). The process **60** may be implemented as executable code or instructions stored in a computer-readable medium (e.g., memory **20**) and executable via one or more processors (e.g., processor **18**).

Beginning at block **62**, the process **60** creates one or more physical catalytic converter models **64**, such as the kinetic model **45**. The control system **16** may employ a model-based control (MBC) technique, in which operating states and conditions of the gas engine system **10** are treated as individual states. In such embodiments, the process **60** may create catalytic converter models **64** based on each individual operating state, each individual operating conditions,

or each combination of the individual operating state and operating conditions. The catalytic converter models **64** may be created during offline simulations of the gas engine system **10** and then be saved in the memory **20** (e.g., as look-up tables) for access during other steps of the process **60**.

At block **66**, the process **60** may create one or more catalytic estimator systems **68**, including the estimator **44** detailed above. As previously described, the estimator **44** may include the AEKF system **46**. The AEKF system **46** may be tuned to more efficiently provide for estimation of the catalytic system **32** for example, by tuning for high gain, low gain, and so forth. At block **70**, the process **60** receives a variety of inputs concerning the state of the gas engine system **10** and the catalytic converter system **32**. In particular, the process **60** receives data from at least the sensors **30A**, **30B**, and **30C**.

The process **60** then selects (block **72**) a catalytic converter model **64** and an estimator **68** based on the received inputs of block **70**. These inputs can include the total air mass flow, the exhaust gas temperature, the oxygen storage capacity of the oxidation structure **40**, the Gibbs energy of the oxidation structure **40**, the inlet gas composition, pressure, and the like. The received inputs include physical characteristics of the catalytic converter system **32** (e.g., the oxygen storage capacity and Gibbs energy of the oxidation structure **40**) that may be stored on the memory **20**, as well as empirical data (e.g., the exhaust gas temperature and the inlet gas composition) that is measured by one or more sensors **30**.

Next, at block **74**, the catalyst estimator system **44** estimates certain system dynamics, such as the oxygen storage dynamics of the catalytic converter system **32**. In particular, the catalyst estimator system **44** may estimate the oxygen storage dynamics for the entire catalytic converter system **32**, at various locations within the catalytic converter system **32**, as well as temperature, pressure, and mass flow for the entire catalytic converter system **32**, including inlet and outlet locations. The catalyst estimator system **44** determines estimates **76** based on the selected catalytic converter model **64** and the various measurements from the sensors **30**, including pre- and post-cat oxygen measurements. The catalyst estimator system **44** may also take into account the mid-cat oxygen measurement, if available, when determining the estimates **76** of oxygen storage dynamics. Additionally, the catalyst estimator system **44** may determine the estimates **76** based on oxygen intake, which is the amount of oxygen present in the exhaust gases and the oxygen stored within the catalytic converter system **30** that is released and consumed when the amount of oxygen in the exhaust gases is insufficient.

The process **60** also derives (block **78**) oxygen storage setpoints **80** for the catalytic converter system **32** based on the selected catalytic converter model **64** and estimator **68**. Advantageously, the process **60** derives the oxygen storage setpoints **80**, for example, to better control emissions, to improve performance of the catalyst system **32**, to account for degradation of the catalyst system **32**, to improve performance of the engine **12**, or a combination thereof. In one embodiment, the individual setpoints **80** may be derived via a simulation (e.g., offline simulation), and then the derivations stored, for example, in one or more lookup tables for use during operations of the system **10**. In another embodiment, the individual setpoints **80** may be derived during operations (e.g., real-time derivation) and used by the engine control unit **16** in real-time.

At block **82**, the process **60** compares the system oxygen storage setpoints **80** to the oxygen storage estimates **76**. The process **60** then provides the results of the comparison to the engine control unit **16**, which uses the comparison to determine (block **84**) an AFR setpoint **86**. The engine control unit **16** then controls one or more actuators **28** (e.g., the throttle **14**) to achieve the AFR setpoint at block **88**. In certain embodiments, the process **60** may store the received inputs, the selected catalytic converter model **64**, and the oxygen storage estimates **76** on the memory **20** at block **90**. The process **60** then analyzes the saved data to determine improvements to the catalytic converter models **64** at block **92**. This may be done using one or more machine learning algorithms, such as neural networks and data clustering. By using the analyzed data to improve the catalytic converter models **64**, the process **60** may account for changes to the gas engine **12** and the catalytic converter system **32** over time, such as system aging and degradation. As will be appreciated, the process **60** may perform any analysis of the saved data while the gas engine system **10** is offline.

In addition to improving the catalytic converter models **64**, the analyzed data may also be used to perform diagnostic tests on the catalytic converter system **32** at block **94**. Based on the analyzed data, the process **60** may assign a health state **96** to the catalytic converter system **32** (e.g., in need of maintenance, excellent performance, etc.). In some embodiments, the health state **94** may include data relating to the catalytic converter system **32**, such as the amount oxygen saturation, the amount of oxygen stored, or the percentage of a specific reaction species conversion out of all conversions. The process **60** may then communicate the health state **94** to the engine control unit **16**, which can take action as necessary.

For example, FIG. **6** depicts an embodiment of a control process **100** that may be used to control the gas engine system **10**. The control process **100** begins with deriving or retrieving the oxygen storage setpoints **80**, as described above. Next, at block **102**, the engine control unit **16** derives an AFR lambda setpoint **104**. The AFR lambda setpoint **104** is a setpoint for the air-to-fuel equivalence ratio, which is often denoted using the Greek letter lambda. The air-to-fuel equivalence ratio measures the ratio of a value of an AFR to the stoichiometric AFR for that particular type of fuel. As such, deriving the AFR lambda setpoint **104** may depend, in part, on deriving the AFR setpoint **86** as described above. Accordingly, block **102** and the AFR lambda setpoint **104** may be considered as a specific example of block **82** and setpoint **86** (shown in FIG. **5**), respectively.

At block **106**, the engine control unit **106** may adjust the AFR of the engine **12** to achieve the AFR lambda setpoint **104**. This action may include controlling the actuators **28** (e.g., the throttle **14**) as described above with reference to block **86**. After adjusting the AFR, the engine control unit **106** may then measure, based on data from the sensors **30**, the actual air-to-fuel equivalence ratio of the engine **12** at block **108**. The engine control unit **16** then compares the actual air-to-fuel equivalence ratio to the AFR lambda setpoint **104** and adjusts the AFR as necessary, thereby completing an AFR inner feedback loop **110**.

At block **112**, the catalyst estimator system **44** may receive the measured air-to-fuel equivalence ratio and, based on the ratio and other inputs (e.g., the pre- and post-cat oxygen measurements, mid-catalyst measurements), estimates the system dynamics **76** of the catalytic converter system **32** as described above with reference to block **74**. After estimating the system dynamics **76**, the catalyst estimator system **44** derives the oxygen storage setpoints **80** at

block **114**. At least one of the newly derived oxygen storage setpoints **80** may then compared to the oxygen storage estimates, as described above with reference to block **82**. The comparison is then used to derive a new AFR lambda setpoint **104**, thereby completing an oxygen storage outer feedback loop **116**.

In another embodiment, the block **102** may receive, additionally or alternative to the oxygen setpoint **80**, setpoints associated with one or more emission species concentrations (e.g., NOx, COx). The engine control unit **16** may then derive the desired AFR setpoint **104** based on the inputted one or more emission species and/or the setpoint **80**. It is also to be noted that the catalyst estimator system **44** may adapt operations to compensate for ageing or degradation. For example, the catalyst estimator system **44** may compare current measurements from sensors **30** with estimates **76**, as well as total running time of the system **10** (e.g., running hours) to determine that degradation is taking place. The engine control unit **16** may then derive the AFR setpoint **104**, for example, to maintain regulatory compliance, based on the degradation.

Technical effects of the invention include controlling a catalytic converter system based in part on the actual and desired performance of the catalytic converter system. For example, the AFR of a gas engine may be controlled to meet certain emissions criteria of the catalytic converter system. Certain embodiments may allow for more accurate determinations of the actual performance of a catalytic converter system. For example, the present catalyst estimator system may estimate the oxygen storage dynamics of the catalytic converter systems based in part on kinetic models and an Adaptive Extended Kalman Filter (AEKF) system. The models and the AEKF system may also be updated over time using previous estimates. Certain embodiments may also allow for determining the actual and desired performance for all or a portion of the catalytic converter system. Certain embodiments may also include analyzing the performance of the catalytic converter system and determining the health of the catalytic converter system based on the analysis. The technical effects and technical problems in the specification are exemplary and not limiting. It should be noted that the embodiments described in the specification may have other technical effects and can solve other technical problems.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

The invention claimed is:

1. A system comprising:
   a controller comprising a processor programmed to:
      receive a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system;
      receive a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein the second oxygen sensor is disposed downstream of the catalytic converter system;

      receive a third signal from a nitrogen oxide (NOx) sensor indicative of NOx emissions of the catalytic converter system;
      execute a catalyst estimator system, wherein the catalyst estimator system is configured to modify a catalytic converter model based at least in part on the third signal and to derive an oxygen storage estimate based on the first signal, the second signal, and the modified catalytic converter model; and
      compare the oxygen storage estimate with a system oxygen storage setpoint, wherein the processor is configured to apply the comparison during control of a gas engine.

2. The system of claim **1**, wherein the catalyst estimator system comprises an Adaptive Extended Kalman Filter (AEKF) system configured to:
   derive the oxygen storage estimate; and
   adjust the oxygen storage estimate based on the first and the second signal via execution of an augmented state-parameter model.

3. The system of claim **2**, wherein the AEKF system is configured to execute the augmented state-parameter model based on an augmented-state parameter vector.

4. The system of claim **1**, wherein the processor is configured to derive an air-to-fuel ratio (AFR) setpoint based on the comparison; and adjust a fuel actuator disposed in the gas engine based on the AFR setpoint.

5. The system of claim **1**, wherein the catalytic converter model comprises a kinetic catalyst model.

6. The system of claim **5**, wherein the kinetic catalyst model models carbon monoxide oxidation, methane oxidation, reduction of nitrogen oxides, or a combination thereof.

7. The system of claim **1**, wherein the processor is configured to apply the comparison during control of the gas engine to at least improve overall performance of the catalytic converter system, carbon monoxide oxidation efficiency of the catalytic converter system, or a combination thereof.

8. The system of claim **1**, wherein the controller is configured to receive an additional signal from an additional sensor disposed upstream of the catalytic converter system, downstream of the catalytic converter system, or inside the catalytic converter system, wherein the additional sensor comprises a carbon monoxide sensor, a mass flow sensor, a pressure sensor, a temperature sensor, an oxygen sensor, or a combination thereof, and wherein the controller is configured to further use the additional signal when modifying the catalytic converter model.

9. The system of claim **1**, wherein the processor is configured to derive an air-to-fuel ratio (AFR) setpoint based at least in part on the third signal; and adjust a fuel actuator disposed in the gas engine based on the AFR setpoint.

10. A system comprising:
   a gas engine system comprising a gas engine fluidly coupled to a catalytic converter system;
   a catalytic controller operatively coupled to the gas engine, and communicatively coupled to the catalytic converter, the catalytic controller comprising a processor programmed to:
      receive a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system;
      receive a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein

the second oxygen sensor is disposed downstream of the catalytic converter system;

receive a third signal from a nitrogen oxide (NOx) sensor indicative of NOx emissions of the catalytic converter system;

execute a catalyst estimator system, wherein the catalyst estimator system is configured to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model;

compare the oxygen storage estimate with a system oxygen storage setpoint, wherein the processor is configured to apply the comparison during control of a gas engine; and

derive an air-to-fuel ratio (AFR) setpoint based on the comparison and the third signal, wherein the AFR setpoint is applied to control the gas engine.

11. The system of claim **10**, wherein the catalyst estimator system comprises an Adaptive Extended Kalman Filter (AEKF) system configured to:

derive the oxygen storage estimate; and

adjust the oxygen storage estimate based on the first and the second signal via execution of an augmented state-parameter model.

12. The system of claim **11**, wherein the AEKF system is configured to execute the augmented state-parameter model based on an augmented-state parameter vector.

13. The system of claim **10**, wherein the controller is configured to receive an additional signal from an additional sensor disposed upstream of the catalytic converter system, downstream of the catalytic converter system, or inside the catalytic converter system, wherein the sensor comprises a carbon oxide (COx) sensor, a mass flow sensor, a pressure sensor, a temperature sensor, or a combination thereof, and wherein the controller is configured to derive the AFR setpoint based additionally on the additional signal.

14. The system of claim **10**, wherein the processor is configured to determine a health state of the catalytic converter system based on the plurality of oxygen storage estimates.

15. A method, comprising:

receiving a first signal from a first oxygen sensor indicative of a first oxygen measurement, wherein the first oxygen sensor is disposed upstream of a catalytic converter system;

receiving a second signal from a second oxygen sensor indicative of a second oxygen measurement, wherein

the second oxygen sensor is disposed downstream of the catalytic converter system;

receiving a third signal from a nitrogen oxide (NOx) sensor indicative of NOx emissions of the catalytic converter system;

executing a catalyst estimator system, wherein the catalyst estimator system is configured to modify a catalytic converter model based on the third signal and to derive an oxygen storage estimate based on the first signal, the second signal, and a catalytic converter model;

deriving a system oxygen storage setpoint for the catalytic converter system based on the catalytic converter model;

comparing the oxygen storage estimate with the system oxygen storage setpoint; and

applying the comparison during control of a gas engine.

16. The method of claim **15**, wherein the catalyst estimator system comprises an Adaptive Extended Kalman Filter (AEKF) system configured to:

derive the oxygen storage estimate; and

adjust the oxygen storage estimate based on the first and the second signal via execution of an augmented state-parameter model.

17. The method of claim **16**, wherein the AEKF system is configured to execute the augmented state-parameter model based on an augmented-state parameter vector.

18. The method of claim **15**, wherein the catalytic converter model comprises a kinetic catalyst model configured to model chemical kinetics of carbon monoxide oxidation, a reduction of nitric oxide, a methane, or a combination thereof.

19. The method of claim **15**, wherein the instructions are configured to receive an additional signal from an additional sensor disposed upstream of the catalytic converter system, downstream of the catalytic converter system, or inside the catalytic converter system, wherein the sensor comprises a carbon oxide (COx) sensor, a mass flow sensor, a pressure sensor, a temperature sensor, or a combination thereof, and wherein the instructions are configured to further use the additional signal when modifying the catalytic converter model.

20. The method of claim **19**, wherein the instructions are configured to derive an air-to-fuel ratio (AFR) setpoint based on the comparison, the third signal, the additional signal, or a combination thereof; and adjust a fuel actuator disposed in the gas engine based on the AFR setpoint.

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