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(54) **SYSTEM AND METHOD FOR IMPROVING THE RESPONSE TIME OF AN ENGINE USING MODEL PREDICTIVE CONTROL**

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(57) **ABSTRACT**

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CPC ... F02D 28/00; F02D 11/105; F02D 2250/18;  
F02D 41/26; F02D 41/0002; F02D 41/1497;  
F02D 41/1498  
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See application file for complete search history.

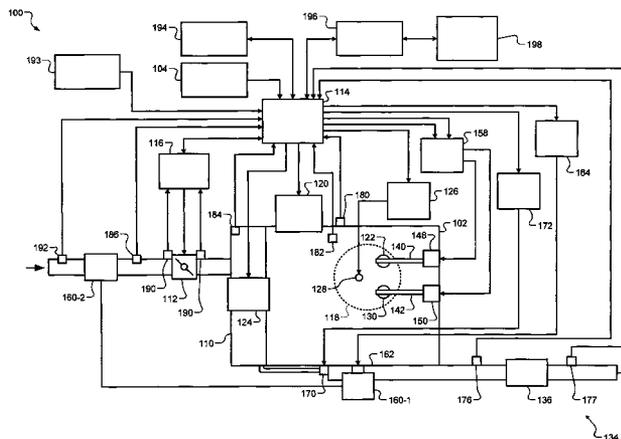
A system according to the principles of the present disclosure includes a model predictive control (MPC) module and an actuator module. The MPC module generates predicted parameters based on a model of a subsystem and a set of possible target values. The MPC module generates a cost for the set of possible target values based on the predicted parameters and at least one of weighting values and reference values. The MPC module adjusts the at least one of the weighting values and the reference values based on a desired rate of change in an operating condition of the subsystem. The MPC module selects the set of possible target values from multiple sets of possible target values based on the cost. The actuator module adjusts an actuator of the subsystem based on at least one of the target values.

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**20 Claims, 6 Drawing Sheets**



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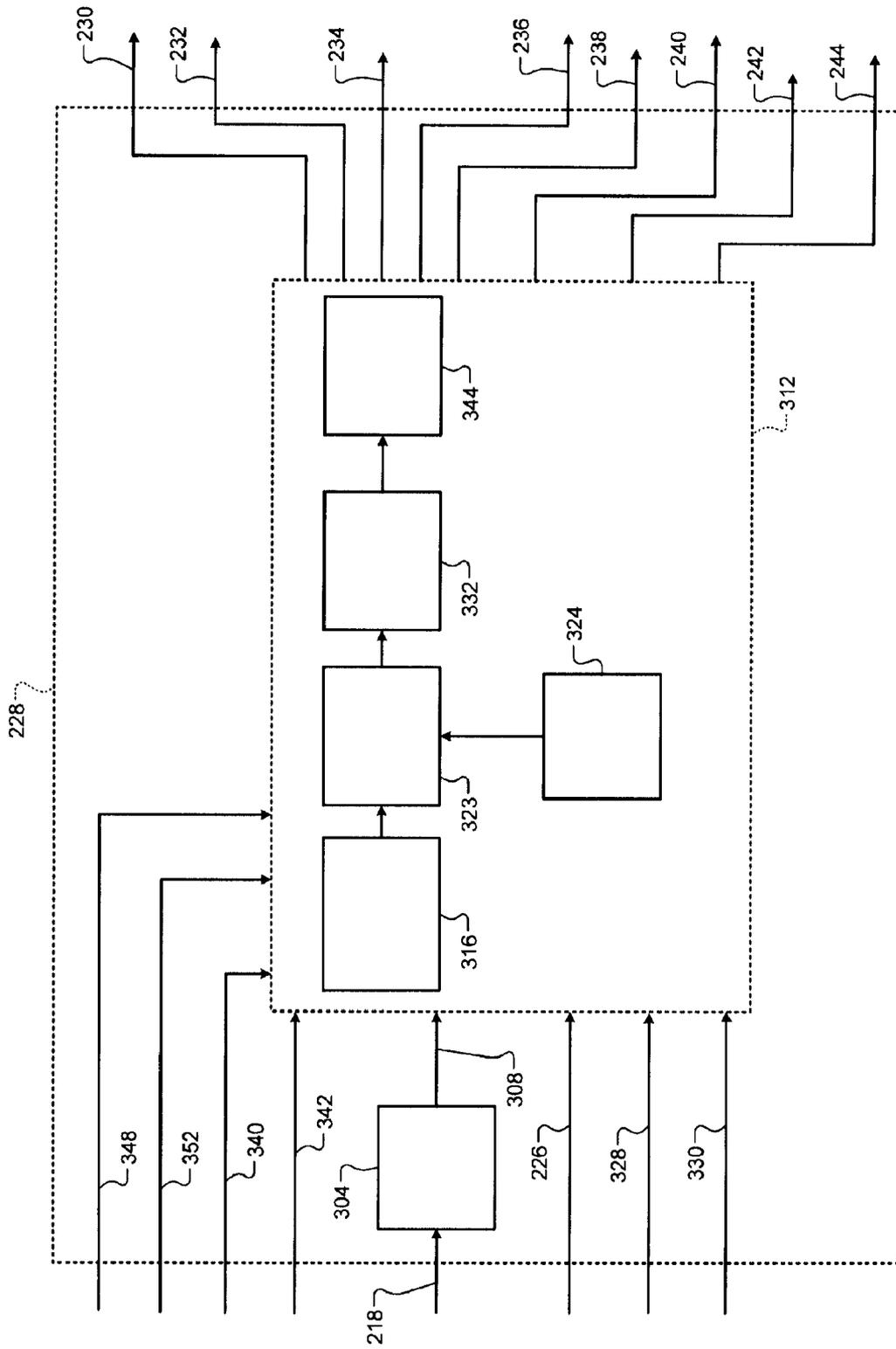


FIG. 3

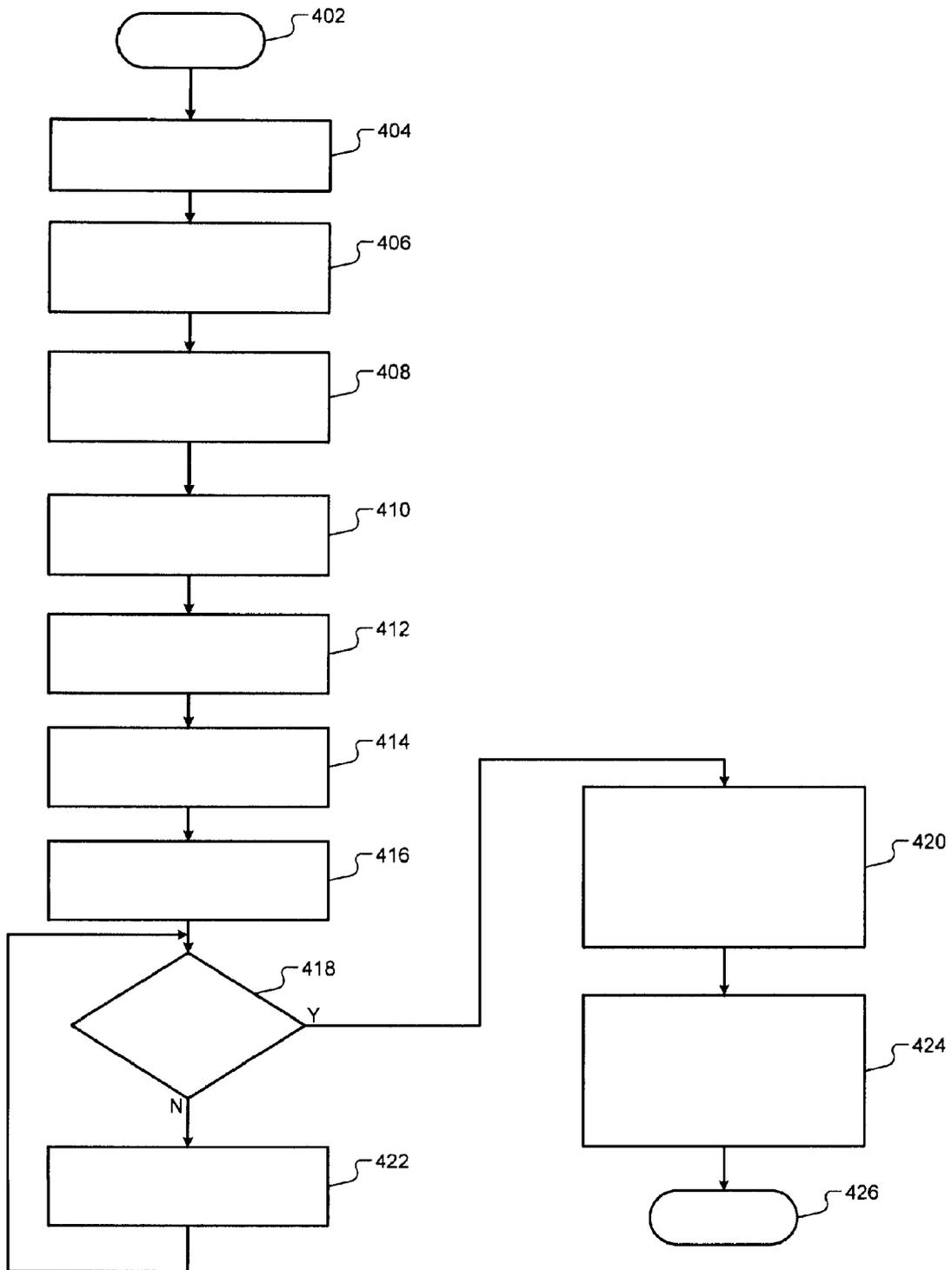
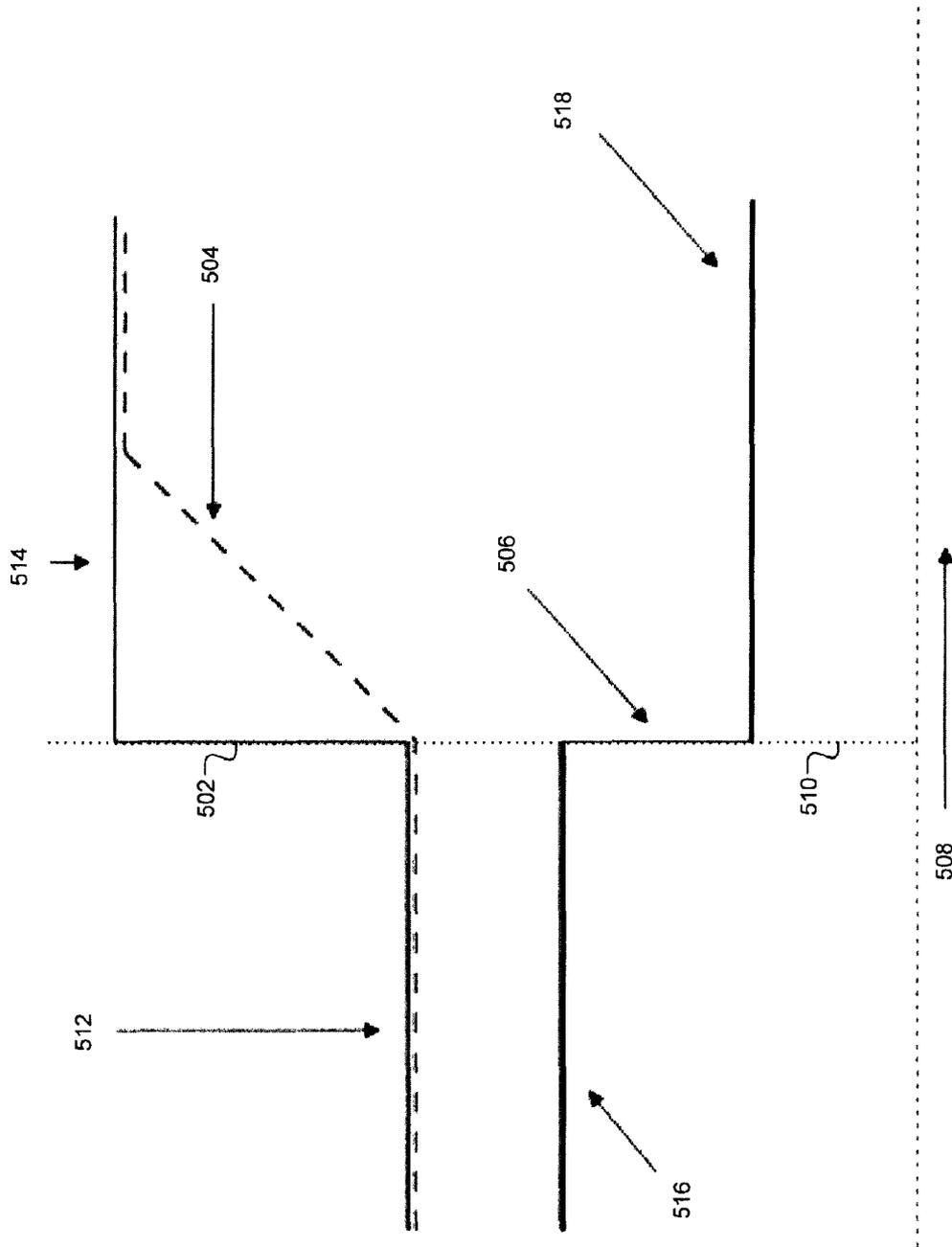


FIG. 4



**FIG. 5**

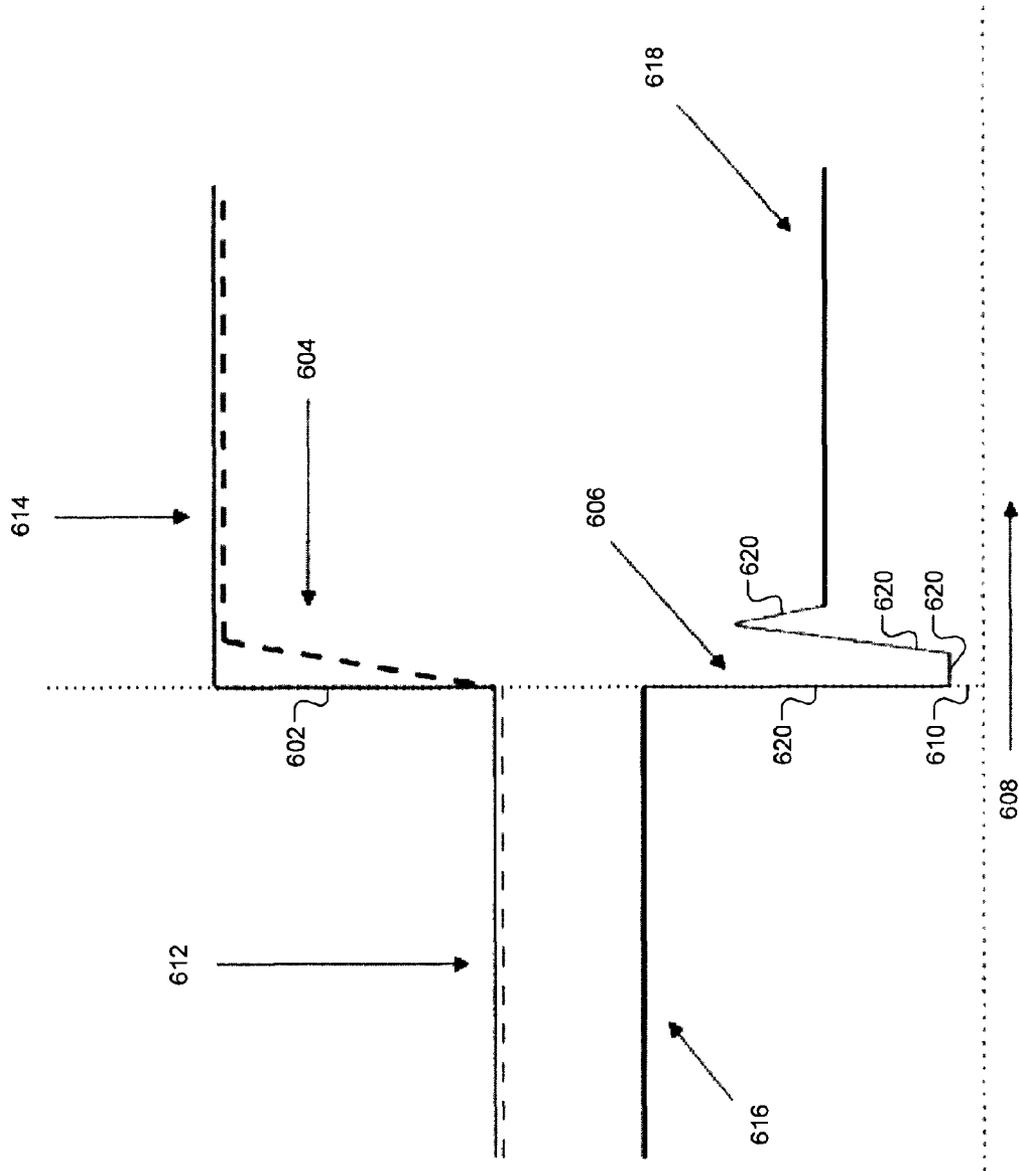


FIG. 6

# SYSTEM AND METHOD FOR IMPROVING THE RESPONSE TIME OF AN ENGINE USING MODEL PREDICTIVE CONTROL

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. patent application Ser. No. 14/225,502 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,516 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,569 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,626 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/225,817 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,896 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,531 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/225,507 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/225,808 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/225,492 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/226,006 filed on Mar. 26, 2014 U.S. patent application Ser. No. 14/226,121 filed on Mar. 26, 2014, U.S. patent application Ser. No. 14/225,496 filed on Mar. 26, 2014 and U.S. patent application Ser. No. 14/225,891 filed on Mar. 26, 2014. The entire disclosures of the above applications are incorporated herein by reference.

## FIELD

The present disclosure relates to internal combustion engines, and more particularly, to systems and methods for improving the response time of an engine using model predictive control.

## BACKGROUND

The background description provided here is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

Internal combustion engines combust an air and fuel mixture within cylinders to drive pistons, which produces drive torque. Air flow into the engine is regulated via a throttle. More specifically, the throttle adjusts throttle area, which increases or decreases air flow into the engine. As the throttle area increases, the air flow into the engine increases. A fuel control system adjusts the rate that fuel is injected to provide a desired air/fuel mixture to the cylinders and/or to achieve a desired torque output. Increasing the amount of air and fuel provided to the cylinders increases the torque output of the engine.

In spark-ignition engines, spark initiates combustion of an air/fuel mixture provided to the cylinders. In compression-ignition engines, compression in the cylinders combusts the air/fuel mixture provided to the cylinders. Spark timing and air flow may be the primary mechanisms for adjusting the torque output of spark-ignition engines, while fuel flow may be the primary mechanism for adjusting the torque output of compression-ignition engines.

Engine control systems have been developed to control engine output torque to achieve a desired torque. Traditional engine control systems, however, do not control the engine output torque as accurately as desired. Further, traditional engine control systems do not provide a rapid response to

control signals or coordinate engine torque control among various devices that affect the engine output torque.

## SUMMARY

A system according to the principles of the present disclosure includes a model predictive control (MPC) module and an actuator module. The MPC module generates predicted parameters based on a model of a subsystem and a set of possible target values. The MPC module generates a cost for the set of possible target values based on the predicted parameters and at least one of weighting values and reference values. The MPC module adjusts the at least one of the weighting values and the reference values based on a desired rate of change in an operating condition of the subsystem. The MPC module selects the set of possible target values from multiple sets of possible target values based on the cost. The actuator module adjusts an actuator of the subsystem based on at least one of the target values.

Further areas of applicability of the present disclosure will become apparent from the detailed description, the claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

FIG. 1 is a functional block diagram of an example engine system according to the present disclosure;

FIG. 2 is a functional block diagram of an example engine control system according to the present disclosure;

FIG. 3 is a functional block diagram of an example target generating module according to the present disclosure;

FIG. 4 is a flowchart depicting an example method of controlling a throttle valve, intake and exhaust valve phasing, a wastegate, an exhaust gas recirculation (EGR) valve, spark timing, and fueling using model predictive control according to the present disclosure; and

FIGS. 5 and 6 are graphs illustrating example desired manifold pressures, example actual manifold pressures, and example reference wastegate opening areas according to the present disclosure.

In the drawings, reference numbers may be reused to identify similar and/or identical elements.

## DETAILED DESCRIPTION

An engine control module (ECM) controls torque output of an engine. More specifically, the ECM determines target values based on a requested amount of torque and controls actuators of the engine based on the target values. For example, the ECM controls intake and exhaust camshaft phasers based on target phaser angles, a throttle valve based on a target throttle opening area, an exhaust gas recirculation (EGR) valve based on a target EGR opening, and a wastegate of a turbocharger based on a target wastegate duty cycle. The ECM also controls spark timing based on target spark timing and controls fueling based on target fueling parameters.

The ECM could determine the target values individually using multiple single input single output (SISO) controllers, such as proportional integral derivative (PID) controllers. However, when multiple SISO controllers are used, the target values may be set to maintain system stability at the expense

of possible fuel consumption decreases. Additionally, calibration and design of the individual SISO controllers may be costly and time consuming.

The ECM of the present disclosure generates the target values using a model predictive control (MPC) module. The MPC module identifies possible sets of target values. The MPC module determines predicted parameters for each of the possible sets based on the possible sets' target values and a mathematical model of the engine. For example, the MPC module may determine a predicted engine torque and one or more other predicted parameters for each of the possible sets of target values.

The MPC module may also determine a cost associated with use of each of the possible sets. For example, the cost of a possible set that is predicted to more closely track an engine torque request may be lower than other possible sets that are not predicted to track the engine torque request as closely. The MPC module may select the possible set that has the lowest cost and that satisfies various constraints for use in controlling the actuators. In various implementations, instead of or in addition to identifying possible sets of target values and determining the cost of each of the sets, the MPC module may generate a surface representing the cost of possible sets of target values. The MPC module may then identify the possible set that has the lowest cost based on the slope of the cost surface.

The cost of a possible set of target values may be determined based on differences between the possible target values and respective reference values. For example, the cost may be determined based on a difference between a possible target throttle opening area and a reference throttle opening area. The reference values may be predetermined and may correspond to steady-state operation of the engine.

The cost of a possible set of target values may also be determined based on a total amount of change in each of the possible target values over a prediction period. For example, the cost may be determined based on the total amount of change in the possible target throttle opening area over the prediction period. In addition, the differences between the possible target values and respective reference values and/or the total amounts of change in the possible target values may be weighted to control the effect that each difference and/or total change amount has on the cost. For example, weighting values may be applied to each difference and/or to each total change amount.

Determining the cost of possible sets of target values in the manner described above may limit the rate at which an operating condition of the engine can be changed. In turn, an operating condition of the engine may not be changed as quickly as desired. Thus, the ECM of the present disclosure may adjust the reference values and/or the weighting values based on a desired rate of change in an operating condition of the engine. For example, the ECM may set one or more of the weighting values to zero so that the corresponding reference values may be adjusted in a manner that achieves the desired rate. In another example, the ECM may adjust one or more of the reference values based on a reference trajectory that achieves the desired rate. Although control systems and methods are described herein in the context of an engine, the same principles may be applied to control systems and methods for other subsystems.

Referring now to FIG. 1, an engine system 100 includes an engine 102 that combusts an air/fuel mixture to produce drive torque for a vehicle. The amount of drive torque produced by the engine 102 is based on a driver input from a driver input module 104. The engine 102 may be a gasoline spark ignition internal combustion engine.

Air is drawn into an intake manifold 110 through a throttle valve 112. For example, the throttle valve 112 may include a butterfly valve having a rotatable blade. An engine control module (ECM) 114 controls a throttle actuator module 116, which regulates opening of the throttle valve 112 to control the amount of air drawn into the intake manifold 110.

Air from the intake manifold 110 is drawn into cylinders of the engine 102. While the engine 102 may include multiple cylinders, for illustration purposes a single representative cylinder 118 is shown. For example, the engine 102 may include 2, 3, 4, 5, 6, 8, 10, and/or 12 cylinders. The ECM 114 may instruct a cylinder actuator module 120 to selectively deactivate some of the cylinders, which may improve fuel economy under certain engine operating conditions.

The engine 102 may operate using a four-stroke cycle. The four strokes, described below, may be referred to as the intake stroke, the compression stroke, the combustion stroke, and the exhaust stroke. During each revolution of a crankshaft (not shown), two of the four strokes occur within the cylinder 118. Therefore, two crankshaft revolutions are necessary for the cylinder 118 to experience all four of the strokes.

During the intake stroke, air from the intake manifold 110 is drawn into the cylinder 118 through an intake valve 122. The ECM 114 controls a fuel actuator module 124, which regulates fuel injection to achieve a target air/fuel ratio. Fuel may be injected into the intake manifold 110 at a central location or at multiple locations, such as near the intake valve 122 of each of the cylinders. In various implementations (not shown), fuel may be injected directly into the cylinders or into mixing chambers associated with the cylinders. The fuel actuator module 124 may halt injection of fuel to cylinders that are deactivated.

The injected fuel mixes with air and creates an air/fuel mixture in the cylinder 118. During the compression stroke, a piston (not shown) within the cylinder 118 compresses the air/fuel mixture. A spark actuator module 126 energizes a spark plug 128 in the cylinder 118 based on a signal from the ECM 114, which ignites the air/fuel mixture. The timing of the spark may be specified relative to the time when the piston is at its topmost position, referred to as top dead center (TDC).

The spark actuator module 126 may be controlled by a timing signal specifying how far before or after TDC to generate the spark. Because piston position is directly related to crankshaft rotation, operation of the spark actuator module 126 may be synchronized with crankshaft angle. Generating spark may be referred to as a firing event. The spark actuator module 126 may have the ability to vary the timing of the spark for each firing event. The spark actuator module 126 may vary the spark timing for a next firing event when the spark timing is changed between a last firing event and the next firing event. The spark actuator module 126 may halt provision of spark to deactivated cylinders.

During the combustion stroke, the combustion of the air/fuel mixture drives the piston away from TDC, thereby driving the crankshaft. The combustion stroke may be defined as the time between the piston reaching TDC and the time at which the piston reaches bottom dead center (BDC). During the exhaust stroke, the piston begins moving away from BDC and expels the byproducts of combustion through an exhaust valve 130. The byproducts of combustion are exhausted from the vehicle via an exhaust system 134. The exhaust system 134 includes a catalyst 136, such as a three-way catalyst (TWC). The catalyst 136 reacts with one or more components of exhaust flowing through the catalyst 136. The catalyst 136 stores oxygen when the exhaust is fuel lean (oxygen rich).

The intake valve 122 may be controlled by an intake camshaft 140, while the exhaust valve 130 may be controlled by

an exhaust camshaft **142**. In various implementations, multiple intake camshafts (including the intake camshaft **140**) may control multiple intake valves (including the intake valve **122**) for the cylinder **118** and/or may control the intake valves (including the intake valve **122**) of multiple banks of cylinders (including the cylinder **118**). Similarly, multiple exhaust camshafts (including the exhaust camshaft **142**) may control multiple exhaust valves for the cylinder **118** and/or may control exhaust valves (including the exhaust valve **130**) for multiple banks of cylinders (including the cylinder **118**). In various other implementations, the intake valve **122** and/or the exhaust valve **130** may be controlled by devices other than camshafts, such as camless valve actuators. The cylinder actuator module **120** may deactivate the cylinder **118** by disabling opening of the intake valve **122** and/or the exhaust valve **130**.

The time when the intake valve **122** is opened may be varied with respect to piston TDC by an intake cam phaser **148**. The time when the exhaust valve **130** is opened may be varied with respect to piston TDC by an exhaust cam phaser **150**. A phaser actuator module **158** may control the intake cam phaser **148** and the exhaust cam phaser **150** based on signals from the ECM **114**. When implemented, variable valve lift (not shown) may also be controlled by the phaser actuator module **158**.

The engine system **100** may include a turbocharger that includes a hot turbine **160-1** that is powered by hot exhaust gases flowing through the exhaust system **134**. The turbocharger also includes a cold air compressor **160-2** that is driven by the turbine **160-1**. The compressor **160-2** compresses air leading into the throttle valve **112**. In various implementations, a supercharger (not shown), driven by the crankshaft, may compress air from the throttle valve **112** and deliver the compressed air to the intake manifold **110**.

A wastegate **162** may allow exhaust to bypass the turbine **160-1**, thereby reducing the boost (the amount of intake air compression) provided by the turbocharger. A boost actuator module **164** may control the boost of the turbocharger by controlling opening of the wastegate **162**. In various implementations, two or more turbochargers may be implemented and may be controlled by the boost actuator module **164**.

An air cooler (not shown) may transfer heat from the compressed air charge to a cooling medium, such as engine coolant or air. An air cooler that cools the compressed air charge using engine coolant may be referred to as an intercooler. An air cooler that cools the compressed air charge using air may be referred to as a charge air cooler. The compressed air charge may receive heat, for example, via compression and/or from components of the exhaust system **134**. Although shown separated for purposes of illustration, the turbine **160-1** and the compressor **160-2** may be attached to each other, placing intake air in close proximity to hot exhaust.

The engine system **100** may include an exhaust gas recirculation (EGR) valve **170**, which selectively redirects exhaust gas back to the intake manifold **110**. The EGR valve **170** may be located upstream of the turbocharger's turbine **160-1**. The EGR valve **170** may be controlled by an EGR actuator module **172** based on signals from the ECM **114**.

An upstream oxygen sensor **176** measures an amount (e.g., concentration) of oxygen in the exhaust gas flowing into the catalyst **136**. A downstream oxygen sensor **177** measures an amount (e.g., concentration) of oxygen in the exhaust gas downstream of the catalyst **136**. The ECM **114** may use signals from the sensors and/or one or more other sensors to make control decisions for the engine system **100**.

A position of the crankshaft may be measured using a crankshaft position sensor **180**. A rotational speed of the

crankshaft (an engine speed) may be determined based on the crankshaft position. A temperature of the engine coolant may be measured using an engine coolant temperature (ECT) sensor **182**. The ECT sensor **182** may be located within the engine **102** or at other locations where the coolant is circulated, such as a radiator (not shown).

A pressure within the intake manifold **110** may be measured using a manifold absolute pressure (MAP) sensor **184**. In various implementations, engine vacuum, which is the difference between ambient air pressure and the pressure within the intake manifold **110**, may be measured. A mass flow rate of air flowing into the intake manifold **110** may be measured using a mass air flow (MAF) sensor **186**. In various implementations, the MAF sensor **186** may be located in a housing that also includes the throttle valve **112**.

The throttle actuator module **116** may monitor the position of the throttle valve **112** using one or more throttle position sensors (TPS) **190**. An ambient temperature of air being drawn into the engine **102** may be measured using an intake air temperature (IAT) sensor **192**. The engine system **100** may also include one or more other sensors **193**, such as an ambient humidity sensor, one or more knock sensors, a compressor outlet pressure sensor and/or a throttle inlet air pressure (TIAP) sensor, a wastegate position sensor, an EGR position sensor, and/or one or more other suitable sensors. The TIAP sensor may measure the pressure downstream from the compressor **160-2** and upstream from the throttle valve **112**. The ECM **114** may use signals from the sensors to make control decisions for the engine system **100**.

The ECM **114** may communicate with a transmission control module **194** to coordinate shifting gears in a transmission (not shown). For example, the ECM **114** may reduce engine torque during a gear shift. The ECM **114** may communicate with a hybrid control module **196** to coordinate operation of the engine **102** and an electric motor **198**.

The electric motor **198** may also function as a generator, and may be used to produce electrical energy for use by vehicle electrical systems and/or for storage in a battery. In various implementations, various functions of the ECM **114**, the transmission control module **194**, and the hybrid control module **196** may be integrated into one or more modules.

Each system that varies an engine parameter may be referred to as an engine actuator. For example, the throttle actuator module **116** may adjust opening of the throttle valve **112** to achieve a target throttle opening area. The spark actuator module **126** controls the spark plugs to achieve a target spark timing relative to piston TDC. The fuel actuator module **124** controls the fuel injectors to achieve target fueling parameters. The phaser actuator module **158** may control the intake and exhaust cam phasers **148** and **150** to achieve target intake and exhaust cam phaser angles, respectively. The EGR actuator module **172** may control the EGR valve **170** to achieve a target EGR opening area. The boost actuator module **164** controls the wastegate **162** to achieve a target wastegate opening area. The cylinder actuator module **120** controls cylinder deactivation to achieve a target number of activated or deactivated cylinders.

The ECM **114** generates the target values for the engine actuators to cause the engine **102** to generate a target engine output torque. The ECM **114** generates the target values for the engine actuators using model predictive control, as discussed further below.

Referring now to FIG. 2, an example implementation of the ECM **114** includes a drive torque module. The driver torque module **202** determines a driver torque request **204** based on a driver input **206** from the driver input module **104**. The driver input **206** may be based on, for example, a position of

an accelerator pedal and a position of a brake pedal. The driver input **206** may also be based on cruise control, which may be an adaptive cruise control system that varies vehicle speed to maintain a predetermined following distance. The driver torque module **202** may store one or more mappings of accelerator pedal position to target torque and may determine the driver torque request **204** based on a selected one of the mappings. The driver torque module **202** may also apply one or more filters to rate limit changes in the driver torque request **204**.

An axle torque arbitration module **208** arbitrates between the driver torque request **204** and other axle torque requests **210**. Axle torque (torque at the wheels) may be produced by various sources including an engine and/or an electric motor. For example, the axle torque requests **210** may include a torque reduction requested by a traction control system when positive wheel slip is detected. Positive wheel slip occurs when axle torque overcomes friction between the wheels and the road surface, and the wheels begin to slip against the road surface. The axle torque requests **210** may also include a torque increase request to counteract negative wheel slip, where a tire of the vehicle slips in the other direction with respect to the road surface because the axle torque is negative.

The axle torque requests **210** may also include brake management requests and vehicle over-speed torque requests. Brake management requests may reduce axle torque to ensure that the axle torque does not exceed the ability of the brakes to hold the vehicle when the vehicle is stopped. Vehicle over-speed torque requests may reduce the axle torque to prevent the vehicle from exceeding a predetermined speed. The axle torque requests **210** may also be generated by vehicle stability control systems.

The axle torque arbitration module **208** outputs an axle torque request **212** based on the results of arbitrating between the received axle torque requests **204** and **210**. As described below, the axle torque request **212** from the axle torque arbitration module **208** may selectively be adjusted by other modules of the ECM **114** before being used to control the engine actuators.

The axle torque arbitration module **208** may output the axle torque request **212** to a propulsion torque arbitration module **214**. In various implementations, the axle torque arbitration module **208** may output the axle torque request **212** to a hybrid optimization module **216**. The hybrid optimization module **216** may determine how much torque should be produced by the engine **102** and how much torque should be produced by the electric motor **198**. The hybrid optimization module **216** then outputs a modified axle torque request **218** to the propulsion torque arbitration module **214**.

The propulsion torque arbitration module **214** converts the axle torque request **212** (or the modified axle torque request **218**) from an axle torque domain (torque at the wheels) into a propulsion torque domain (torque at the crankshaft). The propulsion torque arbitration module **214** arbitrates between the (converted) axle torque request **212** and other propulsion torque requests **220**. The propulsion torque arbitration module **214** generates a propulsion torque request **222** as a result of the arbitration.

For example, the propulsion torque requests **220** may include torque reductions for engine over-speed protection, torque increases for stall prevention, and torque reductions requested by the transmission control module **194** to accommodate gear shifts. The propulsion torque requests **220** may also result from clutch fuel cutoff, which reduces the engine output torque when the driver depresses the clutch pedal in a manual transmission vehicle to prevent a flare in engine speed.

The propulsion torque requests **220** may also include an engine shutoff request, which may be initiated when a critical fault is detected. For example, critical faults may include detection of vehicle theft, a stuck starter motor, electronic throttle control problems, and unexpected torque increases. In various implementations, when an engine shutoff request is present, arbitration selects the engine shutoff request as the winning request. When the engine shutoff request is present, the propulsion torque arbitration module **214** may output zero as the propulsion torque request **222**.

In various implementations, an engine shutoff request may simply shut down the engine **102** separately from the arbitration process. The propulsion torque arbitration module **214** may still receive the engine shutoff request so that, for example, appropriate data can be fed back to other torque requestors. For example, all other torque requestors may be informed that they have lost arbitration.

A torque reserve module **224** generates a torque reserve **226** to compensate for changes in engine operating conditions that may decrease engine output torque and/or to compensate for one or more loads. For example, the air/fuel ratio of the engine and/or the mass air flow may be directly varied, such as by diagnostic intrusive equivalence ratio testing and/or new engine purging. Before beginning these processes, the torque reserve module **224** may create or increase the torque reserve **226** to quickly offset decreases in engine output torque that result from leaning the air/fuel mixture during these processes.

The torque reserve module **224** may also create or increase the torque reserve **226** in anticipation of a future load, such as power steering pump operation or engagement of an air conditioning (A/C) compressor clutch. The torque reserve module **224** may create or increase the torque reserve **226** for engagement of the NC compressor clutch when the driver first requests air conditioning. Then, when the A/C compressor clutch engages, the torque reserve module **224** may decrease the torque reserve **226** by an amount equal to the estimated load of the NC compressor clutch.

A target generating module **228** generates target values for the engine actuators based on the propulsion torque request **222**, the torque reserve **226**, and other parameters as discussed further below. The target generating module **228** generates the target values using model predictive control (MPC). The propulsion torque request **222** may be a brake torque. Brake torque may refer to torque at the crankshaft under the current operating conditions.

The target values include a target wastegate opening area **230**, a target throttle opening area **232**, a target EGR opening area **234**, a target intake cam phaser angle **236**, and a target exhaust cam phaser angle **238**. The target values also include a target spark timing **240**, a target number of cylinders to be activated **242**, and target fueling parameters **244**. The boost actuator module **164** controls the wastegate **162** to achieve the target wastegate opening area **230**. For example, a first conversion module **248** may convert the target wastegate opening area **230** into a target duty cycle **250** to be applied to the wastegate **162**, and the boost actuator module **164** may apply a signal to the wastegate **162** based on the target duty cycle **250**. In various implementations, the first conversion module **248** may convert the target wastegate opening area **230** into a target wastegate position (not shown), and convert the target wastegate position into the target duty cycle **250**.

The throttle actuator module **116** controls the throttle valve **112** to achieve the target throttle opening area **232**. For example, a second conversion module **252** may convert the target throttle opening area **232** into a target duty cycle **254** to be applied to the throttle valve **112**, and the throttle actuator

module **116** may apply a signal to the throttle valve **112** based on the target duty cycle **254**. In various implementations, the second conversion module **252** may convert the target throttle opening area **232** into a target throttle position (not shown), and convert the target throttle position into the target duty cycle **254**.

The EGR actuator module **172** controls the EGR valve **170** to achieve the target EGR opening area **234**. For example, a third conversion module **256** may convert the target EGR opening area **234** into a target duty cycle **258** to be applied to the EGR valve **170**, and the EGR actuator module **172** may apply a signal to the EGR valve **170** based on the target duty cycle **258**. In various implementations, the third conversion module **256** may convert the target EGR opening area **234** into a target EGR position (not shown), and convert the target EGR position into the target duty cycle **258**.

The phaser actuator module **158** controls the intake cam phaser **148** to achieve the target intake cam phaser angle **236**. The phaser actuator module **158** also controls the exhaust cam phaser **150** to achieve the target exhaust cam phaser angle **238**. In various implementations, a fourth conversion module (not shown) may be included and may convert the target intake and exhaust cam phaser angles **236** and **238** into target intake and exhaust duty cycles, respectively. The phaser actuator module **158** may apply the target intake and exhaust duty cycles to the intake and exhaust cam phasers **148** and **150**, respectively. In various implementations, the target generating module **228** may determine a target valve overlap factor and a target effective displacement, and the phaser actuator module **158** may control the intake and exhaust cam phasers **148** and **150** to achieve the target overlap factor and the target effective displacement.

The spark actuator module **126** provides spark based on the target spark timing **240**. The cylinder actuator module **120** selectively activates and deactivates the valves of cylinders based on the target number of cylinders **242**. Fueling and spark may also be disabled to cylinders that are deactivated. The target fueling parameters **244** may include, for example, a target number of fuel injections, a target mass of fuel for each injection, and target start timing for each injection. The fuel actuator module **124** controls fueling based on the target fueling parameters **244**.

FIG. 3 is a functional block diagram of an example implementation of the target generating module **228**. Referring now to FIGS. 2 and 3, as discussed above, the propulsion torque request **222** may be a brake torque. A torque conversion module **304** converts the propulsion torque request **222** from brake torque into base torque. The torque request resulting from conversion into base torque will be referred to as a base torque request **308**.

Base torques may refer to torque at the crankshaft made during operation of the engine **102** on a dynamometer while the engine **102** is warm and no torque loads are imposed on the engine **102** by accessories, such as an alternator and the A/C compressor. The torque conversion module **304** may convert the propulsion torque request **222** into the base torque request **308**, for example, using a mapping or a function that relates brake torques to base torques. In various implementations, the torque conversion module **304** may convert the propulsion torque request **222** into another suitable type of torque, such as an indicated torque. An indicated torque may refer to a torque at the crankshaft attributable to work produced via combustion within the cylinders.

An MPC (model predictive control) module **312** generates the target values **230-244** using MPC. The MPC module **312** may be a single module or may comprise multiple modules. For example, the MPC module **312** may include a sequence

determination module **316**. The sequence determination module **316** determines possible sequences of the target values **230-244** that could be used together during N future control loops. Each of the possible sequences identified by the sequence determination module **316** includes one sequence of N values for each of the target values **230-244**. In other words, each possible sequence includes a sequence of N values for the target wastegate opening area **230**, a sequence of N values for the target throttle opening area **232**, a sequence of N values for the target EGR opening area **234**, a sequence of N values for the target intake cam phaser angle **236**, and a sequence of N values for the target exhaust cam phaser angle **238**. Each possible sequence also includes a sequence of N values for the target spark timing **240**, the target number of cylinders **242**, and the target fueling parameters **244**. Each of the N values corresponds to one of the N future control loops. N is an integer greater than one.

A prediction module **323** determines predicted responses of the engine **102** to the possible sequences of the target values **230-244**, respectively, based on a mathematical model **324** of the engine **102**, exogenous inputs **328**, and feedback inputs **330**. More specifically, based on a possible sequence of the target values **266-270**, the exogenous inputs **328**, and the feedback inputs **330**, using the model **324**, the prediction module **323** generates a sequence of predicted torques of the engine **102** for the N control loops, a sequence of predicted MAPs for the N control loops, a sequence of predicted APCs for the N control loops, a sequence of predicted amounts of external dilution for the N control loops, a sequence of predicted amounts of internal dilution for the N control loops, a sequence of predicted combustion phasing values for the N control loops, a sequence of predicted combustion quality values for the N control loops, and a sequence of predicted effective displacement values for the N control loops.

The model **324** may include a function or a mapping calibrated based on characteristics of the engine **102**. The relationship between the responses of the engine **102**, the target values **230-244**, the exogenous inputs **328**, and the feedback inputs **330** may be nonlinear over the entire range of possible engine speeds and engine loads. However, the model **324** may include a plurality of linear models that each correspond to an engine speed and load range. The prediction module **323** may select one of the models based on the current engine speed and load, and use the selected model to predict the responses of the engine **102**. For example, a first model may be used in an engine speed range from 1000 revolutions per minute (RPM) to 2000 RPM and an engine load range from 100 Newton-meters (Nm) to 150 Nm. A second model may be used in an engine speed range from 1000 RPM to 2000 RPM and an engine load range from 150 Nm to 200 Nm. A third model may be used in an engine speed range from 2000 RPM to 3000 RPM and an engine load range from 100 Nm to 150 Nm.

Dilution may refer to an amount of exhaust from a prior combustion event trapped within a cylinder for a combustion event. External dilution may refer to exhaust provided for a combustion event via the EGR valve **170**. Internal dilution (also referred to as residual dilution) may refer to exhaust that remains in a cylinder and/or exhaust that is pushed back into the cylinder following the exhaust stroke of a combustion cycle. Effective displacement may refer to the volume of air drawn into cylinders of an engine as pistons in the cylinders travel from TDC to BDC, minus losses in air volume due to pistons pushing air back into an intake manifold through intake valves of the cylinders.

Combustion phasing may refer to a crankshaft position where a predetermined amount of fuel injected is combusted

within a cylinder relative to a predetermined crankshaft position for combustion of the predetermined amount of injected fuel. For example, combustion phasing may be expressed in terms of CA50 relative to a predetermined CA50. CA50 may refer to a crankshaft angle (CA) where 50 percent of a mass of injected fuel has been combusted within a cylinder. The predetermined CA50 may correspond to a CA50 where a maximum amount of work is produced from the fuel injected and may be approximately 8.5-approximately 10 degrees after TDC (top dead center) in various implementations. While combustion phasing will be discussed in terms of CA50 values, another suitable parameter indicative of combustion phasing may be used. Additionally, while combustion quality will be discussed as coefficient of variation (COV) of indicated mean effective pressure (IMEP) values, another suitable parameter indicative of combustion quality may be used.

The exogenous inputs 328 may include parameters that are not directly affected by the engine actuators. For example, the exogenous inputs 328 may include engine speed, turbocharger inlet air pressure, IAT, and/or one or more other parameters. The feedback inputs 330 may include, for example, an estimated torque output of the engine 102, an exhaust pressure downstream of the turbine 160-1 of the turbocharger, the IAT, an APC of the engine 102, an estimated internal dilution, an estimated external dilution, MAF, an air/fuel ratio of the engine 102, spark timing, and/or one or more other suitable parameters. The feedback inputs 330 may be measured using sensors (e.g., the IAT sensor 192) and/or estimated based on one or more other parameters.

A cost module 332 determines a cost value for each of the possible sequences of the target values 230-244 based on the predicted parameters determined for a possible sequence and reference values 340. The cost module 332 may determine the cost value for each of the possible sequences based on relationships between the predicted parameters and corresponding ones of the reference values 340. The relationships may be weighted, for example, to control the effect that each of the relationships has on the cost. In other words, the cost module 332 may apply weighting values 342 to each of the relationships.

The cost module 332 may also determine the cost value for each of the possible sequences based on a total amount of change in each of the possible target values over the N control loops. For example, if N is equal to two and the possible target throttle opening area is increased by 50 square millimeters ( $\text{mm}^2$ ) in the first control loop and decreased by 50  $\text{mm}^2$  in the second control loop, the total amount of change in the possible target throttle opening area is 100  $\text{mm}^2$ . Thus, the cost may increase as the total amount of change in a possible target value increases and vice versa. An example cost determination is discussed further below.

A selection module 344 selects one of the possible sequences of the target values 230-244 based on the respective costs of the possible sequences. For example, the selection module 344 may select the one of the possible sequences having the lowest cost while satisfying actuator constraints 348 and output constraints 352.

In various implementations, satisfaction of the actuator constraints 348 and the output constraints 352 may be considered in the cost determination. For example, the cost module 332 may determine the cost value for each of the possible sequences based on relationships between the predicted parameters and corresponding ones of the actuator constraints 348 and the output constraints 352. As discussed further below, based on how the cost values are determined, the selection module 344 will select the one of the possible sequences that best achieves the base air torque request 306

while minimizing APC, subject to the actuator constraints 348 and the output constraints 352.

The selection module 344 may set the target values 230-244 to the first ones of the N values of the selected possible sequence, respectively. In other words, the selection module 344 sets the target wastegate opening area 230 to the first one of the N values in the sequence of N values for the target wastegate opening area 230, set the target throttle opening area 232 to the first one of the N values in the sequence of N values for the target throttle opening area 232, set the target EGR opening area 234 to the first one of the N values in the sequence of N values for the target EGR opening area 234, set the target intake cam phaser angle 236 to the first one of the N values in the sequence of N values for the target intake cam phaser angle 236, and set the target exhaust cam phaser angle 238 to the first one of the N values in the sequence of N values for the target exhaust cam phaser angle 238. The selection module 344 also sets the target spark timing 240 to the first one of the N values in the sequence of N values for the target spark timing 240, the target number of cylinders 242 to the first one of the N values in the sequence of N values for the target number of cylinders 242, and the target fueling parameters 244 to the first one of the N values in the sequence of N values for the target fueling parameters 244.

During a next control loop, the MPC module 312 identifies possible sequences, generates the predicted parameters for the possible sequences, determines the cost of each of the possible sequences, selects one of the possible sequences, and sets of the target values 230-244 to the first set of the target values 230-244 in the selected possible sequence. This process continues for each control loop.

An actuator constraint module 360 (see FIG. 2) sets the actuator constraints 348 for each of the target values 230-244. In other words, the actuator constraint module 360 sets actuator constraints for the throttle valve 112, actuator constraints for the EGR valve 170, actuator constraints for the wastegate 162, actuator constraints for the intake cam phaser 148, and actuator constraints for the exhaust cam phaser 150. The actuator constraint module 360 also sets actuator constraints for the spark actuator module 126, actuator constraints for the cylinder actuator module 120, and actuator constraints for the fuel actuator module 124.

The actuator constraints 348 for each of the target values 230-244 may include a maximum value for an associated target value and a minimum value for that target value. The actuator constraint module 360 may generally set the actuator constraints 348 to predetermined operational ranges for the associated engine actuators. More specifically, the actuator constraint module 360 may generally set the actuator constraints 348 to predetermined operational ranges for the throttle valve 112, the EGR valve 170, the wastegate 162, the intake cam phaser 148, the exhaust cam phaser 150, the spark actuator module 126, the cylinder actuator module 120, and the fuel actuator module 124, respectively. Thus, the maximum value for a target value may be a maximum limit of a corresponding actuator and the minimum value for the target value may be a minimum limit of that actuator.

An output constraint module 364 (see FIG. 2) sets the output constraints 352 for the predicted torque output of the engine 102, the predicted MAP, the predicted APC, the predicted CA50, the predicted COV of IMEP, the predicted internal dilution, the predicted external dilution, and/or the predicted effective displacement. The output constraints 352 for each of the predicted parameters may include a maximum value for an associated predicted parameter and a minimum value for that predicted parameter. For example, the output constraints 352 may include a minimum torque, a maximum

13

torque, a minimum MAP, a maximum MAP, a minimum APC, a maximum APC, a minimum CA50, a maximum CA50, a minimum COV of IMEP, a maximum COV of IMEP, a minimum internal dilution, a maximum internal dilution, and a minimum external dilution, a maximum external dilution, a minimum effective displacement, and/or a maximum effective displacement.

The output constraint module 364 may generally set the output constraints 352 to predetermined ranges for the associated predicted parameters, respectively. However, the output constraint module 364 may vary one or more of the output constraints 352 under some circumstances. For example, the output constraint module 364 may retard the maximum CA50, such as when knock occurs within the engine 102. In another example, the output constraint module 364 may increase the maximum COV of IMEP under low load conditions, such as during engine idling where a higher COV of IMEP may be needed to achieve a given torque request.

A setpoint module 368 (see FIG. 2) generates the reference values 340 for the target values 230-244. The reference values 340 include a reference for each of the target values 230-244. In other words, the reference values 340 include a reference wastegate opening area, a reference throttle opening area, a reference EGR opening area, a reference intake cam phaser angle, and a reference exhaust cam phaser angle. The reference values 340 also include reference spark timing, a reference number of cylinders, and reference fueling parameters. The reference values 340 may also include a reference for each of the output constraints 352. In other words, the reference values 340 may include a reference manifold absolute pressure (MAP), a reference mass of air per cylinder (APC), a reference external dilution, a reference internal dilution, and a reference effective displacement.

The setpoint module 368 also generates the weighting values 342. The weighting values 342 may include a weighting value associated with relationships between: the predicted torque and the base torque request 308; the predicted APC and the minimum APC; the possible target values and the respective actuator constraints 348; the other predicted parameters and the respective output constraints 352; the possible target values and the respective reference values 340; and the total amounts of change in the possible target values. The setpoint module 368 may determine the reference values 340 and/or the weighting values 342 based on a desired rate of change in one or more operation conditions of the engine 102, as discussed in more detail below.

Instead of or in addition to generating sequences of possible target values and determining the cost of each of the sequences, the MPC module 312 may identify a sequence of possible target values having the lowest cost using convex optimization techniques. For example, the MPC module 312 may determine the target values 230-244 using a quadratic programming (QP) solver, such as a Dantzig QP solver. In another example, the MPC module 312 may generate a surface of cost values for the possible sequences of the target values 230-244 and, based on the slope of the cost surface, identify a sequence of possible target values having the lowest cost. The MPC module 312 may then test that sequence of possible target values to determine whether that sequence of possible target values satisfies the actuator constraints 348. If so, the MPC module 312 may set the target values 230-244 to the first ones of the N values of that selected possible sequence, respectively, as discussed above.

If the actuator constraints 348 are not satisfied, the MPC module 312 selects another sequence of possible target values with a next lowest cost and tests that sequence of possible target values for satisfaction of the actuator constraints 348.

14

The process of selecting a sequence and testing the sequence for satisfaction of the actuator constraints 348 may be referred to as an iteration. Multiple iterations may be performed during each control loop.

The MPC module 312 performs iterations until a sequence with the lowest cost that satisfies the actuator constraints 348 is identified. In this manner, the MPC module 312 selects the sequence of possible target values having the lowest cost while satisfying the actuator constraints 348 and the output constraints 352. If a sequence cannot be identified, the MPC module 312 may indicate that no solution is available.

The cost module 332 may determine the cost for the possible sequences of the target values 230-244 based on relationships between: the predicted torque and the base torque request 308; the predicted APC and the minimum APC; the possible target values and the respective actuator constraints 348; the other predicted parameters and the respective output constraints 352; and the possible target values and the respective reference values 340. As discussed above, the relationships may be weighted to control the effect that each of the relationships has on the cost.

For example, the cost module 332 may determine the cost for a possible sequence of the target values 230-244 based on the following equation:

$$\text{Cost} = \sum_{i=1}^N \rho \epsilon^2 + \|wT^*(TP_i - BTR_i)\|^2 + \|wA^*(APC_{P_i} - \text{MinAPC})\|^2,$$

subject to the actuator constraints 348 and the output constraints 352. Cost is the cost for the possible sequence of the target values 230-244,  $TP_i$  is the predicted torque of the engine 102 for an i-th one of the N control loops,  $BTR_i$  is the base torque request 308 for the i-th one of the N control loops, and  $wT$  is the weighting value associated with the relationship between the predicted torque and the base torque request.  $APC_{P_i}$  is the predicted APC for the i-th one of the N control loops,  $\text{MinAPC}$  is the minimum APC, and  $wA$  is the weighting value associated with the relationship between the predicted APC and the minimum APC.

The above equation can be expanded to:

$$\begin{aligned} \text{Cost} = & \sum_{i=1}^N \rho \epsilon^2 + \|wT^*(TP_i - BTR_i)\|^2 + \|wA^*(APC_{P_i} - \\ & \text{MinAPC})\|^2 + \|wTO^*(PTTO_i - TOR_{ref})\|^2 + \\ & \|w\Delta TO^*\Delta TO\|^2 + \|wWG^*(PTWGO_i - WGOR_{ref})\|^2 + \\ & \|w\Delta WG^*\Delta WG\|^2 + \|wEGR^*(PTEGR_i - EGR_{ref})\|^2 + \\ & \|w\Delta EGR^*\Delta EGR\|^2 + \|wICP^*(PTICP_i - ICP_{ref})\|^2 + \\ & \|w\Delta ICP^*\Delta ICP\|^2 + \|wECP^*(PTECP_i - ECP_{ref})\|^2 + \\ & \|w\Delta ECP^*\Delta ECP\|^2 + \|wS^*(PS_i - SR_{ref})\|^2 + \\ & \|w\Delta S^*\Delta S\|^2 + \|wN^*(PNI - NR_{ref})\|^2 + \|w\Delta N^*\Delta N\|^2 + \\ & \|wF^*(PFI - FR_{ref})\|^2 + \|w\Delta F^*\Delta F\|^2, \end{aligned}$$

subject to the actuator constraints 348 and the output constraints 352.  $PTTO_i$  is a possible target throttle opening for the i-th one of the N control loops,  $TOR_{ref}$  is the reference throttle opening for the i-th one of the N control loops, and  $wTO$  is a weighting value associated with the relationship between the possible target throttle openings and the reference throttle openings.  $\Delta TO$  is a total amount of change in the possible target throttle openings over the N control loops and  $w\Delta TO$  is a weighting value associated with the total amount of change in the possible throttle openings.

$PTWGO_i$  is a possible target wastegate opening for the i-th one of the N control loops,  $WGOR_{ref}$  is the reference wastegate opening for the i-th one of the N control loops, and  $wWG$  is a weighting value associated with the relationship between the possible target wastegate openings and the reference wastegate openings.  $\Delta WG$  is a total amount of change in the possible wastegate openings over the N control loops and  $w\Delta WG$  is a weighting value associated with the total amount of change in the possible wastegate openings.

PTEGRO<sub>i</sub> is a possible target EGR opening for the *i*-th one of the *N* control loops, EGRRef is the reference EGR opening for the *i*-th one of the *N* control loops, and wEGR is a weighting value associated with the relationship between the possible target EGR openings and the reference EGR openings. ΔEGR is a total amount of change in the possible target EGR openings over the *N* control loops and wΔEGR is a weighting value associated with the total amount of change in the possible EGR openings.

PTICP<sub>i</sub> is a possible target intake cam phaser angle for the *i*-th one of the *N* control loops, ICPRef is the reference intake cam phaser angle for the *i*-th one of the *N* control loops, and wICP is a weighting value associated with the relationship between the possible target intake cam phaser angle and the reference intake cam phaser angles. ΔICP is a total amount of change in the possible target intake cam phaser angles over the *N* control loops and wΔICP is a weighting value associated with the total amount of change in the possible target intake cam phaser angles.

PTECP<sub>i</sub> is a possible target exhaust cam phaser angle for the *i*-th one of the *N* control loops, ECPRef is the reference exhaust cam phaser angle for the *i*-th one of the *N* control loops, and wECP is a weighting value associated with the relationship between the possible target exhaust cam phaser angle and the reference exhaust cam phaser angles. ΔECP is a total amount of change in the possible target exhaust cam phaser angles over the *N* control loops and wECP is a weighting value associated with the total amount of change in the possible target exhaust cam phaser angles.

PS<sub>i</sub> is a possible target spark timing for the *i*-th one of the *N* control loops, SRef is the reference spark timing for the *i*-th one of the *N* control loops, and wS is a weighting value associated with the relationship between the possible target spark timings and the reference spark timings. ΔS is a total amount of change in the possible target spark timings over the *N* control loops and wΔS is a weighting value associated with the total amount of change in the possible target spark timings.

PN<sub>i</sub> is a possible number of cylinders for the *i*-th one of the *N* control loops, NRef is the reference number of cylinders for the *i*-th one of the *N* control loops, and wN is a weighting value associated with the relationship between the possible number of cylinders and the reference number of cylinders. ΔN is a total amount of change in the possible number of cylinders over the *N* control loops and wΔN is a weighting value associated with the total amount of change in the possible number of cylinders.

PF<sub>i</sub> is possible fueling for the *i*-th one of the *N* control loops, FRef is the reference fueling for the *i*-th one of the *N* control loops, and wF is a weighting value associated with the relationship between the possible fueling and the reference fueling. ΔF is a total amount of change in the possible fueling over the *N* control loops and wΔF is a weighting value associated with the total amount of change in the possible fueling.

$\rho$  is a weighting value associated with satisfaction of the output constraints 352.  $\epsilon$  is a variable that the cost module 332 may set based on whether the output constraints 352 will be satisfied. For example, the cost module 332 may increase  $\epsilon$  when a predicted parameter is greater than or less than the corresponding minimum or maximum value (e.g., by at least a predetermined amount). The cost module 332 may set  $\epsilon$  to zero when all of the output constraints 352 are satisfied.  $\rho$  may be greater than the weighting value wT, the weighting value wA, and the other weighting values (wTO, wΔTO, wWG, wΔWG, wEGR, wΔEGR, wICP, wΔICP, wECP, wΔECP, wS, wΔS, wN, wΔN, wF, wΔF) such that the cost determined for a possible sequence will be large if one or more of the output

constraints 352 are not satisfied. This may prevent selection of a possible sequence where one or more of the output constraints 352 are not satisfied.

The weighting value wT may be greater than the weighting value wA and the weighting values wTO, wΔTO, wWG, wΔWG, wEGR, wΔEGR, wICP, wΔICP, wECP, wΔECP, wS, wΔS, wN, wΔN, wF, and wΔF. In this manner, the relationship between the predicted engine torque and the base air torque request 308 have a larger effect on the cost and, therefore, the selection of one of the possible sequences as discussed further below. The cost increases as the difference between the predicted engine torque and the base air torque request 308 increases and vice versa.

The weighting value wA may be less than the weighting value wT and greater than the weighting values wTO, wΔTO, wWG, wΔWG, wEGR, wΔEGR, wICP, wΔICP, wECP, wΔECP, wS, wΔS, wN, wΔN, wF, and wΔF. In this manner, the relationship between the predicted APC and the predetermined minimum APC has a large effect on the cost, but less than the relationship between the predicted engine torque and the base air torque request 308. The cost increases as the difference between the predicted APC and the predetermined minimum APC increases and vice versa. The predetermined minimum APC may be zero so that the cost increases and the predicted APC increases and vice versa.

Determining the cost based on the difference between the predicted APC and the predetermined minimum APC therefore helps ensure that the APC will be minimized. Decreasing APC decreases fuel consumption as fueling is controlled based on the actual APC to achieve a target air/fuel mixture. As the selection module 344 may select the one of the possible sequences having the lowest cost, the selection module 344 may select the one of the possible sequences that best achieves the base air torque request 308 while minimizing the APC.

The weighting values wTO, wΔTO, wWG, wΔWG, wEGR, wΔEGR, wICP, wΔICP, wECP, wΔECP, wS, wΔS, wN, wΔN, wF, and wΔF may be less than all of the other weighting values. In this manner, during steady-state operation, the target values 266-270 may settle near or at the reference values 340, respectively. During transient operation, however, the MPC module 312 may adjust the target values 266-270 away from the reference values 340 in order to achieve the base air torque request 308, while minimizing the APC and satisfying the actuator constraints 348 and the output constraints 352.

As indicated above, the setpoint module 368 may determine the reference values 340 and/or the weighting values 342 based on a desired rate of change in one or more operating conditions of the engine 102. For example, the setpoint module 368 may determine the reference values 340 and/or the weighting values 342 based on a desired rate of change in the torque output of the engine 102. Thus, the setpoint module 368 may determine the reference values 340 and/or the weighting values 342 based on the rate of change in the propulsion torque request 222 and/or the base torque request 308.

Determining the cost for the possible sequences of the target values 230-244 based on one of the equations describe above may limit the rate at which an operating condition of the engine 102 can be changed. For example, determining the cost based on the differences between the possible target values and the reference values 340 may limit the change rate of an engine operating condition. In another example, determining the cost based on the total amounts of change in the possible target values may limit the change rate of an engine operating condition.

Thus, if a desired rate of change in an engine operating condition corresponds to transient operation, the setpoint module **368** may set one or more of the weighting values **342** to zero. In turn, the corresponding ones of the target values **230-244** may be adjusted in a manner that changes the engine operating condition at the desired rate. The setpoint module **368** may determine that the desired rate corresponds to transient operation when the desired rate is greater than a first rate. Conversely, the setpoint module **368** may determine that the desired rate corresponds to steady-state operation when the desired rate is less than or equal to the first rate. The first rate may be the rate at which the engine operating condition can be changed when determining the cost based on one of the equations described above. The setpoint module **368** may determine the first rate based on a rate of change in a predicted parameter (e.g., the predicted torque output). Alternatively, the first rate may be predetermined.

In one example, determining the cost based on the reference throttle opening area and the total amount of change in the possible target throttle openings may limit the rate at which the torque output of the engine **102** can be changed. Thus, if the driver adjusts the accelerator pedal position to wide open throttle, the weighting values associated with the reference throttle opening area and the total amount of change in the possible target throttle openings may be set to zero. In turn, the target throttle opening area **232** may be adjusted in a manner that changes the torque output of the engine **102** at the desired rate.

In another example, a desired manifold pressure may increase quickly when, for example, one or more cylinders of the engine **102** are deactivated. However, determining the cost based on the reference wastegate opening area and the total amount of change in the possible wastegate opening areas of a sequence may limit the rate at which the torque output of the engine **102** can be changed. Thus, if one or more cylinders of the engine **102** are deactivated, the weighting values associated with the reference wastegate opening area and the total amount of change in the wastegate opening area may be set to zero. In turn, the target wastegate opening area **230** may be adjusted in a manner that changes the manifold pressure at the desired rate.

When the desired rate of change in the engine operating condition corresponds to steady-state operation, the setpoint module **368** may adjust each of the reference values **340** in a stepped manner from a first value to a second value. However, if a desired rate of change in an engine operating condition corresponds to transient operation, the setpoint module **368** may adjust one or more of the reference values **340** in a manner that achieves the desired rate. For example, the setpoint module **368** may adjust the reference value in a manner that initially overshoots or undershoots the second value depending on whether the setpoint module **368** is increasing or decreasing the reference value. When overshooting or undershooting the second value, the setpoint module **368** may adjust the reference value from the first value to a corresponding one of the actuator constraints **348**, and then adjust the reference value to the second value.

In one example, when the base air torque request **308** increases from 50 Nm to 300 Nm, the target throttle opening area **232** may be adjusted in a stepped manner from 100 mm<sup>2</sup> to 500 mm<sup>2</sup> when using the equations described above. However, if the rate of change in the base air torque request **308** corresponds to transient operation, the reference throttle opening area may be adjusted in a manner that achieves the desired rate of change in the engine torque output. For example, the reference throttle opening area may initially be adjusted from 100 mm<sup>2</sup> to 1000 mm<sup>2</sup>, and then adjusted to

500 mm<sup>2</sup>. In turn, the target throttle opening area **232** may be adjusted in a manner that changes the torque output of the engine **102** at the desired rate.

In another example, as discussed above, a desired manifold pressure may increase quickly when one or more cylinders of the engine **102** are deactivated. However, adjusting the reference wastegate opening area in a stepped manner from a first value to a second value may limit the rate at which the manifold pressure can be changed. Thus, if one or more cylinders of the engine **102** are deactivated, the reference wastegate opening area may be adjusted from the first value to a wastegate opening area corresponding to fully closed, and then adjusted to the second value. In turn, the target wastegate opening area **230** may be adjusted in a manner that changes the manifold pressure at the desired rate.

Instead of or in addition to determining whether the desired rate corresponds to transient operation, the setpoint module **368** may determine the reference values **340** based on a predetermined relationship between the desired rate and the reference values **340**. Further, the setpoint module **368** may adjust one or more of the reference values **340** from a first value corresponding to steady-state operation to a second value corresponding to steady-state operation based on a reference trajectory. The reference trajectory may include a plurality of reference values. The reference trajectory may be nonlinear, predetermined, and/or determined based on a predetermined relationship between the desired rate and the reference trajectory. The reference trajectory may also be determined based on the second value corresponding to steady-state operation after the change in the engine operating condition is complete. The predetermined relationships used to determine the reference values and/or the reference trajectory may be embodied in a lookup table and/or an equation and may be linear or nonlinear.

Similarly, instead of or in addition to comparing the desired rate of change to the first rate, the setpoint module **368** may determine the weighting values **342** based on a predetermined relationship between the desired rate and the weighting values **342**. The predetermined relationship may be embodied in a lookup table and/or an equation and may be linear or nonlinear. Further, the weighting values **342** may be set to predetermined values other than zero.

The setpoint module **368** may dynamically adjust the reference values **340** and/or the weighting values **342** based on a desired rate of change in one or more operating conditions of the engine **102**. In other words, the setpoint module **368** may adjust the reference values **340** and/or the weighting values **342** in real-time while the engine **102** is operating (i.e., without shutting down the engine **102** or the ECM **114**). In addition, the reference values **340** and/or the weighting values **342** may or may not be different from one control loop to the next or from one control maneuver to the next.

Referring now to FIG. 4, an example method of controlling the throttle valve **112**, the intake cam phaser **148**, the exhaust cam phaser **150**, the wastegate **162** (and therefore the turbocharger), the EGR valve **170**, spark timing, fueling, and number of cylinders activated/deactivated using MPC (model predictive control) begins at **402**. At **404**, the propulsion torque arbitration module **214** determines the propulsion torque request **222**. At **406**, the torque conversion module **304** converts the propulsion torque request **222** into the base torque request **308** or into another suitable type of torque for use by the MPC module **312**.

At **408**, the setpoint module **368** determines the reference values **340** and the weighting values **342**. As discussed above, the setpoint module **368** may determine the reference values **340** and/or the weighting values **342** based on a desired rate of

change in an operating condition of the engine 102. For example, the setpoint module 368 may set one or more of the weighting values 342 to zero when the desired rate corresponds to transient operation. In another example, the setpoint module 368 may adjust one or more of the reference values 340 based on a reference trajectory when the desired rate corresponds to transient operation.

At 410, the sequence determination module 316 determines possible sequences of the target values 230-244. At 412, the prediction module 323 determines the predicted parameters for each of the possible sequences of target values. The prediction module 323 determines the predicted parameters for the possible sequences based on the model 324 of the engine 102, the exogenous inputs 328, and the feedback inputs 330. More specifically, based on a possible sequence of the target values 230-244, the exogenous inputs 328, and the feedback inputs 330, using the model 324, the prediction module 323 generates a sequence of N predicted torques of the engine 102 for the N control loops, a sequence of N predicted fuel efficiency values for the N control loops, and a sequence of N predicted NVH values for the N control loops.

At 414, the cost module 332 determines the costs for the possible sequences. For example, the cost module 332 may determine the cost for a possible sequence of the target values 230-244 based on the equation:

$$\text{Cost} = \sum_{i=1}^N \rho e^2 + \|wT^*(TP_i - BTR_i)\|^2 + \|wA^*(APCP_i - \text{MinAPC})\|^2,$$

or based on the equation

$$\begin{aligned} \text{Cost} = & \sum_{i=1}^N \rho e^2 + \|wT^*(TP_i - BTR_i)\|^2 + \|wA^*(APCP_i - \text{MinAPC})\|^2 + \\ & \|wTO^*(PTTO_i - TORRef)\|^2 + \|w\Delta PTTO * \Delta PTTO\|^2 + \\ & \|wWG^*(PTWGO_i - WGORRef)\|^2 + \|w\Delta PTWG * \Delta PTWG\|^2 + \\ & \|wEGR^*(PTEGR_i - EGRRef)\|^2 + \|w\Delta PTEGR * \Delta PTEGR\|^2 + \\ & \|wIP^*(PTICP_i - ICPRef)\|^2 + \|w\Delta PTICP * \Delta PTICP\|^2 + \\ & \|wEP^*(PTECP_i - ECPRef)\|^2 + \|w\Delta PTECP * \Delta PTECP\|^2 + \\ & \|wS^*(PS_i - SRef)\|^2 + \|w\Delta PS * \Delta PS\|^2 + \|wN^*(PNI - NRef)\|^2 + \\ & \|w\Delta PN * \Delta PN\|^2 + \|wF^*(PFI - FRef)\|^2 + \|w\Delta PF * \Delta PF\|^2, \end{aligned}$$

subject to the actuator constraints 348 and the output constraints 352, as discussed above.

At 416, the selection module 344 selects one of the possible sequences of the target values 230-244 based on the costs of the possible sequences. For example, the selection module 344 may select the one of the possible sequences having the lowest cost. The selection module 344 may therefore select the one of the possible sequences that best achieves the base torque request 308 and the desired exhaust enthalpy while minimizing the fuel consumption and the particle emissions. Instead of or in addition to determining possible sequences of the target values 230-244 at 410 and determining the cost of each of the sequences at 414, the MPC module 312 may identify a sequence of possible target values having the lowest cost using convex optimization techniques as discussed above.

At 418, the MPC module 312 determines whether the selected one of the possible sequences satisfies the actuator constraints 348. If the selected one of the possible sequences satisfies the actuator constraints 348, the method continues at 420. Otherwise, the method continues at 422, where the MPC module 312 selects the one of the possible sequences with the

next lowest cost. The method then returns to 418. In this manner, the sequence with the lowest cost that satisfies the actuator constraints 348 is used.

At 420, the first conversion module 248 converts the target wastegate opening area 230 into the target duty cycle 250 to be applied to the wastegate 162, the second conversion module 252 converts the target throttle opening area 232 into the target duty cycle 254 to be applied to the throttle valve 112. The third conversion module 256 also converts the target EGR opening area 234 into the target duty cycle 258 to be applied to the EGR valve 170 at 428. The fourth conversion module may also convert the target intake and exhaust cam phaser angles 236 and 238 into the target intake and exhaust duty cycles to be applied to the intake and exhaust cam phasers 148 and 150, respectively.

At 424, the throttle actuator module 116 controls the throttle valve 112 to achieve the target throttle opening area 232, and the phaser actuator module 158 controls the intake and exhaust cam phasers 148 and 150 to achieve the target intake and exhaust cam phaser angles 236 and 238, respectively. For example, the throttle actuator module 116 may apply a signal to the throttle valve 112 at the target duty cycle 254 to achieve the target throttle opening area 232.

Also at 424, the EGR actuator module 172 controls the EGR valve 170 to achieve the target EGR opening area 234, and the boost actuator module 164 controls the wastegate 162 to achieve the target wastegate opening area 230. For example, the EGR actuator module 172 may apply a signal to the EGR valve 170 at the target duty cycle 258 to achieve the target EGR opening area 234, and the boost actuator module 164 may apply a signal to the wastegate 162 at the target duty cycle 250 to achieve the target wastegate opening area 230. Also at 424, the spark actuator module 126 controls the spark timing based on the target spark timing 240, the cylinder actuator module 120 controls cylinder activation and deactivation based on the target number of cylinders 242, and the fuel actuator module 124 controls fueling based on the target fueling parameters 244. At 426, the method may end. Alternatively, FIG. 4 may illustrate one control loop, and control loops may be executed at a predetermined rate.

Referring now to FIG. 5, a desired manifold pressure 502, an actual manifold pressure 504, and a reference wastegate opening area 506 are plotted with respect to an x-axis that represents time 508. At 510, the desired manifold pressure 502 increases from a first pressure 512 to a second pressure 514 in a stepped manner. In response, the setpoint module 368 decreases the reference wastegate opening area 506 in a stepped manner from a first area 516 to a second area 518. The cost module 332 determines the costs of possible sequences of the target values 230-244 based on the equations described above, and the selection module 344 selects the one of the possible sequences having the lowest cost. Thus, the rate at which the actual manifold pressure 504 increases from the first pressure 512 to the second pressure 514 may be less than the rate at which the desired manifold pressure 502 increases from the first pressure 512 to the second pressure 514.

Referring now to FIG. 6, a desired manifold pressure 602, an actual manifold pressure 604, and a reference wastegate opening area 606 are plotted with respect to an x-axis that represents time 608. At 610, the desired manifold pressure 502 increases from a first pressure 612 to a second pressure 614 in a stepped manner. In response, the setpoint module 368 decreases the reference wastegate opening area 506 from a first area 616 to a second area 618 based on a reference trajectory 620. The reference trajectory 620 is determined based on the rate of change in the desired manifold pressure 602. Thus, the rate at which the actual manifold pressure 604

increases from the first pressure **612** to the second pressure **614** is nearly equal to the rate at which the desired manifold pressure **602** increases from the first pressure **612** to the second pressure **614**.

The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A or B or C), using a non-exclusive logical OR. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure.

In this application, including the definitions below, the term module may be replaced with the term circuit. The term module may refer to, be part of, or include an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor (shared, dedicated, or group) that executes code; memory (shared, dedicated, or group) that stores code executed by a processor; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

The term code, as used above, may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, and/or objects. The term shared processor encompasses a single processor that executes some or all code from multiple modules. The term group processor encompasses a processor that, in combination with additional processors, executes some or all code from one or more modules. The term shared memory encompasses a single memory that stores some or all code from multiple modules. The term group memory encompasses a memory that, in combination with additional memories, stores some or all code from one or more modules. The term memory may be a subset of the term computer-readable medium. The term computer-readable medium does not encompass transitory electrical and electromagnetic signals propagating through a medium, and may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory tangible computer readable medium include nonvolatile memory, volatile memory, magnetic storage, and optical storage.

The apparatuses and methods described in this application may be partially or fully implemented by one or more computer programs executed by one or more processors. The computer programs include processor-executable instructions that are stored on at least one non-transitory tangible computer readable medium. The computer programs may also include and/or rely on stored data.

What is claimed is:

1. A system comprising:

a model predictive control (MPC) module that:

- generates predicted parameters based on a model of a subsystem and a set of possible target values;
- generates a cost for the set of possible target values based on the predicted parameters and at least one of weighting values and references values;
- adjusts the at least one of the weighting values and the reference values based on a desired rate of change in an operating condition of the subsystem; and

selects the set of possible target values from multiple sets of possible target values based on the cost; and an actuator module that adjusts an actuator of the subsystem based on at least one of the target values.

2. The system of claim 1 wherein the MPC module adjusts at least one of the weighting values to zero when the desired change rate is greater than a first rate.

3. The system of claim 2 wherein:

the weighting values include a first weighting value associated with a difference between one of the possible target values and one of the reference values; and the MPC module adjusts the first weighting value to zero when the desired change rate is greater than the first rate.

4. The system of claim 2 wherein:

the weighting values include a first weighting value associated with a total amount of change in one of the possible target values over N control loops; the MPC module adjusts the first weighting value to zero when the desired change rate is greater than the first rate; and

N is an integer greater than one.

5. The system of claim 2 wherein the MPC module determines the first rate based on a rate of change in at least one of the predicted parameters.

6. The system of claim 1 wherein the MPC module:

determines a reference trajectory based on the desired change rate; and adjusts at least one of the references values based on the reference trajectory.

7. The system of claim 1 wherein the MPC module adjusts at least one of the references values to one of at least one of a maximum limit of the actuator and a minimum limit of the actuator when the desired change rate is greater than a first rate.

8. The system of claim 1 wherein the subsystem is an engine and the operating condition is a desired torque output of the engine.

9. The system of claim 8 wherein:

the weighting values include a first weighting value associated with a difference between a target throttle opening area and a reference throttle opening area; and the MPC module adjusts the first weighting value to zero when the desired change rate is greater than a first rate.

10. The system of claim 8 wherein:

the reference values include a reference throttle opening area; the MPC module determines a reference trajectory based on the desired change rate; and the MPC module adjusts the reference throttle opening area based on the reference trajectory.

11. A method comprising:

generating predicted parameters based on a model of a subsystem and a set of possible target values; generating a cost for the set of possible target values based on the predicted parameters and at least one of weighting values and references values; adjusting the at least one of the weighting values and the reference values based on a desired rate of change in an operating condition of the subsystem; selecting the set of possible target values from multiple sets of possible target values based on the cost; and adjusting an actuator of the subsystem based on at least one of the target values.

12. The method of claim 11 further comprising adjusting at least one of the weighting values to zero when the desired change rate is greater than a first rate.

## 23

13. The method of claim 12 wherein the weighting values include a first weighting value associated with a difference between one of the possible target values and one of the reference values, the method further comprising adjusting the first weighting value to zero when the desired change rate is greater than the first rate.

14. The method of claim 12 wherein the weighting values include a first weighting value associated with a total amount of change in one of the possible target values over N control loops and N is an integer greater than one, the method further comprising adjusting the first weighting value to zero when the desired change rate is greater than the first rate.

15. The method of claim 12 further comprising determining the first rate based on a rate of change in at least one of the predicted parameters.

16. The method of claim 11 further comprising:  
determining a reference trajectory based on the desired change rate; and  
adjusting at least one of the references values based on the reference trajectory.

17. The method of claim 11 further comprising adjusting at least one of the references values to one of at least one of a

## 24

maximum limit of the actuator and a minimum limit of the actuator when the desired change rate is greater than a first rate.

18. The method of claim 11 wherein the subsystem is an engine and the operating condition is a desired torque output of the engine.

19. The method of claim 18 wherein the weighting values include a first weighting value associated with a difference between a target throttle opening area and a reference throttle opening area, the method further comprising adjusting the first weighting value to zero when the desired change rate is greater than a first rate.

20. The method of claim 18 wherein the reference values include a reference throttle opening area, the method further comprising:

determining a reference trajectory based on the desired change rate; and  
adjusting the reference throttle opening area based on the reference trajectory.

\* \* \* \* \*