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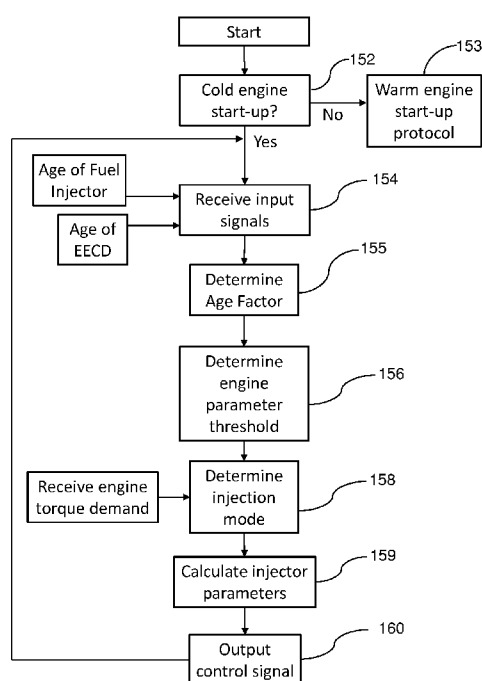


Figure 10

(57) Abstract: A controller for a fuel injector for an engine, the controller comprising: an input arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device; a processor configured to determine at least one operating parameter of the engine; and to determine a fuel injector operating mode based on the first and/or second input signal(s) and on the at least one operating parameter of the engine; and an output configured to output a control signal for controlling the fuel injector according to the determined fuel injector operating mode.

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Controller for a Fuel Injection System

TECHNICAL FIELD

5 The present disclosure relates to a controller for a fuel injection system for an engine of a vehicle. In particular, but not exclusively, the present invention relates to a controller of the fuel injection system for controlling the operation of a fuel injector of the engine. Aspects of the invention relate to a controller, a fuel injection system and a vehicle. Further aspects of the invention relate to a method of controlling a fuel injection system of an engine.

10 BACKGROUND

Fuel injector control systems are commonly used to control the operation of a fuel injector in order to regulate the flow of fuel into a corresponding engine cylinder of an engine. Such control systems may be arranged to adjust the control parameters of the fuel injector as the demands on the engine change.

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A fuel injector includes a needle valve which is actuated by a solenoid or other actuation means. Fuel is delivered by the fuel injector by sending a signal to energise the solenoid to elevate the needle of the valve away from its valve seat. The needle valve is maintained in an open position as long as the signal is provided to the solenoid. The signal duration (known as the injection pulse-width) dictates how long the needle valve is held away from the valve seat, which thereby influences the flow of fuel to the engine cylinder.

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Degradation of the injector over time, due to general wear or a build-up of fuel deposits, means that the fuel flow close to the minimum elevation of the needle is reduced in addition to a delayed opening of the needle. Hence the amount of fuel delivered to the engine cylinder is decreased for a given pulse-width. The flow of fuel from an injector is particularly restricted by the build-up of deposits when the injector is operated in a 'ballistic' (non-linear) flow condition, which is when the pulse-width is such that the needle valve does not reach its fully open position.

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Known fuel injector control strategies rely on sensors to measure the dynamic operating conditions of the injector and use closed-loop feedback systems to dynamically adjust the control of the injector pulse-width in order to compensate for any changes in the injector's performance.

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Closed-loop control systems can use sensors to directly measure the performance of the fuel injector. The sensors must be mounted within the engine, close to the fuel injector, so that they can monitor its real-time performance, typically by measuring the active cylinder pressure or the fuel injector solenoid actuation. However, protecting the sensors from the extreme temperatures and pressures in an engine presents many technical challenges which limit the efficacy of such dynamic monitoring systems. The technical hurdles associated with installing and operating such sensors can also lead to inaccurate measurements of the injector's operating conditions.

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Alternatively, such closed-loop control systems can be arranged to monitor feedback noise in the injector solenoid control signals. The signal noise can be analysed in order to estimate the performance of the fuel injector (i.e. the actual needle lift duration versus the target needle lift duration) however, it is difficult to monitor the signal noise which leads to significant errors in the determination of the injector's performance.

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The above-mentioned limitations in determining the operating performance of the fuel injector can result in the implementation of undesirable injector control strategies. It is also known to implement particular injector control strategies during vehicle drive-away conditions, i.e. when the vehicle is configured by a user to pull away from a stationary position. These drive-away control strategies are employed in an attempt to rapidly heat up an emission control apparatus located downstream from the engine in order so that they may inhibit the increased exhaust emissions that are typically produced during higher engine loads. However, such control strategies are only triggered when an engine torque demand exceeds a particular threshold range with no consideration for the operating efficiency of either the fuel injector or emission control device. The present invention has been devised in order to mitigate or overcome the above-mentioned problems relating to the undesirable implementation of fuel injector control strategies.

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SUMMARY OF THE INVENTION

According to an aspect of the present invention there is provided a controller for a fuel injector for an engine, the controller comprising: one or more input(s) arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device; a processor configured to determine at least one operating parameter of the engine; and to determine a fuel injector operating mode based on the first and/or second input signal(s) and on the at least one operating parameter of the engine; and an output configured to output a control signal for controlling the fuel injector according to the determined fuel injector operating mode.

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The controller is advantageously configured so that it can adjust the fuel injector operating mode based on the operating efficiency of the fuel injector and/or the exhaust emission control device. The controller, therefore, is able to switch control of fuel injector to a fuel injector operating mode which can compensate for the sub-optimal performance of the EEC and/or the fuel injector, for a given engine operating condition, in order to, for example, reduce vehicle emissions or increase torque power output of the engine.

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The controller may be configured to, (i) output a first control signal to control the fuel injector according to a first fuel injector operating mode when the at least one operating parameter is below a threshold value; and (ii) output a second control signal to control the fuel injector according to a second fuel injector operating mode when the at least one operating parameter is above the threshold value; wherein the processor is configured to determine the threshold value in dependence on the first and/or second input signal(s).

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The second operating mode may be configured such that it advantageously reduces the vehicle's emissions by rapidly heating up of the EECD, which thereby enables the EECD to collect more particulate matter from the engine exhaust gases. This is particularly advantageous for a vehicle which has been fitted with a new EECD which is only capable of operating with a sub-optimal level of efficiency. By contrast, the first operating mode may be configured such that the fuel injector injects more fuel into the engine to generate power which thereby increases the relative fuel consumption of the engine.

The processor may be configured to increase the threshold value as the operating efficiency of the exhaust emission control device increases. By determining a lower threshold value for a new EECD compared with an aged EECD, the value of the at least one operating parameter required to trigger the transition between the first and second fuel injector modes can be reduced for situations where the EECD is operating less efficiently.

The processor may be configured to increase the threshold value as the operating efficiency of the fuel injector decreases.

At least one of the first and second fuel injector operating modes may define a plurality of fuel injections for a single cycle of the engine. The first fuel injector operating mode may comprise an initial fuel injection followed by a final injection.

The controller may be configured to operate the fuel injector according to the first fuel injector operating mode during an idling condition of the engine and following a cold engine start-up event.

The second fuel injector operating mode may comprise an initial fuel injection followed by a final injection, the initial fuel injection comprising two or more sub-injections.

The controller may be configured to operate the fuel injector according to the second fuel injector operating mode during a drive away condition of the engine and following a cold engine start-up event.

The controller may be configured to operate the fuel injector according to at least one of the first and second fuel injector operating modes immediately following the engine start-up event.

The at least one operating parameter of the engine may include an indicator of an engine torque demand.

The processor may be configured to determine the threshold value such that it does not exceed a maximum threshold value.

The maximum threshold value may correspond to an engine torque demand of 15-25% of a maximum torque demand.

The maximum threshold value may correspond to an engine torque demand of 20% of a maximum torque demand.

The engine torque demand may be determined by at least one of an air flow into the engine, an engine speed and an engine throttle position.

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The at least one engine operating parameter may include an indicator of an engine temperature.

The controller may be configured to operate the fuel injector according to at least one of the first and second fuel injector operating modes when the engine temperature being between 5°C and 40°C.

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The first and/or second input signal may include an indicator of at least one of an age of the vehicle, a vehicle's mileage, a number of fuel injection events, an oxygen storage value and a number of engine start-up events.

The controller may be configured to operate the fuel injector according to at least one of the first and second fuel injector operating modes during a drive away condition of the engine immediately following engine start-up.

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The output may be configured to output a control signal comprising a current or voltage value which is applied to the fuel injector.

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According to a further aspect of the present invention there is provided a fuel injection system for an engine, the fuel injection system comprising a fuel injector and a controller according to any preceding claim, wherein the fuel injector is configured to control the flow of fuel into a cylinder of the engine in dependence on the control signal.

According to a yet further aspect of the present invention there is provided a vehicle comprising a controller or a fuel injection system according to any of the statements provided above.

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According to a still further aspect of the present invention there is provided a method for controlling a fuel injector for an engine, the method comprising: receiving a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission device; determining at least one operating parameter of the engine; determining an operating mode of the fuel injector based on the first and/or second input signal(s) and on the at least one operating parameter of the engine; and, outputting a control signal for controlling the fuel injector according to the determined fuel injector operating mode.

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The method may comprise: determining a threshold value of the at least one operating parameter in dependence on the first and/or second input signal(s); outputting a first control signal to control the fuel injector according to a first fuel injector operating mode when the at least one operating parameter is below a threshold value; and outputting a second control signal to control the fuel injector according to a second fuel injector operating mode when the at least one operating parameter is above the threshold value.

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The step of determining the threshold value may comprise increasing the threshold value as the operating efficiency of the exhaust emission control device increases.

5 The step of determining the threshold value may comprise increasing the threshold value as the operating efficiency of the fuel injector decreases.

10 According to an aspect of the present invention there is provided a controller for a fuel injector for an engine, the controller comprising: an input arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device; a processor configured to determine a value indicative of a desired mass of fuel to be injected into a cylinder of the engine by the fuel injector; and an output configured to output a control signal for controlling the operation of the fuel injector; wherein the processor is configured to determine at least one parameter of the control signal based on the first and/or second input signal(s) and the value indicative of the desired mass of fuel.

15 The controller advantageously compensates for changes in the operating efficiency of the injector by adjusting at least one control parameter, such as pulse-width or needle lift duration, of the control signal in dependence on the operating efficiency of either the fuel injector or the exhaust emission control device. This is a much simpler approach compared with conventional 'closed loop control' systems, which require complicated sensors in order to monitor the dynamic operating conditions of the engine. Advantageously, the controller of the present invention does not require any additional monitoring apparatus and yet it can be used to account for the effects of deposit build-up around the needle valve seat, particularly during ballistic flow conditions.

25 The effects of the build-up in deposit around the needle valve are made more prevalent by changes to gasoline fuel injection strategies in order to meet more stringent particulate emission standards. These fuel injection control strategies cause the engine to operate closer to a minimum fuel flow threshold (i.e. in the ballistic flow condition), below which there is an increased risk of engine misfire. The controller of the present operation is able to conveniently compensate for the increased risk of misfire associated with an ageing fuel injector, whilst minimising tailpipe emissions during early life of the injector, which enhances the efficient operation of the engine throughout the full engine life.

30 In embodiments, the control signal may be binary such that it is able to switch a solenoid of the injector between an energised and a non-energised state. The control signal may comprise a predetermined time period for which the solenoid may be energised. In this way, the controller may be configured such that the output of the control signal may cause the solenoid to become energised for said predetermined period of time.

35 Alternatively, the controller of the present invention is able to operate the fuel injector so that it compensates for a change in the operating efficiency of the exhaust emission control device. A typical emission control device is initially less efficient at capturing exhaust particles from the engine but improves over time due to ash loading. The controller of the present invention is able to adjust the mass of fuel flowing into the engine as efficiency of the

exhaust emission control device changes so that the risk of engine misfire can be mitigated while minimising the particulate emissions from the vehicle over time.

The input may be arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and a second input signal indicative of the operating efficiency of an exhaust emission control device.

The first input signal may be indicative of the age of the fuel injector and/or the second input signal may be indicative of the age of the exhaust emission device. The age of the fuel injector and/or exhaust emission device may refer to the length of time that the fuel injector or emission device have been installed in the vehicle. Accordingly, the age of the fuel injector and/or exhaust emission device may be reset if either component is replaced or removed to be serviced. The age may, alternatively, be determined in dependence on a length of time that the engine has been active.

The processor may be configured to increase the at least one parameter of the control signal as the age of the fuel injector increases. Advantageously, as the age of the fuel injector increases, deposits build up around its injection needle or seat causing a reduction in the injector's ability to inject fuel into the engine cylinder. By increasing the at least one parameter as the injector increases in age, the control system conveniently compensates for the reduced efficiency of the fuel injector thereby maintaining a performance of the engine. This is particularly important at low engine loads where there is an increased risk of a misfire.

In the situation where the fuel injector is new, the control signal will control the operation of the fuel injector such that the mass of fuel injected into the engine is above a minimum fuel mass value. The minimum value represents the absolute minimum amount of fuel required to robustly prevent misfire, or achieve a target combustion stability level, based on a given desired mass of fuel, when the injector is new.

The processor may be configured to decrease the at least one parameter of the control signal as the age of the exhaust emission control device increases.

In the situation where the exhaust emission control device is new, the control signal may control the operation of the fuel injector such that the mass of fuel injected into the engine is below a maximum fuel mass value, for a given desired mass of fuel. The maximum value represents the absolute maximum mass of fuel that can be injected in to the engine cylinder without breaching a pre-determined vehicle emissions limit.

The first and/or second input signal may include an indicator of at least one of an age of the vehicle, a vehicle's mileage and/or a number of engine start-up events. The age of the vehicle may be determined by measuring the time elapsed since the installation of the system within a vehicle. Alternatively, the age of the vehicle may be measured from the date of initial purchase of the vehicle or from any other suitable starting point indicative of age. For example, the starting point may be pre-determined by a user of the vehicle. The passing of time may be measured using a vehicle's internal clock or through any suitable time recordal means. The number of engine start-

up events may be determined by receiving an input signal indicative of the number of start-up signals from the ECU. The vehicle's mileage may be determined by receiving an input signal indicative of the mileage of the vehicle from a suitable mileage recordal means, such as a vehicle tachograph.

- 5 The processor may be configured to determine the value indicative of a desired mass of fuel in dependence on an operating parameter of the engine. The determination of the desired mass of fuel may be achieved by receiving and interpreting a relevant input signal which is indicative of change in an operating parameter of the engine.

10 The operating parameter of the engine may include an indicator of an engine torque demand and/or an engine speed. In alternative embodiments, the operating parameter may include an indicator of a vehicle speed reduction or braking demand. The indicator of an engine torque demand may be provided by the ECU. Alternatively, engine torque demand may be provided by an automated driving control module of the vehicle, such as a cruise control module of the vehicle. In embodiments, the engine torque demand may be received from a suitable human machine interface such as an accelerator pedal.

15 The at least one parameter of the control signal may comprise an injection pulse-width of the fuel injector. The at least one parameter of the control signal may comprises a time period over which the control signal is applied to the fuel injector.

- 20 The at least one parameter of the control signal may comprise a current or voltage value which may be applied to the fuel injector to actuate the injector such that injects fuel into the engine cylinder.

25 The engine of the vehicle may comprise a plurality of fuel injectors and the control signal may be applied to one or more of the fuel injectors, simultaneously or in a pre-defined sequence. Alternatively, the control signal may be applied to only a portion, or subset, of the fuel injectors. The control signal may only be applied to active fuel injectors in the case where certain fuel injectors are de-activated when operating in a fuel saving mode, for example.

The injection pulse-width may correspond to a final injection pulse of a multi-stage injection sequence.

- 30 The controller may be configured to control the fuel injector during a start-up mode of the engine. The advantageous operation of the controller according to the invention is particularly beneficial during start-up of the engine because there is a greater chance of miss-fire from the engine.

35 The exhaust emission control device may comprise a catalyst device and/or a filter device. The filter device may include a gasoline particulate filter.

According to a further aspect of the present invention there is provided a fuel injection system for an engine, the fuel injection system comprising a fuel injector and a controller according to any one of paragraphs above, wherein

the fuel injector is configured to control the flow of fuel into a cylinder of the engine in dependence on the control signal.

According to a further aspect of the present invention there is provided a vehicle comprising the controller according to any of paragraphs above.

According to a further aspect of the present invention there is provided a vehicle comprising a fuel injection system according to any of the paragraphs above.

According to a still further aspect of the present invention there is provided a method for controlling a fuel injector for an engine, the method comprising: receiving a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission device; determining a value indicative of a desired mass of fuel to be injected into a cylinder of the engine by the fuel injector; and, outputting a control signal for controlling the operation of the fuel injector; wherein the step of outputting the control signal comprises determining at least one parameter of the control signal in dependence on the first and/or second input signal(s) and the value indicative of the desired mass of fuel.

The first input signal may be indicative of the age of the fuel injector and/or the second input signal is indicative of the age of the exhaust emission device.

The step of outputting the control signal may comprise increasing the at least one parameter of the control signal as the age of the fuel injector increases.

The step of outputting the control signal may comprise decreasing the at least one parameter of the control signal as the age of the exhaust emission control device increases.

A further aspect of the invention relates to computer software that, when executed, is arranged to perform a method according to the method of the previous aspect.

A yet further aspect of the invention relates to a non-transitory computer readable storage medium storing instructions thereon that, when executed by one or more electronic processors, causes the one or more electronic processors to carry out the method of the previous aspect.

The parameters and instructions associated with the method steps of the invention are provided as electronic data stored on a non-volatile memory component of a computer or logic system embedded within a control unit of the engine control unit.

As used herein, the term "controller" will be understood to include both a single controller or control unit and a plurality of controllers or control units collectively operating to provide the required control functionality. A set of

instructions could be provided which, when executed, cause said controller(s) or control unit(s) to implement the control techniques described herein (including the method(s) described below). The set of instructions may be embedded in one or more electronic processors, or alternatively, the set of instructions could be provided as software to be executed by one or more electronic processor(s). For example, a first controller may be implemented in software run on one or more electronic processors, and one or more other controllers may also be implemented in software run on one or more electronic processors, optionally the same one or more processors as the first controller.

It will be appreciated, however, that other arrangements are also useful, and therefore, the present invention is not intended to be limited to any particular arrangement. In any event, the set of instructions described above may be embedded in a computer-readable storage medium (e.g. a non-transitory storage medium) that may comprise any mechanism for storing information in a form readable by a machine or electronic processors/computational device, including, without limitation: a magnetic storage medium (e.g., floppy diskette); optical storage medium (e.g., CD-ROM); magneto optical storage medium; read only memory (ROM); random access memory (RAM); erasable programmable memory (e.g., EPROM and EEPROM); flash memory; or electrical or other types of medium for storing such information/instructions.

It will be appreciated that the foregoing represents only some of the possibilities with respect to the particular subsystems of a vehicle that may be included, as well as the arrangement of those subsystems with the control unit. Accordingly, it will be further appreciated that embodiments of a vehicle including other or additional subsystems and subsystem arrangements remain within the spirit and scope of the present invention. Additional sub-systems may include, for example, systems relating to any engine control function or fuel injector function.

Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a vehicle comprising an engine and fuel injection system according to an embodiment of the invention;

Figure 2 is a schematic drawing of a controller according to an embodiment of the invention;

Figure 3 is a drawing of a fuel injector of the fuel injection system of Figure 1;

Figure 4 is an enlarged view of the portion of the fuel injector of Figure 3, as identified by the circled area A;

Figure 5 is a flow diagram of a method of controlling a fuel injector according to an embodiment of the invention;

Figure 6 is a flow diagram of a method of determining an age factor of a fuel injector according to an embodiment of the invention;

Figure 7 is a flow diagram of a method of determining a minimum injection time of a fuel injector according to an embodiment of the invention;

Figure 8 is a schematic graph showing fuel injector energising time vs. fuel flow of a series of fuel injectors with different levels of ageing;

Figure 9 is a schematic graph showing the change in fuel injector opening time vs. fuel flow of a series of fuel injectors with different levels of ageing;

Figure 10 is a flow diagram of a further method of determining an controlling a fuel injector according to an embodiment of the invention; and

Figure 11 is a flow diagram of a method of determining a minimum torque demand for controlling a fuel injector according to an embodiment of the invention.

DETAILED DESCRIPTION

Embodiments of the invention relate to apparatus for controlling the fuel injection of an internal combustion engine (ICE) of a vehicle. With reference to Figure 1, a controller 14 of a fuel injection system 15 is arranged to control the operation of a fuel injector (not shown) so as to reduce the exhaust emissions of the engine 12, whilst maintaining stable engine operation over the life of the fuel injector. Aspects of the invention relate to a fuel injection system 15 whose operation is applied to a vehicle 10 having an engine exhaust system 18 which is fitted with an exhaust emission control device 16 (EECD), as shown in Figure 1. Aspects of the invention further relate to a method of controlling the injection of fuel into an engine 12, as shown in Figure 5, the method being implemented by the controller 14 of the fuel injection system 15.

The engine 12 is a gasoline engine although it will be appreciated that the functionality of the fuel injection system 15 and the controller 14 could be applied to other engine types. The exhaust emission control device 16 is a gasoline particulate filter (GPF) which is arranged to reduce the tailpipe particulate emissions of the engine 12 by capturing particles, or particulates, from the exhaust gases that are emitted therefrom. It will be appreciated that the exhaust emission control device 16 may further comprise a catalyst device for removing other combustion products from the engine exhaust gas flow.

The controller 14 is shown in Figure 2 as a conventional microcomputer including a processor 40, an input 42, an output 44 and a memory 46 (e.g. non-transitory memory). It will be appreciated that the input and output 42, 44 may be arranged as wired or wireless ports of the microcomputer. Alternatively, the controller 14 may define a virtual module of an engine control unit (ECU) which is programmed to control the operation of the engine 12 including, for example, when and how long each fuel injection of the fuel injector(s) should last.

The controller 14 is able to receive input signals, via the input 42, from a variety of different data sources including, for example, a plurality of vehicle sensors. In particular, the input 44 is arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and a second input signal indicative of the operating efficiency of the exhaust emission control device 16. The controller 14 is also configured to output control signals, via the output 44, to one or more fuel injector(s) of the engine 12. In this way, the output 44 is configured to output a control signal for controlling the operation of the fuel injector.

The processor 40 of the controller 14 is configured to determine a value indicative of a desired mass of fuel that is to be injected into a cylinder of the engine 12 by the fuel injector. The desired mass of fuel is representative of the demand which is placed on the engine 12, as determined by a user applying pressure to an accelerator pedal, or by some other suitable control means (e.g. in response to a torque demand signal from a cruise control module of the ECU). For example, the processor 40 will determine that an increased torque demand from a user will require an increased engine speed which will require an increased mass of fuel to be injected into the engine 12. The processor 40 is also arranged to determine the parameters of the control signal based on the various input signal(s) it receives and also in dependence on the value indicative of the desired mass of fuel.

Before moving on to consider embodiments of the invention in detail, in order to put the invention into context a mode of operating a fuel injector 20, to which such embodiments are applicable, is described with reference to Figures 3 and 4, in which a fuel injector 20 is shown positioned to inject fuel directly into a cylinder (not shown) of the engine 12. This arrangement of a fuel injector 20 is known to those skilled in the art as direct fuel injection, however, it will be appreciated that the fuel injection system may also be applied to a port injector. The fuel injector 20 delivers liquid fuel in proportion to a fuel injector pulse-width of a control signal which it receives from the controller 14. The pulse-width may relate to the width of a characteristic pulse in the voltage of the control signal which corresponds to a period of time that the fuel injector is held open in order to allow fuel to enter the engine cylinder. The fuel is delivered to the fuel injector 20 by a fuel system (not shown) including a fuel tank, fuel pump, and fuel rail. Figure 4 shows an enlarged view (labelled as 'A' in Figure 3) of the base of the fuel injector 20 where

a head 30 of a valve needle 28 of the fuel injector is arranged to sit against a valve seat 32, when the fuel injector 20 is closed.

5 The fuel injector 20 has an actuator 26 which is coupled directly to the valve needle 28 to control the movement of the needle 28. Both piezoelectric and electromagnetic direct acting injectors are known. In an electromagnetic direct acting injector, the movement of a plunger 22 is controlled by applying a current through a solenoid of the actuator 26. The plunger 22 acts on a chamber 24 of fuel arranged at the upper end of a valve needle 28. As the plunger 22 is actuated and pulled upwards, the volume of the control chamber 24 increases causing fuel pressure within the control chamber 24 to reduce and hence reducing the force tending to act to hold the valve needle 28
10 against its valve seat 30. This results in fuel flowing out of the chamber through a series of jets 34 located at the bottom of the valve seat 32.

If the actuation force is removed by removing or reducing the current applied to the solenoid, the plunger 22 moves downwardly under a spring force, reducing the volume of the control chamber 24 and increasing fuel pressure in
15 the control chamber 24 so as to seat the head 30 of the valve needle 28 against the valve seat 32.

The fuel injection system 15 is configured for a gasoline engine 12 and uses of a multi-stage injection sequence in which fuel is directly injected into the combustion chamber in multiple (e.g. two or more) distinct bursts during the course of a single intake stroke of the piston. The parameters of each injection of the multi-stage sequence can be
20 adjusted depending on the operating conditions of the engine 12. For example, a cold engine start-up control strategy may be employed in which the final injection of the multi-stage injection sequence is used to generate high turbulence within the combustion chamber close to the spark plug and at around the spark timing, which causes a faster initial burn rate of the fuel and results in an improvement in the combustion stability in the engine cylinder. The cold engine start-up control strategy, or protocol, is used to control the fuel injector during cold start conditions,
25 which occur following a cold engine start-up event, i.e. where the engine is started from being at an ambient temperature having been inactive for a prolonged period.

The multi-stage injection sequence may comprise an 'initial injection' which is followed by a 'final injection'. The initial and final injections are separated from each other by a predetermined time period of approximately 5 ms.
30 The initial injection is longer than the final injection. The initial injection may comprise two sub-injections, or bursts, which are separated by a time period of approximately 2 ms.

For vehicles fitted with catalyst devices, or catalytic converters, there is a further need to use multi-stage injection sequences in order quickly heat up the catalyst devices to a temperature at which they achieve optimal conversion
35 of target gases from the engine exhaust flow. Heating up the catalyst device to its optimal operating temperature is achieved by injecting a small mass of fuel in a very late final injection stage, however, this results in an increased concentration of particulate matter in the exhaust gases.

Part of the problem is that the final injection of the multi-stage sequence tends to occur when the engine piston is close to top dead centre (TDC), which leaves little time for the fuel to properly mix with the air in the combustion chamber. It also increases the risk of piston wetting which leads to an increase in the concentration of particulate matter in the exhaust gases, due to late evaporation from the surface when the flame front hits the surface causing an excessively rich combustion locally within the chamber.

More stringent vehicle emissions regulations require a reduction in engine emissions during every operating mode of the engine 12. Consequently, the fuel mass of the final injection must be precisely controlled in order to give the correct balance between particulate emissions and combustion stability (also referred to herein as misfire robustness). However, the control of fuel flow is often hampered by the build-up of deposits of particulate matter at the injector nozzle. The effects of deposit build-up are particularly relevant when the engine 12 is being run in a low fuel injection mode (i.e. less than 0.5mg for any individual injection), for example, during engine tick-over where the torque demand is low and so the priority of the ECU is to reduce the level of hydrocarbon emissions from the engine 12. Injecting such a small fuel mass into the combustion chamber is achieved by an incomplete elevation of the injector valve needle 30, which can only provide limited control of the flow of fuel through the injector. The low fuel flow causes ballistic flow conditions in the engine 12, which is characterised as resulting in an increased risk of instability and misfire. The use of multiple injections with the aim of improving the engine combustion makes it difficult to correct the fuel flow for each individual injection using conventional feedback and fuelling adaptation or correction methods.

The amount of deposit build-up on the needle 30 and needle seat 32 has been shown to gradually increase over time, or more precisely with increasing use of the engine 12. However, the rate of deposit build-up changes considerably depending on the properties of the fuel and also the level of detergent that is present in the fuel. The rate of deposit build-up also varies greatly with changing engine operating conditions (e.g. engine temperature and fuel pressure). Consequently, the effects of deposit build-up can result in highly variable fuel injector performance, which is difficult to manage using conventional closed-loop feedback systems, which are primarily configured to dynamically adjust the control of the injector pulse-width based on the measured parameters of each injection. Closed-loop feedback systems are particularly ineffective at compensating for the effects of deposit build-up during ballistic flow conditions due to the increased variability between the pulse-width, as defined by the ECU, and the resulting fluid flow that is achieved by the injector.

The fuel injection system according to an aspect of the present invention is configured to compensate for the variability in fuel injector performance by controlling the actuation of the fuel injector (i.e. by adjusting the pulse-width or needle lift duration), not by closed loop control, but according to a predetermined compensation value which is indicative of the operating efficiency of the fuel injector 20 and/or the exhaust emission control device 16.

The compensation value is used by the controller 14 as a correction factor by which the controller 14 is able to adjust the actuation of the fuel injector 20 based on a predetermined relationship between the flow of fuel from the injector and the injector solenoid energising pulse-width. This approach is much simpler than a conventional closed-

loop control system since it does not require any sensors for monitoring the dynamic conditions of the fuel injector itself. Yet, despite the simplicity of this approach, it can still be used to account for the effects of deposit build-up around the needle valve seat 32, particularly when operating the engine 12 during ballistic flow conditions.

5 Referring again to Figure 2, the controller 14 begins its operation by first determining that the engine 12 is operating in an engine start-up mode corresponding to an idling condition of the engine 12. This is achieved by determining the engine speed from the ECU. Upon confirming that the engine 12 is working under idling conditions it proceeds with its operation to control the fuel injector 20. The controller 14 is further configured to determine a parameter of the control signal based on a first input signal and a value indicative of the desired mass of fuel. The first input
10 signal is indicative of the operating efficiency of the fuel injector 20, whereas the value indicative of a desired mass of fuel is an indicator of an engine torque demand which is received from the ECU as a further input signal. The torque demand indicator represents a response to the user applying pressure to the accelerator pedal. The control parameter is a pulse-width of the injector comprising a current pulse-width value, which is applied to the fuel injector solenoid thereby causing the injector valve to open for a required time period. This injection pulse-width
15 corresponds to a final injection pulse of a multi-stage injection sequence.

In embodiments, the controller 14 is arranged to control the fuel injector 20 in dependence on the engine 12 being operated in a cold-start condition, whereby the engine has been left idle for a predetermined period. The controller 14 is arranged to evaluate the operating parameters of the engine 12 including, for example, the engine
20 temperature and/or the time that has elapsed since the last engine switch-off event. In this way the controller 14 may determine whether the engine is being operated under cold-start conditions.

The operating efficiency of the injector corresponds to its age as is determined by an engine start-up value, which is received by the controller 14 from the ECU. The engine start-up value corresponds to the number of times the
25 engine 12 has been started over a period of time and is therefore indicative of both the number of journeys and also the length of each journey for the given time period. Such information provides an indication as to the condition of the fuel injector 20. For example, a small number of short journeys, over a given time period is likely to be more detrimental to the fuel injector 20 than a relatively large number of long journeys because the engine 12 is forced to operate for a significant proportion of the time at a sub-optimal temperature.

30 Upon determining the required torque demand, the processor 40 is configured to evaluate the age of the fuel injector 20 and increase the current pulse-width value component of the control signal if the age of the fuel injector 20 has increased, thereby maintaining the flow of fluid into the engine cylinder for the given torque demand.

35 In an alternative embodiment the controller 14 is configured to determine the current pulse-width based on the second input signal, which is indicative of the age of the gasoline particulate filter (GPF), which forms part of the EECD 16. The current pulse-width is also determined in dependence on the engine start-up value. The efficiency of the GPF is significantly lower when new but its efficiency improves over time due to 'ash loading', which is caused by the accumulation of ash in the GPF. The ash consists of various metallic compounds originating from

lubricant additives, trace elements in the fuel, and engine wear and corrosion products. Similarly to the fuel injector 20, the age of the GPF is derived from the engine start-up value which provides information relating to the engine operation from which the level of ash build-up can be determined.

- 5 The processor 40, upon determining the torque demand from the ECU, is configured to evaluate the age of the GPF and increase the current pulse-width value component of the control signal as the age of the GPF increase, thereby maintaining the flow of fluid into the engine cylinder for the given torque demand.

- 10 In a further embodiment, the controller 14 is configured to control the fuel injector 20 based on both the first and second input signals. Accordingly, the controller 14 is configured to receive both input signals and then calculate the current pulse-width for a given torque demand based on the relative ages of the fuel injector 20 and the EECD 16. According to an embodiment of the invention, the controller 14 may be configured to bias the control signal towards preventing engine misfire of the engine at the expense of increased tailpipe emissions, provided that the tailpipe emissions are maintained below a predetermined threshold value. This threshold emission value may
15 correspond to a legal limit. Accordingly, if the tailpipe emissions were to exceed the threshold emission value the controller 14 would be configured to bias the control signal towards reducing the tailpipe emissions at the expense of misfire robustness.

- It would be understood by the skilled person that the terms 'age' or 'ageing', used with respect to the fuel injector
20 20, may refer to the degradation or fatigue of the fuel injector 20, which can occur over time due to the general wear (or polishing) caused by multiple combustion events. The term age, as used herein, may also refer to the build-up of fuel deposits at the injector nozzle. The ageing of the fuel injector 20 causes a reduction in the operating efficiency of the fuel injector 20 over time, which requires a positive adjustment to the injector pulse-width, as determined by the control signal of the controller 14. The positive adjustment to the injector pulse-width enables
25 the injector to maintain a steady mass of fuel flowing into the combustion chamber for a given torque demand, which thereby compensates for the reduction in the operating efficiency of the injector.

- By contrast, the efficiency of the EECD 16 is observed to increase with time, which means a greater mass of fuel can be injected into the engine cylinder for a given torque demand without emitting more particulate matter into the
30 atmosphere. The increasing efficiency of the EECD 16 means that the controller 14 is able to increase the injector pulse-width, as determined by the control signal, such that the risk of engine misfire can be reduced.

- The age of the fuel injector 20 and/or the EECD 16 may be calculated using a number of different engine parameters including, for example, the total number of engine cycles, the distance (or mileage) travelled by the
35 vehicle and the number of engine start-up events. Alternatively, the age of the fuel injector 20 is calculated based on a predicted deposit build-up value which is determined from empirical results which have been gathered from the testing of an equivalently configured test engine rig. In embodiments, the age of the fuel injector 20 is derived from measured parameters of the engine 12 (or fuel injector 20) such as, for example, the number of fuel injection events, the oil temperature and/or fuel pressure in the engine 12. In embodiments, an exhaust emission control

device includes a catalyst element, whose age may be calculated in dependence on the oxygen storage capacity value of the catalyst, which can be modelled using empirically derived data taken from a suitably configured test engine rig.

- 5 Empirical data is provided to construct a digital map of relevant parameters relating to the rate of deposit build-up and removal corresponding to a number of common engine operating conditions. The digital map is based on the predetermined knowledge of the temperatures at which deposit build-up is more likely to occur and temperatures at which deposit build-up is more likely to be cleaned off by detergents in the fuel. In alternative embodiments, an ethanol sensor in the exhaust system is used to determine the chemical content of the exhaust gases from which
10 the performance (or fatigue state) of the fuel injector 20 can be determined.

In an example of the operation of an aspect of the invention, a series of method steps are described with reference to the flow chart shown in Figure 5.

- 15 The method starts with step 52 in which the controller 14 determines whether the engine 12 is operating in a cold engine start-up condition. If the answer is no, then the controller 14 continues to control the fuel injector 20 according to a warm engine start-up protocol 53 without consideration of the first or second input signals. If the answer is yes then the method proceeds to step 54 in which the first and second input signals are received by the controller 14.

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The controller 14 is able to determine whether the engine is cold through the inspection of various engine operating parameters, including engine temperature, engine speed, engine torque demand and throttle position. If the controller identifies that the engine is operating between 5°C and 40°C, it determines that the engine is operating under cold start conditions. Similarly, if the controller identifies that the engine torque demand is below a threshold
25 value of 20% then it determines that the engine is operating in a start-up, or idling, condition.

- Turning now to step 55, the processor 40 calculates an age factor value, corresponding to the EECD 16 and/or fuel injector 20, from the received input signals. At step 56 the processor 40 determines a minimum injection timing value for the fuel injector 20, i.e. the minimum period of time that the fuel injector 20 can remain open in order to
30 ensure efficient operation of the engine. As will be described in more detail below, the minimum injection timing value is related to the operating efficiency of the EECD 16 and/or the fuel injector 20 as defined by the age factor value as calculated in step 55. At step 58, the processor 40 receives an input signal from the ECU. The input signal is indicative of an engine operating parameter such as an engine torque demand, from which the controller is able to determine a corresponding desired mass of fuel to be injected into the engine cylinder during the final injection
35 of the engine cycle. At step 58, the processor 40 calculates the current pulse-width component of the control signal which is then output to the solenoid of the fuel injector 20 at step 60. The method then repeats until the engine 12 is turned off.

The method of calculating the age factor value, as referred to in step 55, will now be explained in more detail with reference to Figure 6. A first step of the method comprises analysing the first and/or second input signal(s) that have been received in the preceding method step. Each of the first and/or second input signal(s) comprise data corresponding to a measured age parameter of either the fuel injector 20 and/or the EECD 16. The age parameters include a number of fuel injection events (A), the total ash accumulated in the EECD (B), a total distance travelled by the vehicle (C) and an oxygen storage capacity of the EECD (D).

Upon receiving the first and/or second input signal(s), the processor 40 first compares the received age parameter values A, B, C and D with a corresponding lookup table which is stored on an internal memory of the controller 14.

The lookup tables each comprise a list of stored age parameter values which are compared against corresponding age factor values ranging from 0 (for a new fuel injector 20 and/or EECD 16) to 1 (for an aged fuel injector 20 and/or EECD 16). If any of the received age parameter values A, B, C and D do not precisely match a stored value from the lookup table, the processor 40 applies suitable linear interpolation techniques in order to estimate an appropriate age factor value. At step 57, the processor 40 identifies a received age parameter value A, B, C and D with the highest relative value (i.e. the value which would render the largest age factor value). The largest age factor value is then read from the relevant lookup table and implemented as the age factor value 59 in the subsequent processing steps of the controller 14. The age factor calculation is repeated periodically over time or whenever an updated first and/or second input signal is received by the controller 14.

Over the lifetime of the vehicle it may be necessary to replace a vehicle component from which at least one of the age parameter values A, B, C and D is derived, thereby effectively causing an age parameter value to be reset. The controller 14 reduces the risk of the age factor being adversely affected by the resetting of any single parameter value by determining the outputted age factor value based on a plurality of different data input sources.

It will be appreciated by the skilled person that the lookup table may be populated over time using data that is gathered during the normal operation of the vehicle. Alternatively, the lookup table can be populated using data generated from a vehicle test rig or from a model simulation of the vehicle, such that the lookup table may be pre-populated prior to the vehicle being delivered to the user.

The method of determining the minimum injection timing value 66, as referred to in step 56 of Figure 5, will now be described in more detail with reference to Figure 7. According to this calculation, the controller 14 is arranged to generate a minimum injection timing value 66 in dependence on the age factor value 59 as calculated in the preceding method step. The resulting minimum injection timing value 66 will be used in step 58 to ensure that no miss-fire events can occur in the engine cylinder during subsequent engine cycles.

To calculate the minimum injection timing value 66, the controller 14 is pre-installed with an aged injection timing value 62 and a green injection timing value 64. The aged and green injection timing values 62, 64 each define a minimum time period over which the fuel injector valve should be opened in order to prevent a misfire event. The green injection timing value 64 corresponds to the minimum injector valve opening time period for a new fuel

injector, whereas the aged injection timing value 62 corresponds to the minimum injector opening time period for an aged fuel injector. An 'aged' fuel injector is defined as one in which the operating efficiency of the fuel injector 20 has significantly reduced to a minimum level over time. A 'green' fuel injector is substantially new, or unused, such that it may be capable of operating at its maximum efficiency.

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In contrast to the fuel injector 20, the 'aged' EECD 16 is capable of operating close to its maximum efficiency whereas a 'green' EECD 16 refers to an emissions apparatus which has not yet been 'de-greened' through the build-up of exhaust particulates and which as a result can only operate at a reduced efficiency level. Thus, the green injection timing value 64 relates to the preferred minimum injector opening time period for a new EECD and the aged injection timing value 62 corresponds to the preferred minimum injector valve opening time period for a de-greened EECD. In the above described embodiment, the green timing value 64 relates to a minimum fuel injector pulse width of approximately 0.26 ms whereas the aged injection timing value 62 corresponds to a minimum pulse width of approximately 0.28 ms.

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A first step in determining the minimum injection timing value 66 comprises calculating the difference between the aged injection timing value 62 and the green injection timing value 64. The resulting differential value is multiplied, in a second step, by the age factor value 59 and then added to the green injection timing value 64 in order to produce the outputted minimum injection timing value 66. In this way, the method of step 56 is arranged to gradually update the minimum injection time value 66 over time as the age factor 59 transitions between 0 and 1.

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Updating the outputted minimum injection timing value 66 results leads to the controller 14, in step 58, calculating a longer pulse-width for a given torque demand. The longer pulse width is then output, in step 60, as a control signal. As long as the control signal is provided to the solenoid, the fuel injector valve will be urged towards its open position. Therefore, the duration of the provision of the control signal to the fuel injector 20 (i.e. the pulse width of the control signal) dictates the amount of fuel that is delivered to the combustion chamber per injection cycle. Therefore, the control signal comprising the longer pulse width value is arranged to control the fuel injector 20 to perform a longer final injection, which thereby reduces the risk of engine misfire as the operating efficiency of the fuel injector 20 decreases with age.

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The processing steps of Figures 5, 6 and 7 are performed by the controller 14 of Figure 2 and are stored, as a set of executable instructions, on its non-transitory memory 46. Furthermore, the processing steps 54, 55 and 56 can be performed as a background process of the controller 14 such that they do not require an input from either the ECU or the vehicle user.

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As explained above, the advantageous method as shown in Figures 5, 6 and 7 results in improvements in the operating parameters of a fuel injector 20 as will now be explained with reference to Figures 6 and 7. As was explained above, the present invention is particularly applicable to a fuel injector 20 operating in the Ballistic fuel flow condition. Therefore, the performance of fuel injectors of different ages, operating within the ballistic region will be described below, with reference to Figures 6 and 7.

A fuel injector 20 begins to operate in a ballistic range when injection pulse-widths are less than about 0.5 ms. At higher or longer pulse-widths, i.e. greater than 0.5 ms, the injector operates outside the ballistic range.

- 5 Figure 6 shows the relationship between the fuel injector energising time (ms) and the resulting flow of fuel into the engine cylinder (mg), whereas Figure 7 describes the corresponding relationship between the fuel flow (mg) and the actual fuel injector opening time (ms). The arrow labelled A shows the change in the fuel flow as the age of the fuel injector increases. The solid line represents a 'new' fuel injector and the dashed-dot line represents a fuel injector that has aged a third of its design life having operated under average fuel conditions. The design life of such an injector is approximately 190,000 miles. It will be appreciated that the operating efficiency of fuel injectors, such as those described herein, would likely deteriorate at varying rates depending on operational fuelling conditions. For example, the performance of a fuel injector operating with low quality fuel will deteriorate more rapidly over time due to the increased levels of contaminants and impurities that are contained within fuel.
- 10
- 15 Below a fluid flow value of around 1.5 mg, the injector is at increased risk of misfiring. This threshold fluid flow value represents a minimum fuel mass that can be injected by the injector without there being an increased risk of engine misfire. The lower threshold region is indicated by the dashed box B shown in Figures 6 and 7. Above a fluid flow value of around 3.3 mg, the injector is likely to produce a greater number of particulates such that the engine 12 would exceed the E6d particulate regulations. Hence, the upper threshold fuel flow value represents the maximum fuel mass value that can be injected into the engine 12 during the final injection pulse. The maximum fuel mass value is identified by the dashed box E shown in Figures 6 and 7.
- 20

In order to achieve the lowest possible particulate emissions in a vehicle comprising a new engine 12, the injection pulse-width must be set very low, typically 0.26 ms to 0.27 ms, which corresponds to a valve opening duration of typically 0.1 ms. However, if this pulse-width is used for the whole vehicle life then there would be a significant risk of misfiring (due to increasing instability) as the fuel injectors age if the valve opening duration were maintained at this level. Consequently, a value of 0.28 ms pulse-width (which corresponds to a 0.16 ms valve opening duration) is required later in the life of the fuel injector in order to avoid a significant increase in misfire events.

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- 30 According to an embodiment of the invention, the controller 14 is configured to make a step-wise increase in the pulse-width of the final injection pulse of the fuel injection, from 0.26ms to 0.28ms, in dependence on the age of the fuel injector 20 exceeding a threshold age value. Alternatively, the controller 14 may be arranged to gradually ramp up the pulse-width over a predetermined range of the parameter value. For example, the pulse-width increase may start at approximately 3,000 miles, ramping up to 0.28 ms at approximately 20,000 miles at which point the pulse-width would cease to increase any further.
- 35

In an alternative embodiment, the controller 14 is arranged to only affect the step-change increase in pulse-width in dependence on the age of the exhaust emissions device exceeding a threshold value. Alternatively, the pulse-

width may only be increased in dependence on both the fuel injector 20 and the exhaust emissions device exceeding a predetermined age.

Advantageously, the strategy for increasing the injector pulse-width over the life of the vehicle can be simplified to a step-change increase in the mass of fuel being injected into the engine cylinder. This can be readily achieved because the controller 14 is able to harness the improvement in the efficiency of the EECD 16 in order to offset the reduction in the performance of the fuel injector 20.

In alternative embodiments, the increase in pulse-width is altered according to a ramped strategy in order to further minimise the particulate emissions throughout the life of the vehicle, whilst also reducing the risk of misfires caused due to insufficient fuel flowing into the engine cylinder. It is particularly advantageous to avoid cylinder misfires because it leads to high carbon emissions and it also increases the risk of causing damage to the EECD 16.

A further embodiment of the invention will now be described in which the controller 14 is arranged to adjust the operating mode of a fuel injector 20 in dependence on the operating efficiency of the fuel injector 20 and/or the operating efficiency of the exhaust emission control device 16. With reference to Figures 1 to 3, the controller 14 includes a processor 40, an input 42, an output 44 and a memory 46 (e.g. non-transitory memory). The processor 40 is configured to determine at least one operating parameter of the engine based on a input signal indicative of a user's torque demand. The controller 14 is arranged to receive a first input signal indicative of the operating efficiency of a fuel injector 20 and/or a second input signal indicative of the operating efficiency of the exhaust emission control device (EECD). The controller 14 is further arranged to determine the parameters of a control signal based on the various input signal(s) it receives and also in dependence on the determined fuel injector operating mode. The controller 14 is also arranged output the control signal to the fuel injector 20.

According to the presently described embodiment of the invention, the controller 14 is configured to operate the fuel injector 20 according to a multi-stage injection sequence in which fuel is directly injected into the combustion chamber in multiple (e.g. two or more) distinct bursts during the course of a single intake stroke of the engine's piston.

The multi-stage injections are controlled according to a fuel injector control strategy, or operating mode, of the fuel injector 20. The operating mode defines the control parameters that determine how the fuel injector 20 is operated in order to achieve a desired performance from the engine. The operating mode comprises control parameters which correspond to the number of injections and sub-injections of the fuel injector 20 for a given engine cycle. The parameters also comprise information relating to the timing, duration and separation of the injections and sub-injections of the injector.

The fuel injector operating mode is determined in dependence on an operating temperature of the engine. The thermal efficiency of the engine is significantly reduced during cold-start conditions owing to the sub-optimal

lubricant properties at lower temperatures. It is desirable, therefore, to increase the operating temperatures of the engine and the EECD 16 during cold start conditions in order to reduce the emissions from the engine.

The controller 14 is arranged to operate the fuel injector 20 in such a way so as to minimise the time it takes for the EECD 16 to reach its operating temperature range by operating the fuel injector 20 according to the cold engine start-up control strategy. Once the EECD 16 is up to temperature, the fuel injector 20 is operated according to a conventional operating protocol which configures the engine to maintain the temperature of the exhaust gases at a substantially steady state.

If the engine is turned on having recently been operated within its operating temperature range, or substantially close to it, then the controller 14 will operate the fuel injector 20 according to the warm engine start-up protocol without first reverting to the cold engine start-up control strategy. If the controller 14 determines that the temperature of the engine during start-up is below 40°C and/or above 5°C it will operate the fuel injector 20 according to the cold engine start-up control strategy.

The controller 14 is arranged to evaluate the operating parameters of the engine 12 including, for example, the engine temperature and/or the time that has elapsed since the last engine switch-off event. In this way the controller 14 may determine whether the engine is being operated under cold-start conditions. In embodiments, the controller 14 is operable to determine the operating temperature of the engine 12 and/or EECD 16 using a suitable temperature monitoring means as would be readily understood by the skilled person. For example, the controller 14 is arranged to receive signals from a temperature sensor which is arranged to monitor the temperature of the engine 12 and/or the EECD 16.

The controller 14 is further arranged to operate the fuel injector 20 according to different fuel injector operating modes depending on the torque demand of the engine. An idling operating mode is arranged to operate the fuel injector 20 when a minimal, or substantially zero, torque demand is required of the engine, i.e. when the engine is in an idling condition and the vehicle is stationary. Accordingly to the idling operating mode, the fuel injector 20 is operated to inject only the minimal amount of fuel required to prevent the engine misfire.

When the user requires the vehicle to drive away from the stationary position, the fuel injector 20 is operated according to a drive-away operating mode, which causes the engine output to increase in order to match the user's increasing torque demand. Accordingly, the drive-away operating mode results in greater fuel consumption by the engine which thereby increases the output of exhaust emissions. It will be appreciated by the skilled person that in particular embodiments the controller 14 may be configured to operate with alternative and/or additional operating modes corresponding to different engine operating conditions without diverging from the scope of the present invention.

The idling operating mode defines a first operating mode in which the fuel injector 20 is operated to perform an initial longer injection and final shorter injection. The initial and final injections are separated from each other by a

predetermined time period of approximately 5 ms. A second operating mode defines the drive-away operating mode, which again comprises an initial and a final injection separated by a predetermined time period. The second operating mode differs from the first operating mode due to the fact that the initial injection comprises two sub-injections, or pulses, which are separated by a predetermined time period of approximately 2 ms. Each of the first and second operating modes may be used to control at least one of the fuel injector(s) immediately following start-up of the engine. In other words, at least one of the first and second operating modes may be employed to control at least one fuel injector without first employing any other intervening control strategy and/or without any intervening time having passed following ignition of the engine.

The two pulses of the initial injection are each performed during the intake stroke of the engine cycle which causes an increase in the turbulence and temperature of the exhaust gases. This leads to a rapid increase in the temperature of the exhaust after-treatment apparatus (i.e, the EECD 16). Operating the fuel injector 20 according to the second operating mode results in an advantageous reduction in the vehicle's emissions due to the rapid heating up of the EECD 16 which enables the EECD 16 to collect more particulate matter from the engine exhaust gases. This is particularly advantageous for a vehicle fitted with a new EECD which is only capable of operating with sub-optimal level of efficiency. By contrast, the first operating mode uses more of the injected fuel to generate power from the engine which thereby increases the relative fuel consumption of the engine.

The first and second operating modes are defined relative to a threshold value. Below the threshold value, the fuel injector 20 is arranged to operate in the first operating mode and above the threshold value the fuel injector 20 is configured to operate in the second operating mode. According to the present embodiment, the controller 14 is configured to transition from the first operating mode to the second operating mode as the received torque demand exceeds a threshold torque demand value. In alternative embodiments, the controller 14 is configured to determine the fuel injector operating mode in dependence on any suitable engine parameters, including engine speed and throttle position.

The controller 14 is configured to determine the threshold value in dependence on the operating efficiency of the fuel injector 20 and/or the operating efficiency of the EECD 16. In particular, the threshold value is determined in dependence on a first input signal indicative of the operating efficiency of the fuel injector 20 and/or a second input signal indicative of the operating efficiency of the EECD 16.

Advantageously, the controller 14 is configured to determine a lower threshold value for a new EECD compared with an aged EECD, such that the torque demand required to trigger the transition between the first and second fuel injector modes is reduced for situations where the EECD 16 is operating less efficiently. Accordingly, the controller 14 is able to employ the second operating mode during lower engine outputs in order to heat up the EECD 16 more quickly. Hence, the rapidly energized EECD 16 can thereby capture more particulate matter from the exhaust gases and thereby reduce the vehicle's emissions at a time when the EECD's baseline efficiency is sub-optimal.

The controller 14 is further configured to increase the threshold value as the operating efficiency of the EECD 16 increases such that a greater torque demand is needed to trigger the transition from the first to the second operating mode. Over time, as the operating efficiency of the EECD 16 increases due to the build-up of exhaust particulates within a filter of EECD 16, the second operating mode is no longer required to rapidly increase the operating efficiency of the EECD 16 at lower engine outputs. Therefore, the controller 14 is able to operate the fuel injector 20 according to the first operating mode at greater torque demand values. Thus, the controller 14 is able to take advantage of the increased operating efficiency of the EECD 16 by using more of the fuel from each injection event to generate power from the engine whilst maintaining vehicle emissions at acceptable levels.

As explained in the foregoing, the ageing EECD 16 and/or fuel injector 20 leads to a gradual change in the threshold value, which then determines the transition between the first and second fuel injection operating modes. The engine parameter threshold value is determined with respect to a normalised age factor value, which takes into account the change in the relative efficiency of the fuel injector 20 and/or EECD 16 over time. The age factor value is calculated according to the method as described above with reference to Figure 6.

The method of controlling the fuel injector 20 according to the present embodiment of the invention will now be describe with reference to the flow chart shown in Figure 10. The method starts with step 152 in which the controller 14 first determines whether the engine 12 is operating under cold-start conditions by evaluating temperature signals that are indicative of the engine temperature. If the answer is no, then the controller 14 proceeds to control the fuel injector 20 according to a warm engine start-up protocol. If the answer is yes then the method proceeds to step 154 in which first and/or second input signal(s) are received by the controller 14. If the engine temperature is between 5°C and 40°C then the controller 14 determines that the engine is operating under cold-start conditions. Above 40°C the controller 14 determines that the engine is operating in a warm start-up condition.

At step 155, the processor 40 evaluates received input signals and calculates an age factor value corresponding to the current operating efficiency of the EECD 16 and/or fuel injector 20. At step 156, the processor 40 determines an engine parameter threshold, i.e. the torque demand threshold, which defines the transition between the first and second fuel injector operating modes. The torque demand threshold is calculated in dependence on the operating efficiency of the EECD 16 and/or the fuel injector 20 as defined by the age factor value that was calculated in preceding method step 155.

The method steps involved in determining the engine parameter threshold value 166 are shown in the flow chart of Figure 11. As described above, the engine parameter threshold value 166 is determined in dependence on the relative age of the fuel injector 20 and/or the EECD 16. The controller 14 is initially provided with an aged parameter threshold value 162 and a green parameter threshold value 64. The aged parameter threshold value 162 is optimized for controlling a fuel injector 20 in situations where the first and/or second signal(s) indicate that the EECD 16 and/or fuel injector 20 are in an aged condition. The green parameter threshold value 164 is configured to control the operation of a fuel injector 20 in situations where the EECD 16 and/or fuel injector 20 are in a green or new condition.

A first step in determining the engine parameter threshold value 166 comprises taking the difference between the aged parameter threshold value 162 and the green aged parameter threshold value 164. The resulting differential value is multiplied by the age factor value 159 and then added to the green parameter threshold value 164 to produce the outputted engine parameter threshold value 166. The calculation in step 156 causes a gradual change in the engine parameter threshold value 166 as the age factor value 159 transitions between 0 (for a new fuel injector 20 and/or EECD 16) to 1 (for an aged fuel injector and/or EECD 16). An increase in the age factor value 159 results in a subsequent increase in the engine parameter threshold value 166, whereas a decrease in the age factor value 159 causes a corresponding decrease in the engine parameter threshold value 166. Put another way, the processor 40 is configured to increase the threshold value as the operating efficiency of the EECD 16 increases and increase the threshold value as the operating efficiency of the fuel injector 20 decreases. In embodiments, the processor 40 is configured to increase the threshold value up to a maximum threshold value corresponding to an engine torque demand of 20% of the maximum torque demand, wherein the maximum torque demand defines the total possible engine torque demand from a user of the vehicle and/or the ECU. In embodiments, the maximum torque demand corresponds to a user demand to fully open a throttle of the engine.

Returning now to Figure 10, the fuel injector control method continues with step 158, in which the processor 40 receives an input signal indicative of an the engine torque demand. The controller 14 assesses whether or not the engine torque demand exceeds the torque demand threshold from step 156 and thereby determines an operating mode by which to control the fuel injector 20.

At step 159, the processor 40 calculates suitable fuel injector operating parameters which correspond to the previously determined fuel injector operating mode. Finally, in step 160 a control signal comprising the calculated operating parameters is outputted to the fuel injector 20. The method then repeats until the engine 12 is turned off.

According to the herein described embodiment of the present invention, the controller 14 is configured to decrease the torque demand threshold for a new fuel injector 20 and/or EECD 16 and to increase the torque demand threshold for an aged fuel injector 20 and/or EECD 16. This means that when the fuel injector 20 and/or EECD 16 are new, the fuel injector 20 will be operated according to drive-away operating mode at comparatively low torque demand values. The drive-away operating mode causes the EECD 16 to be energised more rapidly, which allows it to absorb more particulate matter from the exhaust gases thereby reducing the vehicle's emissions during cold start conditions. As the fuel injector 20 and/or EECD 16 begin to age the torque demand threshold is increased in line with the age factor value such that the fuel injector 20 is operated according to the drive-away operating mode at increasingly greater torque demand values. Accordingly, the controller 14 is now able to operate the fuel injector 20 according to the first operating mode at greater torque demand values, so that more of the fuel from each injection cycle is used to generate power from the engine whilst maintaining vehicle emissions within acceptable limits.

Many modifications may be made to the above examples without departing from the scope of the present invention as defined in the accompanying claims.

CLAIMS

1. A controller for a fuel injector for an engine, the controller comprising:
one or more input(s) arranged to receive a first input signal indicative of the operating efficiency of the fuel
5 injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device;
a processor configured to determine at least one operating parameter of the engine; and to determine a
fuel injector operating mode based on the first and/or second input signal(s) and on the at least one operating
parameter of the engine; and
an output configured to output a control signal for controlling the fuel injector according to the determined
10 fuel injector operating mode.
2. The controller of claim 1, wherein the controller is configured to:
(i) output a first control signal to control the fuel injector according to a first fuel injector operating mode
when the at least one operating parameter is below a threshold value; and
15 (ii) output a second control signal to control the fuel injector according to a second fuel injector operating
mode when the at least one operating parameter is above the threshold value;
wherein the processor is configured to determine the threshold value in dependence on the first and/or
second input signal(s).
3. The controller of claim 2, wherein the processor is configured to increase the threshold value as the
operating efficiency of the exhaust emission control device increases and/or as the operating efficiency of the fuel
injector decreases.
4. The controller of any one of claims 2 to 3, wherein at least one of the first and second fuel injector operating
25 modes defines a plurality of fuel injections for a single cycle of the engine.
5. The controller of claim 4, wherein the first fuel injector operating mode comprises an initial fuel injection
followed by a final injection, optionally wherein the controller is configured to operate the fuel injector according to
the first fuel injector operating mode during an idling condition of the engine and following a cold engine start-up
30 event.
6. The controller of any one of claims 4 to 5, wherein the second fuel injector operating mode comprises an
initial fuel injection followed by a final injection, the initial fuel injection comprising two or more sub-injections,
optionally wherein the controller is configured to operate the fuel injector according to the second fuel injector
operating mode during a drive away condition of the engine and following a cold engine start-up event.
35
7. The controller of any preceding claim, wherein the at least one operating parameter of the engine includes
an indicator of an engine torque demand.

8. The controller of claim 7, when dependent through claim 2, wherein the processor is configured to determine the threshold value such that it does not exceed a maximum threshold value.

9. The controller of claim 8, wherein the maximum threshold value corresponds to an engine torque demand of 15-25% of a maximum torque demand, optionally wherein the maximum threshold value corresponds to an engine torque demand of 20% of a maximum torque demand.

10. The controller of any preceding claim, wherein the at least one engine operating parameter includes an indicator of an engine temperature.

11. The controller of claim 10, when dependent through claim 2, wherein the controller is configured to operate the fuel injector according to at least one of the first and second fuel injector operating modes when the engine temperature is between 5°C and 40°C.

12. The controller of any preceding claim, wherein the first and/or second input signal includes an indicator of at least one of an age of the vehicle, a vehicle's mileage, a number of fuel injection events, an oxygen storage value and a number of engine start-up events.

13. A controller for a fuel injector for an engine, the controller comprising:

an input arranged to receive a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device;

a processor configured to determine a value indicative of a desired mass of fuel to be injected into a cylinder of the engine by the fuel injector; and

an output configured to output a control signal for controlling the operation of the fuel injector;

wherein the processor is configured to determine at least one parameter of the control signal based on the first and/or second input signal(s) and the value indicative of the desired mass of fuel.

14. A fuel injection system for an engine, the fuel injection system comprising a fuel injector and a controller according to any preceding claim, wherein the fuel injector is configured to control the flow of fuel into a cylinder of the engine in dependence on the control signal.

15. A vehicle comprising the controller of claims 1 to 13 or a fuel injection system of claim 14.

16. A method for controlling a fuel injector for an engine, the method comprising:

receiving a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission device;

determining at least one operating parameter of the engine;

determining an operating mode of the fuel injector based on the first and/or second input signal(s) and on the at least one operating parameter of the engine; and,

outputting a control signal for controlling the fuel injector according to the determined fuel injector operating mode.

17. A method for controlling a fuel injector for an engine, the method comprising:

5 receiving a first input signal indicative of the operating efficiency of the fuel injector and/or a second input signal indicative of the operating efficiency of an exhaust emission control device;

determining a value indicative of a desired mass of fuel to be injected into a cylinder of the engine by the fuel injector; and,

10 outputting a control signal for controlling the operation of the fuel injector; wherein the step of outputting the control signal comprises determining at least one parameter of the control signal in dependence on the first and/or second input signal(s) and the value indicative of the desired mass of fuel.

18. Computer software that, when executed, is arranged to perform a method according to any one of claims 16 to 17.

15 19. A non-transitory, computer-readable storage medium storing instructions thereon that, when executed by one or more electronic processors, causes the one or more electronic processors to carry out the method of claim 16 to 17.

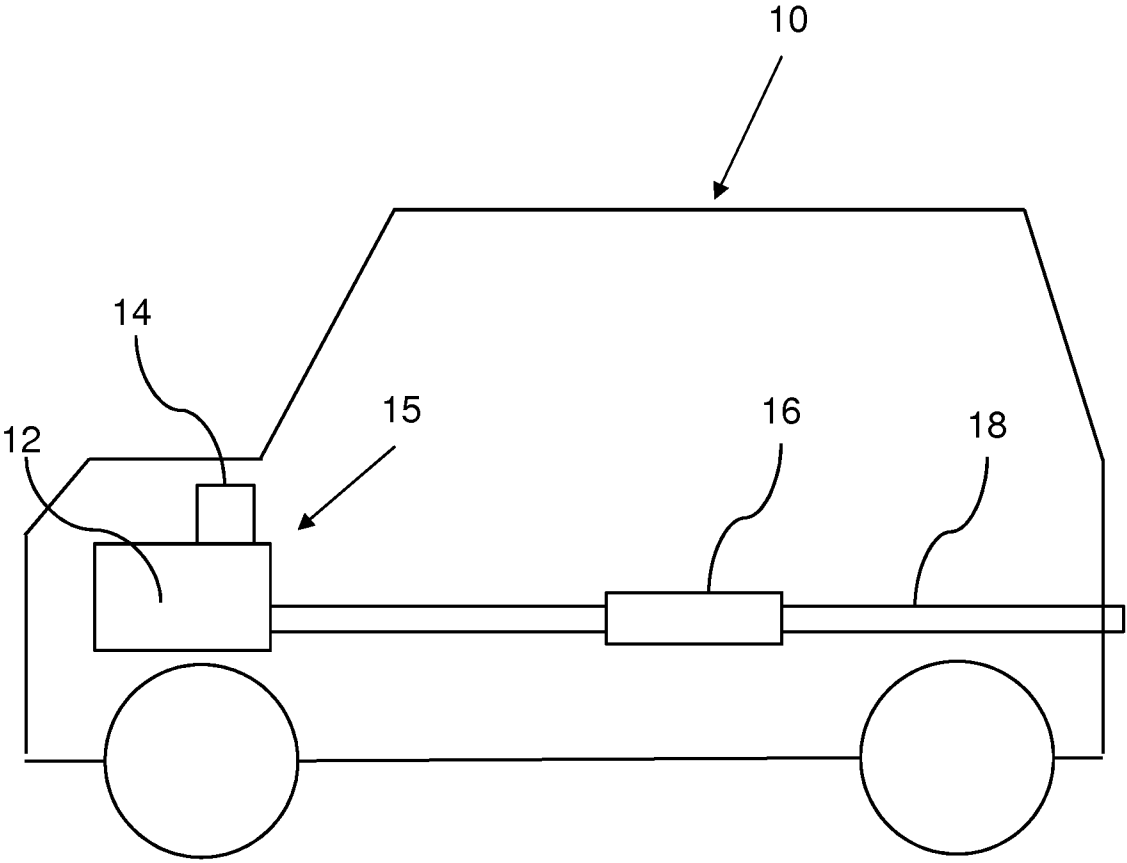


Figure 1

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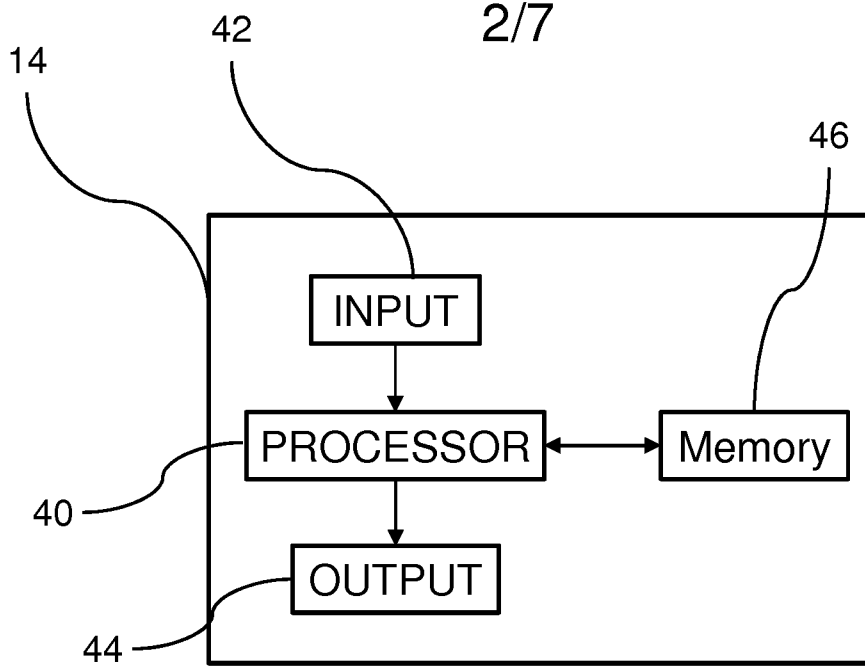


Figure 2

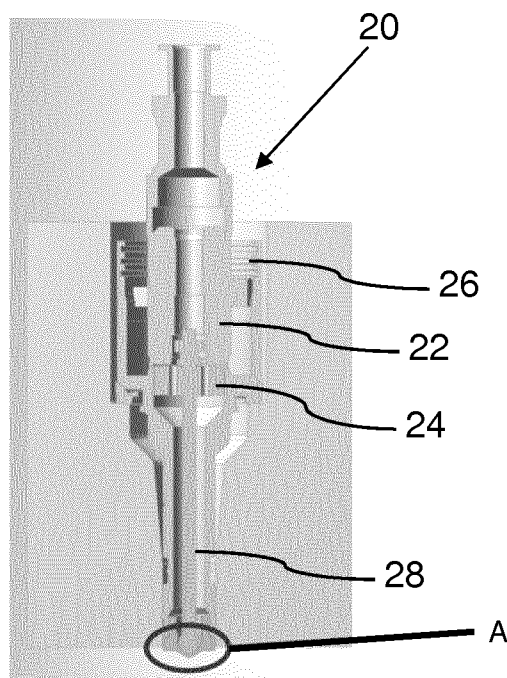


Figure 3

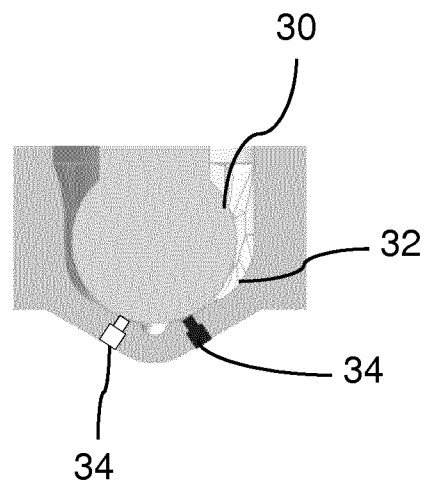


Figure 4

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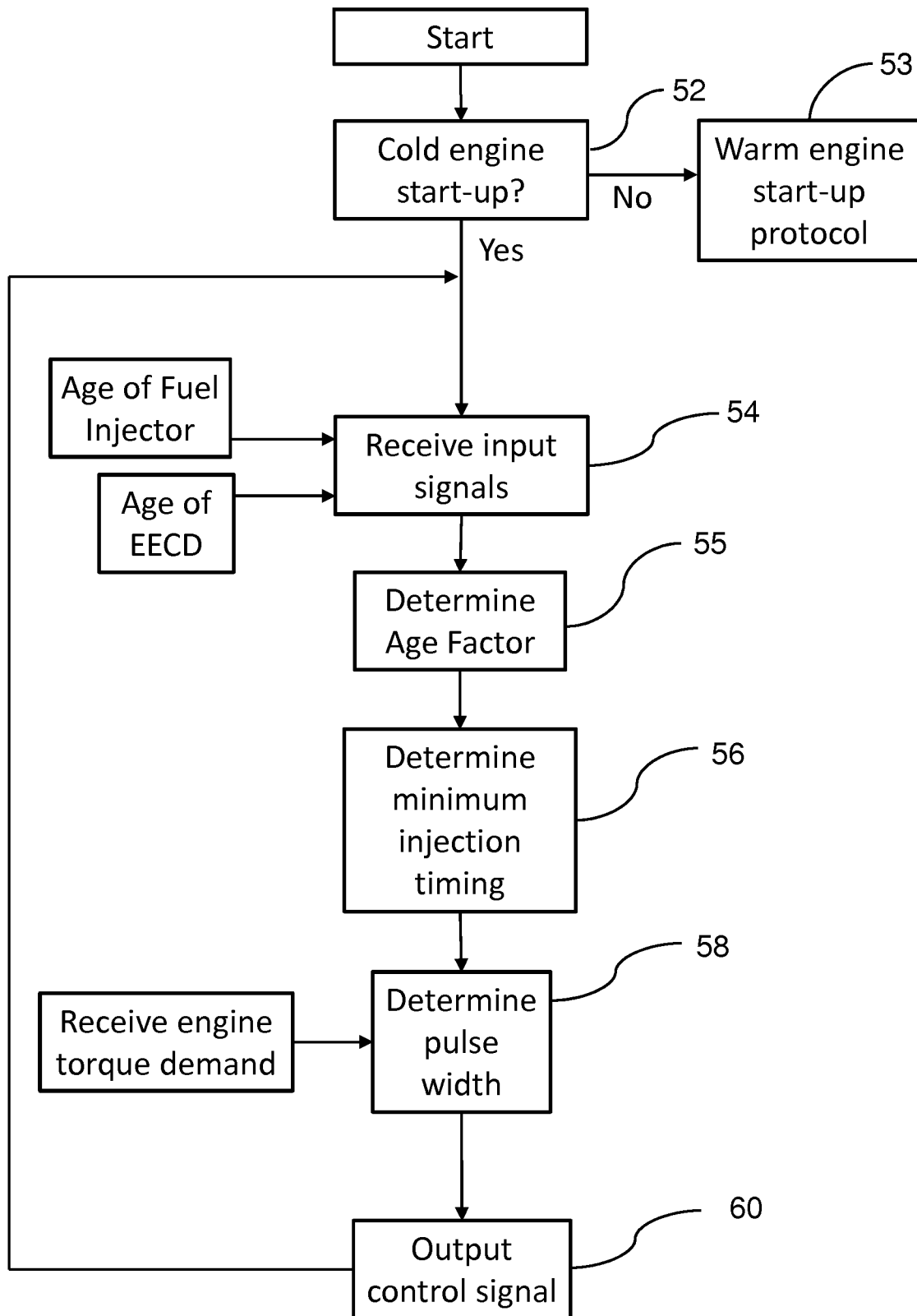


Figure 5

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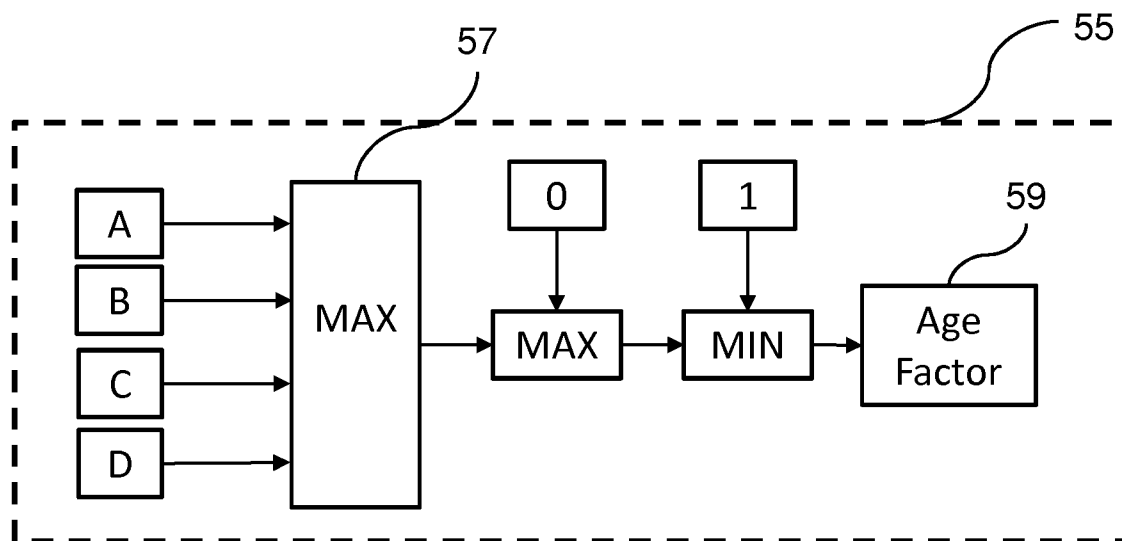


Figure 6

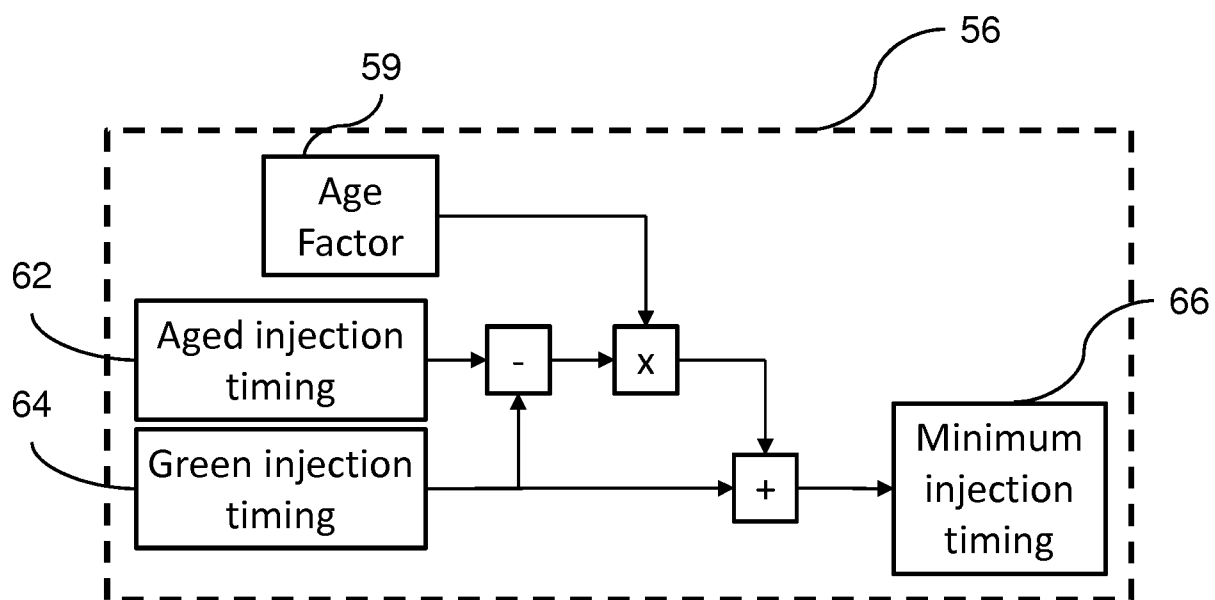


Figure 7

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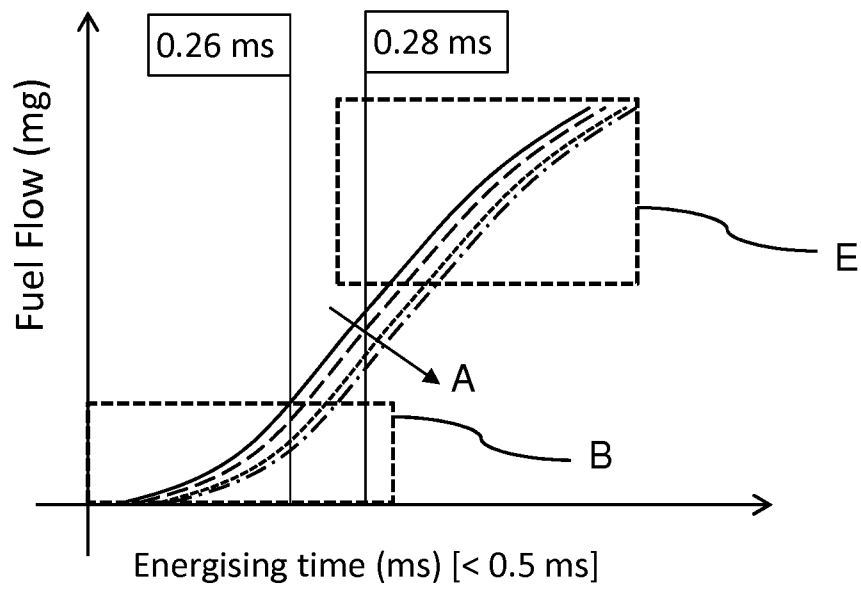


Figure 8

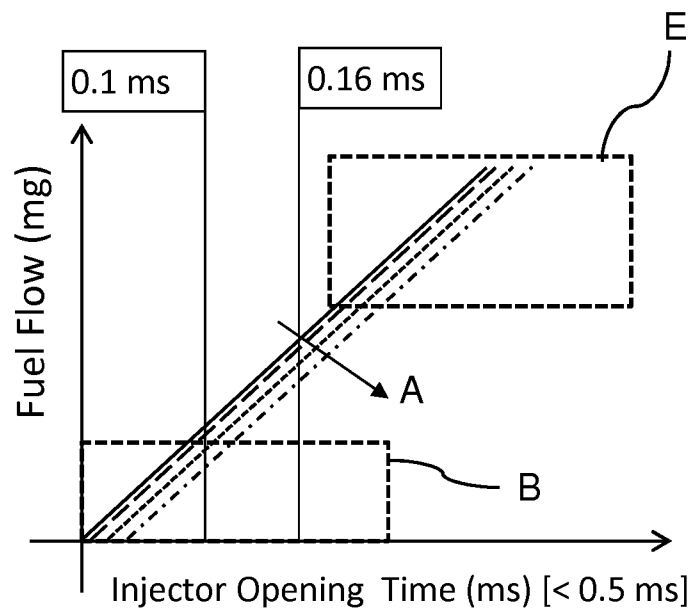


Figure 9

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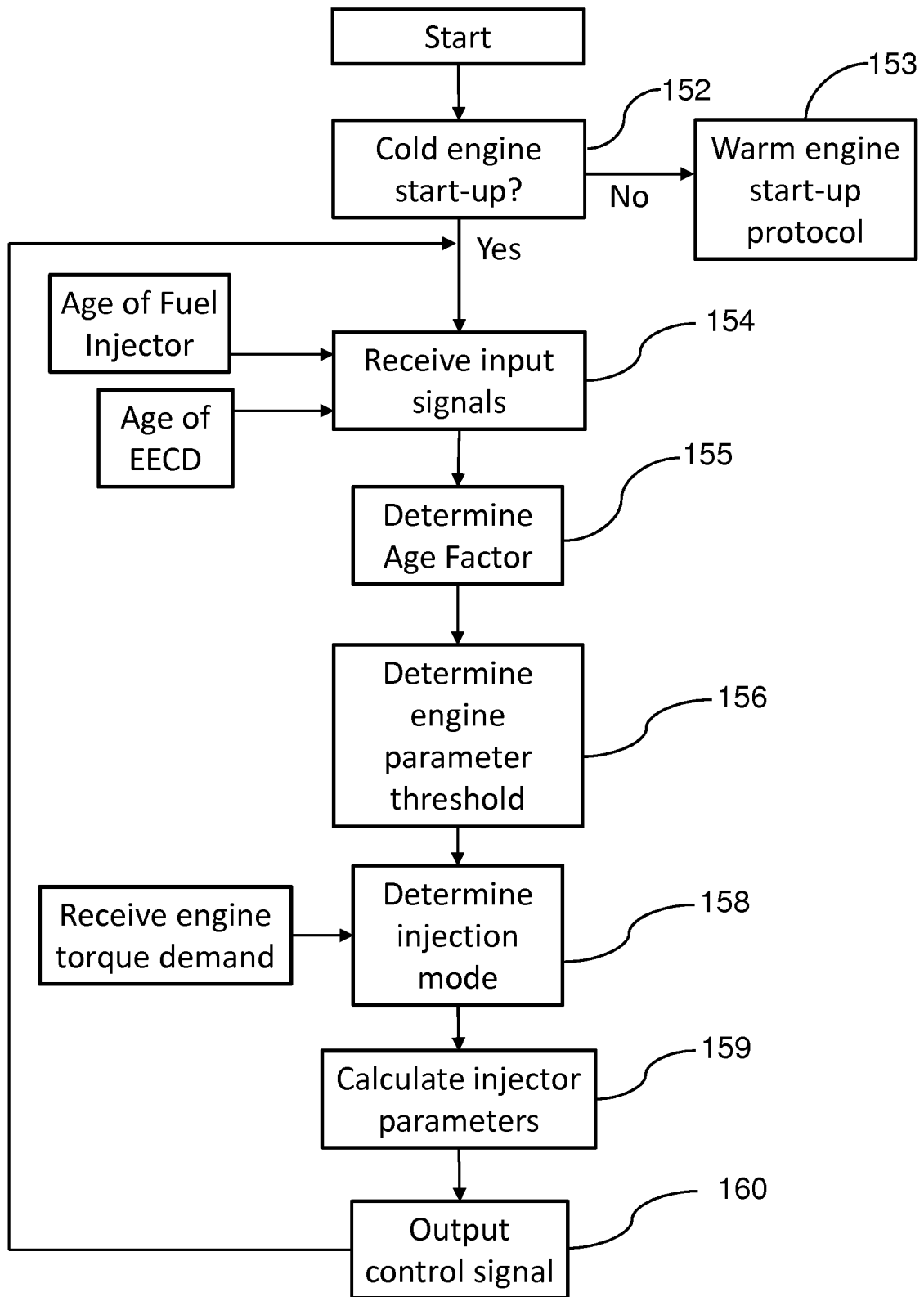


Figure 10

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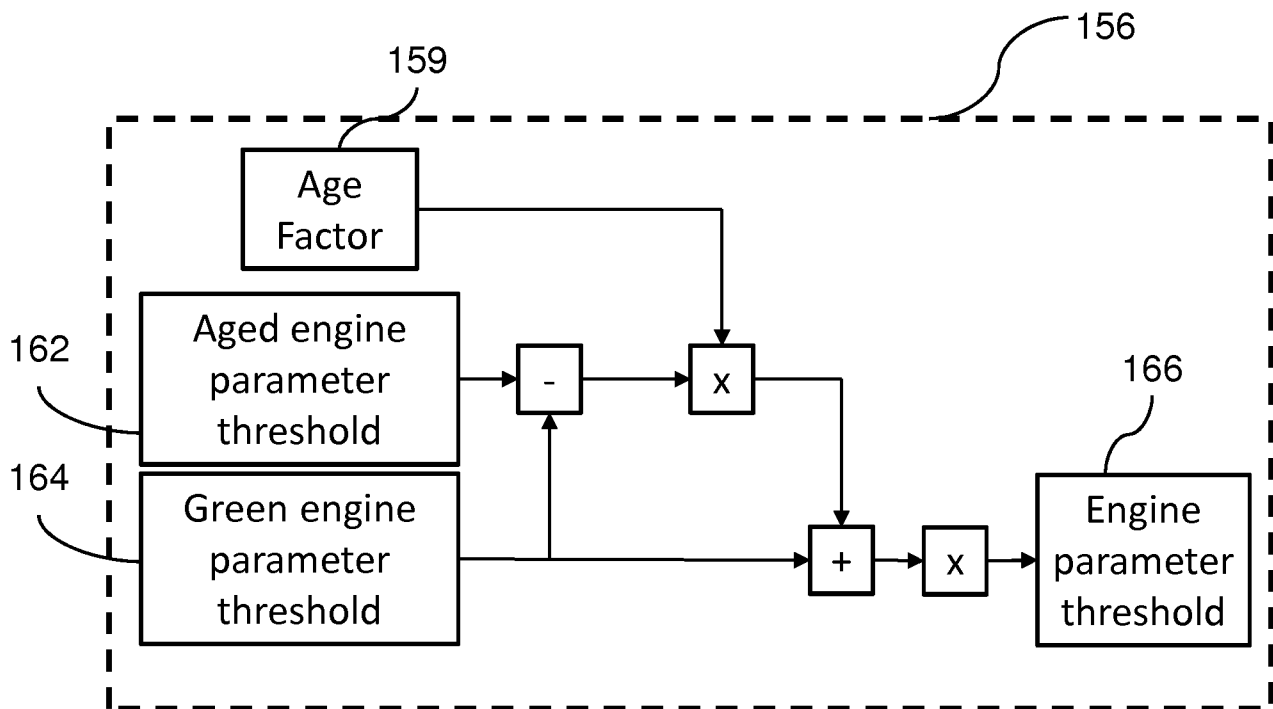


Figure 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/067022

A. CLASSIFICATION OF SUBJECT MATTER

INV. F02D41/24 F02D41/02 F02D41/06
ADD. F02D41/40

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F02D

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

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

EPO-Internal, WPI Data

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Y	paragraphs [0058] - [0065]; figure 4 -----	3,12
X	US 2006/016425 A1 (KONO TOSHIYA [JP] ET AL) 26 January 2006 (2006-01-26)	1,2, 7-11, 13-19
Y	paragraphs [0074] - [0077]; figure 14 -----	3,12
X	US 7 958 720 B2 (NISSAN MOTOR [JP]) 14 June 2011 (2011-06-14)	1,2, 4-11, 13-19
Y	column 6, line 66 - column 8, line 59; figures 3-5 column 10, line 14 - column 10, line 16 ----- -/--	3,12



Further documents are listed in the continuation of Box C.



See patent family annex.

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

30 August 2019

Date of mailing of the international search report

06/09/2019

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/067022

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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Information on patent family members

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