The present invention describes a fuel-management system for minimizing particulate emissions in turbocharged direct injection gasoline engines. The system optimizes the use of port fuel injection (PFI) in combination with direct injection (DI), particularly in cold start and other transient conditions. In the present invention, the use of these control systems together with other control systems for increasing the effectiveness of port fuel injector use and for reducing particulate emissions from turbocharged direct injection engines is described. Particular attention is given to reducing particulate emissions that occur during cold start and transient conditions since a substantial fraction of the particulate emissions during a drive cycle occur at these times. Further optimization of the fuel management system for these conditions is important for reducing drive cycle emissions.
**Port Injection System For Reduction of Particulates from Turbocharged Direct Injection Gasoline Engines**

This application claims priority of U.S. Provisional Patent Application Serial No. 61/734,438, filed December 7, 2012, the disclosure of which is incorporated herein by reference in its entirety.

**BACKGROUND**

Particulate matter (PM) emissions from turbocharged direct injection spark ignition engines using gasoline and gasoline-ethanol blends are an increasing concern. A key factor that produces this problem is poor mixing from directly injected fuel (fuel that is directly introduced into the engine cylinder as liquid). The particulate emissions problem is increased in turbocharged engines due to increase in the absolute pressure in the cylinder. The concern about particulate emissions relates to both the total mass of the particulates and the number of particulates. Meeting anticipated European requirements for reducing the number of particulates appears to be especially demanding.

Port and direct injection have complimentary advantages. Due to better mixing, reduced wall wetting and improved evaporation of the fuel, both particulate mass/km and number of particulates/km emissions from port injection, where the fuel is introduced in a region outside the cylinders, are typically less than one tenth those from direct injection (when the fuel is introduced as a liquid into the cylinder). On the other hand, direct injection provides better knock resistance due to greater evaporative cooling of in cylinder charge and thus allows operation at higher levels of torque for a given engine displacement and/or compression ratio. Direct injection can also be used to provide better control of fueling and to further increase efficiency by use of stratified operation to enable lean operation at low loads.
SUMMARY

The present invention describes a fuel-management system for minimizing particulate emissions. The system optimizes the use of port fuel injection (PFI) in combination with direct injection (DI), particularly in cold start and other transient conditions.

An important aspect of using the combination of port and direct injection to reduce particulate emissions is the employment of control systems, such as those described in US patent 8,146,568, to minimize the fraction of the fuel that is directly injected into the engine while also preventing knock as the torque is increased. Both closed loop control with a knock detector and open loop control with a look up table can be employed. These control systems can provide better mixing throughout a drive cycle with essentially no compromise in engine efficiency and performance. The engine can be operated with port fuel injection alone, direct injection alone or a combination of port and direct injection. The fraction of fuel that is port fuel injected can be controlled to prevent knock as a function of both torque and engine speed since the engine speed also affects the onset of knock.

In the present invention, the use of these control systems together with other control systems for increasing the effectiveness of port fuel injector use and for reducing particulate emissions from turbocharged direct injection engines is described. Particular attention is given to reducing particulate emissions that occur during cold start and transient conditions since a substantial fraction of the particulate emissions during a drive cycle occur at these times. Further optimization of the fuel management system for these conditions is important for reducing drive cycle emissions.
FIG. 1 illustrates an engine with two injectors; a port fuel injector that provides fuel to a region in the manifold, which is outside of the cylinder, one per cylinder, and a direct injector that introduces fuel directly into the cylinder, one per cylinder, with the ratio of fuel injected by each injector changed in an optimized way so as to reduce particulate emissions;

FIG. 2 is a schematic of an engine of FIG. 1, and shows an engine control system where information about the engine condition, such as temperature, that influences particulate formation and the load demand from the operator are used to determine the ratio of fuel injected through the port fuel and the direct injectors;

FIG. 3 illustrates an engine system with both port fuel and direct fuel injectors, as shown in FIG. 2, with additional engine performance sensors that measure the engine operation and/or emissions. This type of engine performance sensor could be a knock sensor, a misfire sensor, an exhaust sensor, or any combination of the three, where the exhaust sensor could monitor, in real time or near real time, the particulate emissions;

FIG. 4 shows the engine system of FIG. 3 with the introduction of spark timing so that spark retard may be adjusted to allow more PFI use when needed to reduce particulate emissions;

FIG. 5 illustrates an engine system with both port fuel injectors and direct injectors, as shown in FIG. 2, with an additional injector or set of injectors upstream from the compressor blades of the booster, which could be a turbocharger or a supercharger; and
FIG. 6 shows the engine system of FIG. 3 with the introduction of valve timing (inlet, exhaust or both), which may be adjusted to allow more PFI use when needed to reduce particulate emissions.

DETAILED DESCRIPTION

As described above, the present invention uses an engine control system to monitor and regulate the operation of the engine to both maximize engine performance and efficiency, and to minimize particulate emission. The engine control system may affect the fraction of fuel that is introduced using PFI and DI, based on engine conditions, particulate emissions and other factors.

Closed loop control, open loop control or a combination of open and closed loop may be used to optimize particulate emissions reduction while providing the desired amount of knock control. Various embodiments of these control systems are shown in the accompanying figures.

FIG. 1 shows a diagram of an engine system that has two sets of injectors, a port fuel injector 10 that introduces fuel into a region outside of the cylinder, such as manifold 15, one per cylinder, and a direct injector 20 that introduces fuel directly into the cylinder 30 as a liquid, one per cylinder. The engine may be a spark ignited engine, although other types of engine operation, such as HCCI (Homogeneous Charge Compression Ignition) or its variants (such as RCCI, Reaction Controlled Compression Ignition, or PCI, Premixed Compression Ignition, other low temperature combustion processes) may be employed. The engine control unit 40 uses information that relates to particulate emissions and adjusts the ratio of the amount of fuel that is port injected to the amount of fuel that is directly injected so as to reduce particulate emissions. In this embodiment, the engine control unit 40 does not have any feedback about engine performance. Thus, the information
related to engine performance could be in the form of a look up table or a formula. The look up table or tables may use the engine map to estimate engine performance.

FIG. 2 shows a diagram of the engine control system of FIG. 1 during engine operation. The engine control unit 40, also referred to as the fuel management system, determines, in response to the load demand from the operator and using information about the engine condition 50 that influences particulate emissions, the proper operation of the injectors 10, 20. The engine condition 50 may include information about engine temperature, coolant temperature, time since start, status of the fuel pool in the manifold, and other factors that influence particulate emission.

Using these inputs, the engine control unit 40 may regulate the ratio of the fuel that is injected through the port fuel injector 10 as compared to that directly injected into the cylinder 30, and other injection characteristics. For example, the engine control unit 40 may also adjust the start of injection, the end of injection, the injection rate. In the case of the direct injector 20, injection rate may be adjusted through management of the fuel rail pressure, for example, or through control of the pulse width for a system that uses pulse-width modulation. The engine control unit 40 may also control the valve timing, allowing for the injection of port fuel injection through an open inlet valve, where the PFI fuel is introduced into the cylinder as liquid droplets, instead of as a gas vaporized by the hot valves. All of these various actions may be referred to as "injector operation".

FIG. 3 shows the engine system of FIG. 2, with the addition of engine performance sensors 60 that measure the engine operation and/or emissions. An engine performance sensor 60 may be, for example, a knock sensor, a misfire sensor, an exhaust sensor, or any combination of the three. Information from the knock sensor can be used to reduce the relative amount of fuel that is port fuel injected as the torque is increased so as to prevent knock. In some embodiments, the exhaust
sensor could monitor, in real time or near real time, the particulate emissions. The exhaust sensor may determine the number of particulates or the mass number of the particulates. The exhaust sensors could be electrostatic (measuring charge), optical (counting particles or extinction of an optical signal) or mass based (where the presence of the particulate mass changes a measurement, such as the resonant frequency of a system). This engine system may regulate the injection operation based on information from these engine performance sensors 60. Thus, while the embodiment of FIG. 2 uses a lookup table or equation to estimate engine performance, this embodiment may use information from the engine performance sensors 60.

FIG. 4 shows a diagram of a control system, similar to FIG. 3, which controls the ratio of the amount of fuel that is port fuel injected to the amount of fuel that is directly injected. The engine control unit 40 may receive information on engine condition and engine performance. The engine control unit 40 also controls the amount of spark retard 70 that is used to enable a higher relative amount of fuel that is port injected. Using this information, at some times, such as in the cold start or warm restart periods, the ratio of the amounts of port injected fuel to directly injected fuel can be greater than would be used at other times in the drive cycle at the same value of engine torque and speed. Spark retard may be increased to prevent knock that would otherwise occur. The maximum ratio of port fuel injection to direct injection would be determined by the maximum amount of spark retard that could be used without an unacceptable reduction in engine efficiency and performance. Spark retard, with the resulting decrease in efficiency, can be used at these times to substantially reduce particulate emissions with only a minimal effect on engine efficiency during a drive cycle. Large spark retard during cold start or warm restart can have the additional advantage of rapid engine and catalyst heating (as the engine is less efficient). The amount of spark retard can be limited so that the engine efficiency and performance do not fall below selected values. The engine control unit 40 of FIG. 4 also controls injector operation, as described above.
FIG. 5 shows the engine system shown in FIG. 2, with both port fuel injectors 10 and direct injectors 20. In this embodiment, an additional injector or set of injectors (not shown), referred to as upstream injectors, are disposed upstream from the compressor blades of the booster 80, which could be a turbocharger or a supercharger, are used. It may be advantageous to introduce the port fuel injected fuel upstream from the turbocharger 80. The high velocity of the blades induces strong turbulence in the air/fuel mixture and blasts the impinging liquid fuel, improving atomization of the fuel. One advantage of injection upstream from the turbocharger 80 is reduced number of injectors, as a single injector is needed. In order to improve air/fuel ratio, it may be possible to adjust the fuel that is introduced into every cylinder 30. It may be possible to combine a single injector upstream from the turbocharger or turbochargers 80 with additional port fuel injectors 10 that provide fuel to the inlet valves of the cylinders. Even under conditions when the blades of the compressor are not spinning very fast, there are enough surfaces for allowing evaporation of the fuel during transients that would allow for sufficient fuel vapors to enter the cylinder 30. The rest of the fuel will be deposited on the walls of the manifold 15 and will be evaporated later in the engine operation. Thus, the compressor in the booster 80 and the fuel injector operate as a carburetor, allowing for increased flexibility of control of the engine operation for controlling particulate emissions. The advantages of this configuration are rapid and effective evaporation of the fuel, allowing the fuel injected through the manifold to be in the vapor phase. In addition to smaller particular matter formation in cylinder, hydrocarbon emissions, especially during cold start and during transients, may also be decreased. Thus, in this embodiment, the engine control unit 40 may control injector operation of the direct injectors 20, the port fuel injectors 10, and the additional upstream injectors.

FIG. 6 shows the engine system of FIG. 3 with port fuel injectors 10 and direct injectors 20 where variable valve timing 90 is used to allow a higher fraction of fuel provided by port fuel injection during conditions with increased particulate
generation would occur. In this embodiment, the engine control unit 40 may employ variable valve timing to compensate for the reduced direct injected fuel. For example, at certain times, the use of direct injected fuel may cause excessive particulate emission. In these times, rather than using the requisite amount of direct injected fuel, variable valve timing 90 is used to insure no-knock operation. For instance, it may be possible to operate the engine with increased value of residuals for knock control, through appropriate choice of valve timing.

These figures show the sensors 50, 60 can be employed to monitor engine conditions and/or engine performance. One or more of these types of sensors can be used in an embodiment. Additionally, these figures show various compensation techniques that are used to allow the use of an amount of port injected fuel that would otherwise cause knock. These compensation techniques include, but are not limited to valve timing, injector timing, upstream injectors, and spark timing. Although each figure shows the use of only one of these compensation techniques, it is noted that more than one compensation technique may be used in a single embodiment. For example, spark timing and valve timing may both be employed in some configurations. Therefore, the figures should not be construed as limiting the disclosure to those particular configurations. Rather, these figures simply show various components that may be used.

Compensation Techniques

The above description discloses various compensation techniques, such as spark timing, and variable valve timing. However, other compensation techniques may also be used.

In addition to the use of variable valve timing, the use of on-demand cylinder deactivation can also be used in combination with two injectors. During transients at relatively low load, some of the cylinders can be deactivated. If the exhaust valves are not opened or only open partially or during a short time, during the following
cycle, the high pressure, hot gases in the cylinder can be used to help vaporize the port fuel injected fuel in that same cylinder. When the inlet valve opens following the cycle with exhaust restricted, high pressure, heated air enters the manifold and helps vaporize the gasoline in the manifold and on the valves. The process can be repeated in the same cylinder, and the process can be arranged so that it occurs also, in a staggered manner, at other cylinders.

In the same manner, it would be possible to have a cycle with restricted inlet valve opening, with limited ingestion of port fuel, that goes through compression, power stroke and exhaust cycle without firing the spark and without opening inlet or exhaust valves. In the next intake valve opening, the air leaving the cylinder is hot and can vaporize the fuel in the valve or the manifold. If done in all cylinders, the engine actually fires only on about half the cycles. Alternatively, in the following cycle, direct injection can be used to inject into a hot cylinder charge, facilitating droplet evaporation and minimizing potential wall wetting and production of particulate matter.

Another compensation technique that may be used is as follows. It may be possible to adjust the pressure of the direct injected fuel, such as by adjusting the pressure in the common fuel rail. This serves to minimize the impingement on the combustion chamber walls (cylinder walls, piston and valves), especially at transient conditions or at cold start. If the pressure is difficult to manage, a strategy that can be used to avoid the injection of very high speed droplets that will wet the wall is to use PWM (Pulse Width Modulation) of the direct injector. Injectors have transients during turning on and turning off that can be used to modify the conditions of injection of the fuel, even at constant rail fuel pressure. Through short pulses allowed by PWM fuel control, it would be possible to inject short sprays of fuel that modify the jets interaction with the gas in the cylinder, for example, by preventing them from reaching the far wall. Although atomization may not be as good, the production of particulate matter could be reduced by the use of multiple pulses, and in particular, short pulses that are dominated by transient behavior of the injector. Because of the
short duration of the times where PM is produced, the injectors can be prevented
from overheating due to the large number of pulses required that heat the solenoid
valve, the piezoelectric components or other components from the direct fuel
injector.

Another compensation technique includes open-valve port fuel injection. The
fueling system may use port fuel injection, when the intake valve is open, as an
additional means for reducing particulates. Port fuel injection with the intake valve
open enables some of the fuel to enter the cylinder in the liquid form and provide
some vaporization cooling. This would provide knock suppression from charge
cooling that could replace that which is typically provided by direct injection.
Although less knock suppression by charge cooling is obtained for a given amount of
fuel, the net result could be less particulate formation, especially during transients.
The same port fuel injector could be used for both conventional port fueling
injection with the intake valve closed and for open-valve port fuel injection where
increased knock resistance could be provided.

**Engine Control Unit Operation**

In addition to information that is used to determine how much port fuel injection
can be used without encountering knock, the fuel management system may also
employ additional information and requirements to control the relative amounts of
fuel that are port and directly injected. This may include information related to cold
start, such as engine temperature, and information that determines when stratified
injection would be used. Additional information for controlling of the ratio of
directly injected fuel to port injected fuel could be provided by sensors that
determine particulate mass and number, as described above.

The control system uses some or all of this information in conjunction with the
requirement to avoid knock to determine the ratio of port fuel injection to direct
injection that is used at a given value of torque and speed. The ratios may be
different depending on whether the primary objective is reduction of engine particulate mass or engine particulate number. It would also be possible to trade-off particulate matter and hydrocarbon emissions. In addition to the combustion information, information on the nature of the fuel can be used to adjust the ratio of the direct injected and port injected fuels. If the fuel has substantial content of saturated hydrocarbons or oxygenates (alcohols), the ratio of direct injected to port fuel injected fuel can be adjusted to provide best emissions. The nature of the fuel can be determined by the past history of the vehicle. For example, when the fuel contains a substantial fraction of alcohols, direct injection of the fuel can be used to decrease simultaneously hydrocarbon emissions and particulate emissions, compared to the case with port fuel injection of the same fuel, which produces little particulate matter but substantial hydrocarbon vapor during cold start and warm restart.

In addition, as described above, closed loop control using measurements of particulate mass and number can be employed. The fuel management system can control the fraction of fuel that is introduced by port fuel injection so to minimize particulate mass or number or some combination of the two.

The parameters that are inputs to the control system can include engine temperature; time after ignition; rate of change of engine fueling; rate of change of engine speed; rate of change of torque, engine speed and engine torque; fuel composition. The control system could also take into account the use or non-use of stratified direct injection.

These various embodiments, such as shown in FIGs. 1-6, can be used to decrease particulate emission during various critical times. Some times where particulate emission is known to be excessive are engine cold start and engine shutdown. Thus, the engine control unit described herein can be used to adjust the engine operating conditions, such that when particulate emissions would be high, the control system will adjust the port fuel injection to directly injected fuel ratio so as to use a greater
fraction of port injected fuel than would be used if particulate emissions were not a concern.

Cold Start

For example, when the engine is operated during cold start at a value of torque where a substantial amount of directly injected fuel would otherwise be needed to prevent knock, one or more compensation techniques may be introduced to reduce the relative amount of directly injected fuel without resulting in knock.

One such compensation technique is spark retard. Increased spark retard results in decreased efficiency. However, operation with reduced fuel efficiency during cold start and other transients, for most driving cycles, does not substantially affect the overall fuel efficiency. Moreover, the lower efficiency of engine operation during the short cold start transient can have the beneficial effect of increasing the rate of warm-up of engine and aftertreatment components.

During cold start, particulate control can be achieved through similar means used to minimize the production of hydrocarbons that would result in fast engine and catalyst warm-up. Thus, spark retard beyond what is required to control knock, valve timing adjustment to maximize pressure in the cylinder and residuals, and possible injection of a small fraction of the fuel through the direct injector can be used to minimize the formation of particulates during the cold start. Either the timing of the inlet valve, the exhaust valve or both can be adjusted by the operating system in order to minimize the production of particulates. The effect can be adjustment modification of the pressure, composition or flow dynamics in the cylinders. In the case of the flow dynamics, the flow can be modified from that during steady state conditions (either tumble or swirl or quiescent) so that the resulting flow during the transient minimizes wall wetting and production of particulates. In the case of multiple inlet valves or multiple exhaust valves, the
timing of each valve may be adjusted independently in order to modify the flow in cylinder.

Another control feature for reducing particulate emissions during cold start is to reduce the amount of direct injection that is used in order to minimize hydrocarbon vapor emissions. The fueling of the engine at the earliest time in the cold start period could be by direct injection alone or mainly by direct injection and the relative amount of fueling by port fuel injection could increased as a function of time as the engine and catalyst warm up. Information on the fuel composition (mostly alcohol content) can be used to adjust the amount of directly injected fuel.

The increased role of port injection as a function of time would be determined by the tradeoff between the benefit of using direct injection for better fuel control through precise injection of the amount of the fuel that is needed for near stoichiometric combustion and the detriment of the greater larger inhomogeneity of the air fuel mixture. Port fuel injection results in improved mixture uniformity while at the same time less precise control of the fuel injection, as the fuel transport occurs through the film established near the inlet valve or valves. The relative amounts of port fuel and direct fuel injection would be optimized as a function of time after the fuel has been ignited so as to minimize particulate emissions. This optimization could be facilitated by allowing a greater relative amount of port fuel injection, when needed, by increasing spark retard.

The use of multiple points and forms of fuel introduction into the cylinder is useful during these times. For example, during cold start operation, the control system could call for direct injection for a few cycles during the startup, for precise metering of the fuel, followed by increased use of port fuel that could reduce the particulate emissions. Multiple injections from the direct injectors could be used to minimize the production of particulates.
Engine Shutdown

Employment of an optimized combination of port fuel injection and direct injection during engine shutdown could also be employed. Operation for the few cycles after engine shutdown without use of port injection could reduce the film at the valves and reduces the amount of fuel in the puddle near the inlet valves for the subsequent start.

Other Transients

The control approach described above could also be applied to certain transient conditions during the rest of the drive cycle.

This strategy can also be used for transient operation in vehicles with directly injected spark ignition engines that use engine shutdown and restart for improved efficiency; this stop-start operation is used during vehicle deceleration and idle to improve efficiency by not using the engine when it operates very inefficiently. The strategy can also be used for vehicles with full hybrid powertrains.

In addition to use at cold start and engine shutdown, the optimized port fuel injection - direct injection system discussed above can be useful for operation with certain transients where there is rapid variation in engine speed or torque. This can be especially important at high engine speeds. At high engine speeds, there are issues with mixture formation because of the shortened times, although there is increased turbulence in the cylinders. Direct injection should be minimized because mixture formation issues resulting in particulate emissions. However, since operation at high speed usually is associated with increased temperatures, this need could be reduced by increased particulate matter oxidation occur under these conditions.
Other techniques

While direct injection may be useful for controlling hydrocarbon vapor emissions during cold start and other transients, these emissions can be controlled with conventional means. In contrast, particulate emissions, if not sufficiently reduced by fuel management, could require use of a gasoline particulate filter (GPF), which can result in significant additional complexity and cost. Thus, it may be attractive for the control systems to change the relative amounts of port and direct injected fuel so as to reduce particulate emissions at the expense of more hydrocarbon emissions.

Progress in fueling system technology can make it possible to control the fuel injected in each cylinder. Thus, instead of commanding all the injectors to introduce the same amount of fuel, and same injector timing and other conditions, the fuel injection conditions for each cylinder could be controlled separately. It is known that there are variations of performance of different cylinders, and the computers can now control each cylinder separately. It may be possible, for example, to run some cylinders at different stoichiometries than others, with an overall correct stoichiometry of the air/fuel mixture. It may also be possible during transients, such as cold start or hard acceleration, to change temporarily the overall stoichiometry.

Another option is to use different fuels during cold startup and transients, if available on board. Fuels that can be easily evaporated (fuels that have high vapor pressure, such as alcohols, low heat of evaporation or fuels with low evaporation temperature, or fuels with mostly saturated carbon bonds) can be used to minimize particulate production. The fuel that can be easily evaporated or fuel that have low propensity for making soot (such as methanol or ethanol) can be used during these conditions to minimize particulate matter. Although methanol and ethanol have relatively high heat of vaporization, they have relatively low propensity for making soot, and they have high vapor pressure. The fuels that can be easily evaporated, or
the fuel that has low propensity for making soot can be either provided through external means to a separate container (i.e., external fill) or can be separated on-board from a single fuel that is a mixture of gasoline and alcohol and stored in a separate container. Since only a small amount of fuel is required, the size of the tank and/or the capacity of the onboard separating system can be relatively small.

The ratio of the amount of fuel that is port fuel injected to the fuel that is directly injected can be varied according to the amount of alcohol (ethanol or methanol), if any, that is mixed in with the gasoline. The use of alcohol can reduce particulate mass and number and thus reduce the relative amount of port fuel injection that is needed to reduce particulate emissions. The relative amount of port fuel injection can be decreased when alcohol is mixed with gasoline or the relative amount of alcohol in a mixture with gasoline is increased.

The embodiments that have been described can also be utilized with a supercharged engine or with a direct injection engine that does not use pressure boosting. They can also be used with engines that are operated with a substantially stoichiometric fuel air ratio with or without EGR; and with engines operated with either rich or lean fuel air mixtures.
What is claimed is

1. A turbocharged direct injection spark ignition engine where fuel is introduced into the cylinders by direct injection and also by introduction into the manifold and where the engine is operated at a given time with either both injection into the manifold and direct injection, manifold injection alone or direct injection alone; and where the fraction of the fuel that is introduced into the manifold is decreased so that knock does not occur as torque is increased; and where the fraction of fuel that is introduced into the manifold at a given value of torque and speed is varied so as to reduce particulate emissions at various engine operating conditions.

2. The turbocharged direct injection engine of claim 1, where at cold start or at other transient conditions the fraction of fuel that is introduced into the manifold by port fuel injection is greater than at other times in the drive cycle at the same values of torque and speed.

3. The turbocharged direct engine of claim 2, where spark retard is increased to prevent knock that would otherwise occur.

4. The turbocharged direct injection engine of claim 2, where the amount of spark retard that is used is limited so that engine efficiency or performance does not degrade below selected values.

5. The turbocharged direct injection engine of claim 1, where during cold start, direct injection alone is first used at and immediately after ignition and is then followed by a combination of direct injection and port injection during the cold start period.

6. The turbocharged direct injection engine of claim 2, where the relative amount of fuel that is port injected is determined by a fuel management control system that uses information about parameters that affect the mass and number of particulates that are produced.
7. The turbocharged direct injection engine of claim 2, where the fuel management control system uses information about engine temperature.

8. The turbocharged direct injection engine of claim 2, where the fuel management control system uses information about the time that has elapsed since the fuel in the engine was ignited.

9. The turbocharged direct injection engine of claim 2, where the fuel management control system uses information about the fuel pool in the manifold.

10. The turbocharged direct injection engine system of claim 2, where the fuel management control system uses information about the rate of change in engine torque or speed.

11. The turbocharged direct injection engine system of claim 2, where the fuel management control system uses information about particulate emissions in a closed loop control system.

12. The turbocharged direct injection engine system of claims 2, where the engine is fueled with gasoline.

13. The turbocharged direct injection engine system of claim 2, where the engine is fueled with an alcohol-gasoline mixture.

14. The turbocharged direct injection engine of claims 1 and 2, where the relative amount of port fuel injection is deceased when the gasoline is mixed with alcohol or the amount of alcohol that is mixed with gasoline is increased.

15. The turbocharged direct injection engine of claims 1 and 2, where the fuel management system uses open loop control.

16. A fuel management system for a turbocharged direct injection engine that uses port fuel introduction of varying fractions of the fuel to reduce particulate
emissions while preventing the occurrence of knock as torque increases; and where the fraction of fuel that is introduced at a given value of torque and speed varies with engine condition parameters that affect particulate emission.

17. The fuel management system of claim 16, where spark retard is increased so as to enable a higher fraction of fuel introduction by port fuel injection during a time in the cold start period and where particulate emissions are reduced by the larger fraction fuel that is port fuel injected.

18. The fuel management system of claim 16, where valve timing (inlet valve or valves timing, and exhaust valve or valves timing) are adjusted so as to enable composition (such as increased residuals) or flows that minimize particulate formation, such as by wall wetting of the introduced flows and increase gas temperature of the gas flowing out of the engine through the inlet manifold after inlet valve or valves opening.

19. The fuel management system of claim 16, where spark retard is increased so as to enable a higher ratio of port injection to direct injection during rapid acceleration and where particulate emissions are reduced by the larger relative amount of port fuel injection.

20. The fuel management system of claim 16, where the engine is fueled with gasoline or with a fuel with lower heat of vaporization.

21. The fuel management system of claim 16, where a control system uses information about engine conditions, knock and particulate emissions to control the ratio of fuel that is port fuel injected to fuel that is directly injected.

22. The fuel management system of claim 16, where engine shutdown and restart is used to increase efficiency and where the fuel management system changes the relative amount of fuel that is directly injected to fuel that is port injected so as to reduce particulate emissions.
23. The fuel management system of claim 22, where spark retard is increased so as to enable a greater relative amount of port fuel injection without the occurrence of knock.

24. The fuel management system of claim 16, where the fraction of fuel that is port fuel injected is optimized to minimize particulate mass.

25. The fuel management system of claim 16, where the fraction of fuel that is port fuel injected is optimized to minimize particulate number.

26. The fuel management system of claim 16, where during cold start direct injection alone is initially used and is then followed by a combination of port injection and direct injection.

27. The fuel management system of claim 16, where the direct injection alone is used for the first few cycles and is followed by a combination of port and direct injection.

28. The fuel management system of claim 16, where the engine is operated at a substantially stoichiometric fuel-air ratio.

29. The fuel management system of claim 16, a open-valve port fuel injection is employed.

30. The fuel management system of claim 16 and 29, where port injected fuel is introduced upstream from the turbocharger.

31. A turbocharged direct injection spark ignition engine where fuel is introduced into the cylinders by direct injection and also by introduction into the manifold and where the engine is operated at a given time with either both injection into the manifold and direct injection, manifold injection alone or direct injection alone, comprising a fuel management system which monitors engine conditions and
employs compensation techniques to increase an amount of fuel that is port injected to a level where knock would otherwise occur, so as to reduce particulate emissions.

32. The turbocharged direct injection engine of claim 31, where the compensation technique comprises increased spark retard.

33. The turbocharged direct injection engine of claim 31, where the compensation technique comprises variable valve timing.

34. The turbocharged direct injection engine of claim 31, wherein the compensation technique comprises open-valve port injection.

35. The turbocharged direct injection engine of claim 31, wherein the compensation technique comprises port injection in a region upstream of the turbocharger.
FIG. 1

Engine Control Unit for particulate reduction

Engine Cylinder

Manifold

PFI

DI

FIG. 2

Operator (load demand)

Engine Condition

Engine Control Unit for particulate reduction

Engine Cylinder

Manifold

PFI

DI
**INTERNATIONAL SEARCH REPORT**

**Box No. II**  
**Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. □ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:

2. □ Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. □ Claims Nos.: 14, 15 and 30  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III**  
**Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

1. □ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. □ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. □ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. □ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

- □ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- □ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- □ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (July 2009)
INTERNATIONAL SEARCH REPORT

INTERNATIONAL APPLICATION

PCT/US 13/73334

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F02B 7/00 (2014.01)
USPC - 123/445

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC (8) - F02B 7/00 (2014.01)
USPC - 123/445

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): F02B 7/00 (2014.01) USPC: 123/299,300,304,305,406.21

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST(PGPB,USPT,USOC,EPAB,JPAB); PatBase; Google (Patents, Scholar, Web) Search terms used: direct injection port fuel fraction knock particulate emission soot mass number sensor cold start alone only time manifold fuel pool elapse torque ratio turbocharge retard spark acceleration speed increase decrease open closed loop change stoichiometric m

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
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<tbody>
<tr>
<td>X</td>
<td>US 20110162620 A1 (BIDNER et al.) 07 July 2011 (07.07.2011), entire document, especially para [0005], [0018], [0020], [0029], [0032], [0034], [0037]-[0039], [0041], [0050], [0057], [0058]</td>
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<tr>
<td>Y</td>
<td>US 2012/0024262 A1 (LEONE) 02 February 2012 (02.02.2012), para [0022]</td>
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<td>Y</td>
<td>US 2012/0107203 A1 (ARNOLD et al.) 03 May 2012 (03.05.2012), para [0121]</td>
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<td>Y</td>
<td>US 2012/0102925 A1 (LEONE et al.) 03 May 2012 (03.05.2012), para [0036]</td>
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<tr>
<td>Y</td>
<td>US 6,637,386 B2 (MURATA et al.) 28 October 2003 (28.10.2003), col 5, ln 64 to col 6, ln 9; col 10, ln 28-45</td>
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</tbody>
</table>

Further documents are listed in the continuation of Box C.

Date of the actual completion of the international search: 24 March 2014 (24.03.2014)
Date of mailing of the international search report: 16 APR 2014

Authorized officer: Lee W. Young

Form PCT/ISA/210 (second sheet) (July 2009)
<table>
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<tbody>
<tr>
<td>Y</td>
<td>US 7,647,916 B2 (LEONE et al.) 19 January 2010 (19.01.2010), col 8, In 50-67; col 45, ln 66 to col 46, ln 2</td>
<td>29, 34</td>
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Form PCT/ISA/210 (continuation of second sheet) (July 2009)