(12) UK Patent Application (19) GB (11) 2 293 895 (13) A

(43) Date of A Publication 10.04.1996

(21) Application No 9519789.3

(22) Date of Filing 28.09.1995

(30) Priority Data
(31) 324185 (32) 03.10.1994 (33) US

(51) INT CL^6
F02M 37/08, F02D 41/30

(52) UK CL (Edition O)
G3N NGE1A N288A N404
G3R RBF RB28
U1S S1990

(56) Documents Cited
GB 2272078 A

(58) Field of Search
UK CL (Edition N) G3N NGBB3 NGBX NGE1 NGE1A NGE1B, G3R RBE72 RBF
INT CL^6 F02D 41/30, F02M 37/08
Online: WPI

(71) Applicant(s)
Ford Motor Company Limited

(Incorporated in the United Kingdom)

Eagle Way, BRENTWOOD, Essex, CM13 3BW, United Kingdom

(72) Inventor(s)
James Craig Smith
Edwin Joseph Matysiewicz
Robert Steven Mihora
Darwin Allen Becker

(74) Agent and/or Address for Service
A Messulam & Co
24 Broadway, LEIGH-ON-SEA, Essex, SS9 1BN, United Kingdom

(54) **Returnless fuel delivery system**

(57) A returnless fuel delivery system controls the pressure across the fuel injectors (19A, 19B, 19C) of an internal combustion engine (20) without the use of a mechanical pressure regulator, and without returning any fuel to the fuel tank (14). Injection pressure is controlled using feedback and feedforward dynamic control, and accounts for variations in fuel temperature and supply voltage. The optimum injection pressure is determined by considering both the need to prevent fuel from boiling in the fuel rail (18) and the need to keep the injectors (19A, 19B, 19C) flowing in their linear flow region.

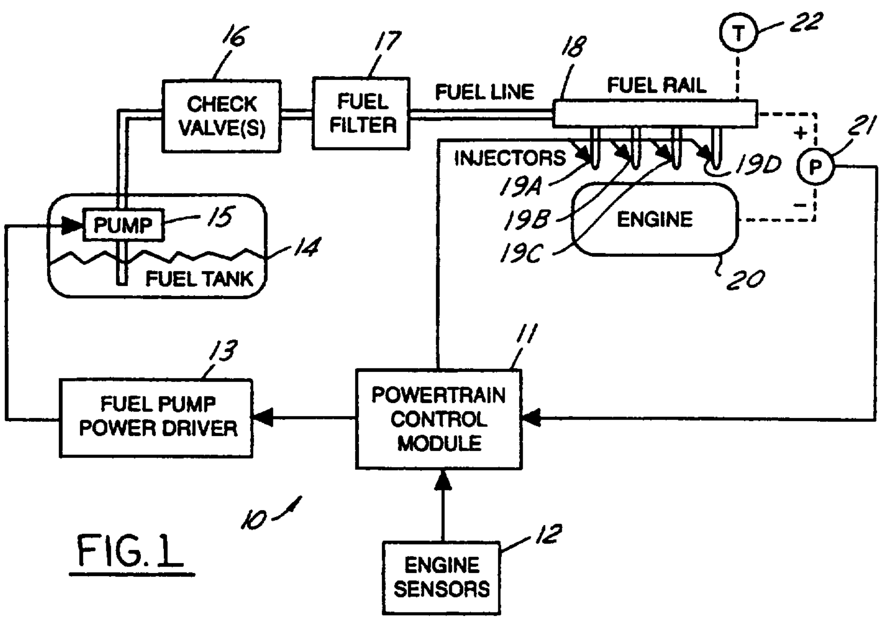

FIG. 1

GB 2 293 895 A

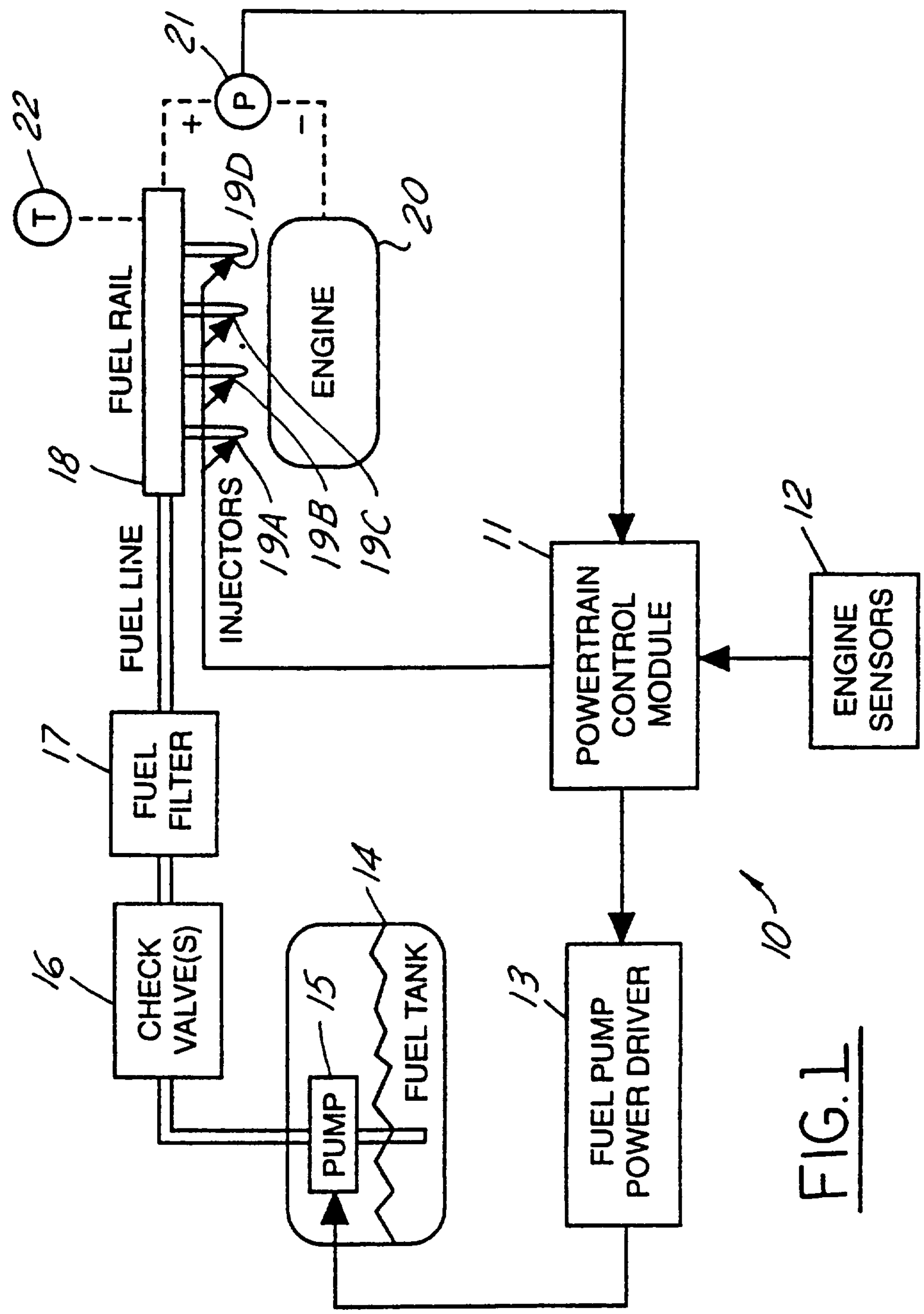
FUEL RAIL
FUEL LINE
INJECTORS
ENGINE
FUEL FILTER
CHECK VALVE(S)
PUMP
FUEL TANK
POWERTRAIN CONTROL MODULE
ENGINE SENSORS
FUEL PUMP POWER DRIVER
T
P
+
−
10
11
12
13
14
15
16
17
18
19A
19B
19C
19D
20
21
22

FIG. 1

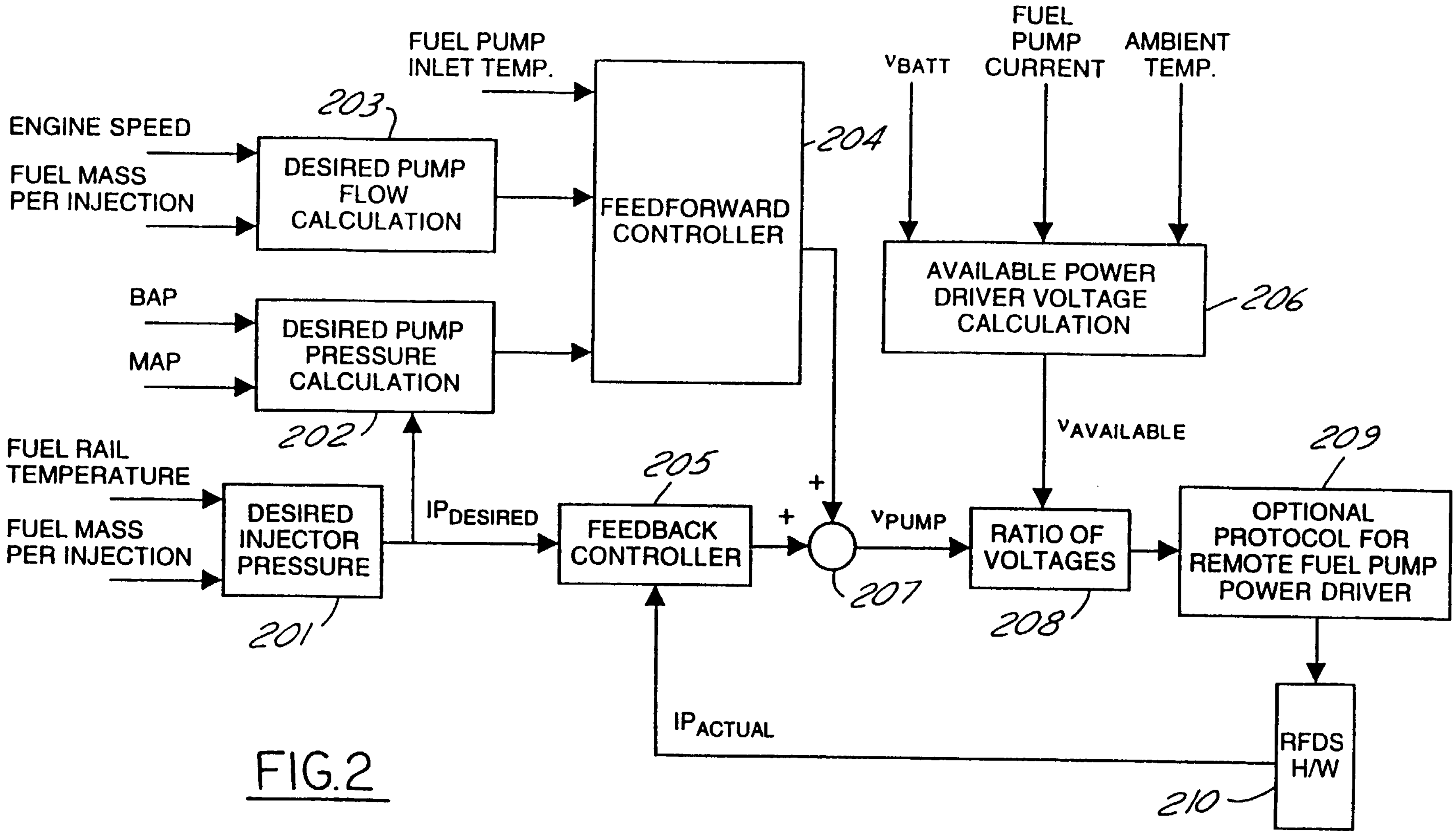
ENGINE SPEED
FUEL MASS PER INJECTION
DESIRED PUMP FLOW CALCULATION
203
FUEL PUMP INLET TEMP.
FEEDFORWARD CONTROLLER
204
BAP
MAP
DESIRED PUMP PRESSURE CALCULATION
202
FUEL RAIL TEMPERATURE
FUEL MASS PER INJECTION
DESIRED INJECTOR PRESSURE
201
IPDESIRED
FEEDBACK CONTROLLER
205
+
+
207
VPUMP
VBATT
FUEL PUMP CURRENT
AMBIENT TEMP.
AVAILABLE POWER DRIVER VOLTAGE CALCULATION
206
VAVAILABLE
RATIO OF VOLTAGES
208
OPTIONAL PROTOCOL FOR REMOTE FUEL PUMP POWER DRIVER
209
RFDS H/W
210
IPACTUAL

FIG.2

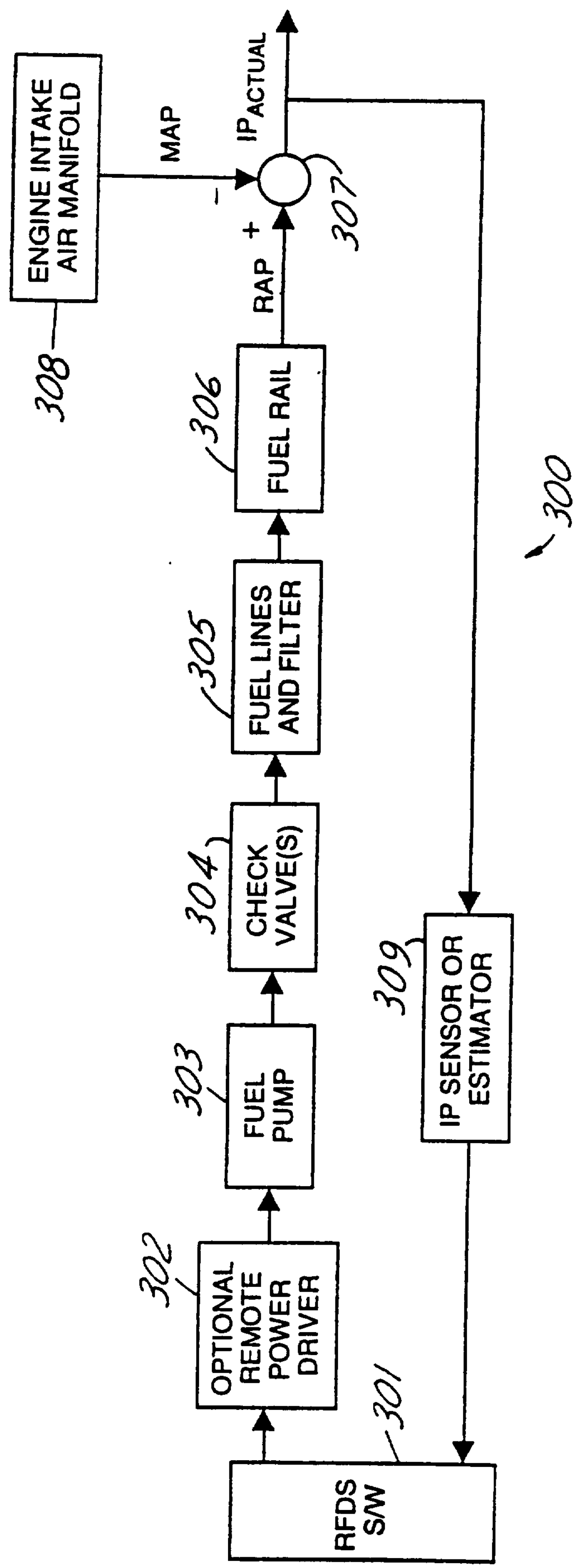
ENGINE INTAKE AIR MANIFOLD
308
MAP
IP ACTUAL
307
RAP
306
FUEL RAIL
305
FUEL LINES AND FILTER
304
CHECK VALVE(S)
303
FUEL PUMP
302
OPTIONAL REMOTE POWER DRIVER
301
RFDS S/W
309
IP SENSOR OR ESTIMATOR
300

FIG.3

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RETURNLESS FUEL DELIVERY SYSTEM

This invention relates to fuel delivery in an internal combustion (IC) engine having fuel injectors.

A returnless fuel delivery system to an IC engine operates without sending fuel back from the engine to the fuel tank. This is advantageous because fuel returning from the engine is typically much hotter than that in the tank, and thus heats the fuel in the tank. This, in turn, creates higher vapour pressures requiring these vapours to be purged out of the tank for ingestion by the engine. If they were not purged to the engine, they would leak to the atmosphere. Moreover, under certain conditions, the rate at which vapours are being created is greater than the rate at which they can be ingested by the engine. This might happen for a four cylinder vehicle coming to an idle after a long fast drive, with high ambient temperatures. This highlights some of the problems of operating a returnless fuel delivery system and the need for blocking the return of fuel to the tank. These are some of the problems this invention overcomes.

A returnless fuel delivery system, in accordance with an embodiment of this invention, uses temperature compensation based on rail absolute pressure to prevent fuel from boiling. This invention provides control of the optimum injection pressure (IP) without returning any fuel from the engine back to the fuel tank, in spite of variations in temperature and supply voltage. Fuel injection pressure control in a returnless fuel delivery system is optimised by accounting for injection mass, prevention of fuel boiling in the fuel rail, supply voltage fluctuations and pump-inlet temperature fluctuations.

The invention will now be described further, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic block diagram of a fuel system in accordance with an embodiment of this invention;

Fig. 2 is a block diagram of logic flow for a fuel delivery system in accordance with an embodiment of this invention; and

Fig. 3 is a block diagram of the hardware connection of a fuel delivery system in accordance with an embodiment of this invention.

Fig. 1 is a basic schematic diagram in accordance with an embodiment of this invention which uses both software algorithms and hardware. The software logic flow of a control scheme 200 is shown separately in Fig. 2.

Referring to Fig. 1, a fuel delivery system 10 includes a powertrain control module 11 which receives inputs from engine sensors 12 and a differential pressure sensor 21 for providing the differential pressure across the fuel injectors. An output from control module 11 is applied to a fuel pump power driver 13 which applies a signal to a pump 15 immersed in a fuel tank 14. Fuel is pumped by pump 15 to check valve 16, a fuel filter 17, and a fuel rail 18 which delivers fuel to fuel injectors 19A, 19B, 19C and 19D. Injectors 19A, 19B, 19C, 19D receive an input from powertrain control module 11 to determine activation. The fuel is delivered to an engine 20. Fuel pressure sensor 21 is coupled across engine 20 and fuel rail 18. A temperature sensor 22 is coupled to fuel rail 18.

Referring to Fig. 2, control scheme 200 includes a feedback controller 205 and a feed forward controller 204 which both apply positive inputs to a summer 207 which then provides a voltage to a block 208 to determine a ratio of voltages. Block 208 also has an input from a block 206 which determines available power driver voltage calculation. Inputs to block 206 include the battery voltage, fuel pump current and ambient temperature. The output of block 208 is applied to a block 209 which provides for optional protocol for remote fuel pump power driver. The output of block 209 is applied to a block 210 which is the returnless fuel delivery system hardware. Block 210 provides the actual injection pressure as an input to feedback controller 205. Feedback controller 205 also receives the desired injection pressure from a block 201 which provides desired injector pressure. Inputs to block 201 include the fuel rail temperature and the fuel mass per injection. Feedforward controller 204 includes an input from a block 203 providing desired pump flow calculation. Block 203 has inputs of engine speed and fuel mass per fuel injection. Feedforward controller 204 has as an input from a block 202 which provides a desired pump pressure calculation and has as inputs barometric absolute pressure (BAP) and manifold absolute pressure (MAP). Feedforward controller 204 also has as an input the fuel pump inlet temperature.

Referring to Fig. 3, a hardware system 300 has a block 301 which provides for returnless fuel delivery system software and provides an input to a block 302 which is an optional remote power driver. The output of block 302 is applied to a block 303 which is a fuel pump. The output of fuel pump 303 is applied to check valves 304. The output of check valves 304 is applied to fuel lines and filter 305, a fuel rail 306 and a summer 307. Summer 307 also receives an input from engine intake air manifold 308 as a negative input. A positive input from fuel rail 306 to summer 307 is the rail absolute pressure. A negative input from engine intake air manifold 308 is the manifold absolute pressure. The output of summer 307 is the actual injection pressure. This output is applied to block 309 which is the injection pressure sensor or estimator.

Control scheme 200 includes an algorithm to determine the optimum IP at which the system is to control. The optimum reference pressure or desired IP ($IP_{desired}$) then drives a feedback controller 205 whose purpose is to compare the actual IP (IP_{actual}), which is either measured or estimated, to this reference. Any error between these two values excites controller 205 which responds by appropriately varying the command voltage to the fuel pump via Pulse Width Modulation (PWM) or a continuously varying analogue voltage.

To assist the feedback leg of the control, a feed forward controller 204 is added to control scheme 200. This feed forward may be either static, as a look-up table or algebraic polynomial, or it may be dynamic, as a set of differential equations. This feed forward will take, as inputs, desired engine fuel intake flow rate, and the desired pressure across the fuel pump, and possibly fuel pump inlet temperature. The engine fuel intake rate may be calculated by combining engine RPM and the fuel mass per injection scheduled for injection into the engine. Pump inlet temperature may be either measured or estimated.

The desired pressure across the fuel pump ($\Delta\rho_{pump}$) may be closely approximated as the absolute pressure at the fuel rail (Rail Absolute Pressure or RAP) minus Absolute Fuel Tank Pressure (AFTP). Specifically this is:

Equation 1. $\Delta\rho_{pump} \equiv RAP - AFTP$

Equation 2. $RAP = IP + MAP$

where IP = Injector pressure, and

MAP = engine air intake Manifold Absolute Pressure.

Eq. 2 may be used, or RAP may be measured directly or estimated. AFTP also may either be measured directly, indirectly, estimated or approximated. If Barometric Absolute Pressure (BAP) is known along with Relative Fuel Tank Pressure (RFTP) referenced to BAP, then:

Equation 3. $AFTP = RFTP + BAP$

A RFTP sensor can be used and, for the typical application, where $\Delta\rho_{pump}$ is on the order of 40 psi, and RFTP is on the order of ±0.5 psi maximum, accounting for RFTP makes little difference. Thus:

Equation 4a. $AFTP \equiv BAP$

Equation 4b. $\Delta\rho_{pump} \equiv RAP - BAP$

Equation 4c. $\equiv (IP + MAP) - BAP$

MAP can be estimated from other engine parameters or can be measured.

The result of the feed forward calculation at block 204 is a pump voltage that for the nominal RFDS, will result in the desired IP to be produced at the fuel injectors, without any feedback. This helps to off load control effort needed from the feedback algorithm, and allows for lower, less oscillatory feedback gains to be used without sacrificing IP control performance. The feedback and feed forward pump control voltages are summed at a summer 207 to result in the voltage command (v_{pump}) that is issued to the fuel pump.

To simultaneously account for fluctuations in supply voltage and determine the duty cycle to control the fuel pump, v_{pump} is divided by the voltage actually available ($v_{available}$) at the pump power driver so:

Equation 5. duty cycle command to pump = $v_{pump} / v_{available}$

where $v_{available}$ = vehicle battery voltage (v_{batt}) minus the voltage drop between the battery and the power driver. This duty cycle must be limited to values between 0(0%) and 1(100%), since values outside this region hold no physical meaning.

In the case where the pump driver is a remote unit separate from powertrain control module (PCM) 11 of Fig. 1, it is advantageous to use a duty cycle protocol that can run the pump from 0% to 100% duty cycle, without letting 0% and 100% be actual signals traversing the electronic signal command line between the PCM and power driver 13. This prevents certain failure modes from being interpreted by power driver 13 as normal conditions. Specifically, if the command line were to be shorted to ground, this would look like 0%, and a short to power would look like 100%.

For the case where PCM 11 contains sufficient power driver capabilities, the fuel pump control may be issued directly without any protocol. Or PCM 11 may send out an analogue voltage to drive the pump instead of using pulse width modulation.

The remainder of the RFDS control loop is hardware as shown in Fig. 3. The power-level control voltage arriving at the fuel pump's input causes the pump's armature to rotate at a given speed which produces a corresponding fuel flow at a given head pressure. This pressure propagates forward through the (bi-directional) check valve, fuel lines and filter, up to the fuel rail where it is metered out by the fuel injectors for ingestion by the engine. To provide cushion in this pressurised lines, a pulsation damping device may be included to reduce higher frequency pressure waves. The resulting RAP from this command fuel flow influences IP as shown in Eq. 2 which here is rewritten for clarity as Eq. 6.

Equation 6. $IP = RAP - MAP$

IP_{actual}, either measured or estimated, is then used to close the control loop when it is compared to $IP_{desired}$ in software.

The function of a check valve in the fuel line between the fuel pump and the fuel rail, is to keep the fuel line full of fuel when the pump and engine are not running. This allows for shorter engine start-up crank times. This check valve will open when the pump output pressure is roughly 1 psi higher than the down stream pressure.

An optional second check valve could be placed in parallel to the first, only facing the opposite direction. This second valve would allow large rail pressures (relative to the pump's output pressure) to vent in order to prevent damaging the hardware. This valve would open when rail pressure is in excess of the pump output pressure by roughly 40 psi. This setting satisfies both the need for keeping fuel in the line during engine-off conditions, and the need for protection against large over pressures usually encountered in an engine-off hot soak condition.

CLAIMS

1. A method for controlling a returnless fuel delivery system for an internal combustion engine having fuel injectors supplied by a fuel pump through a fuel rail, the fuel pump being driven by a fuel pump power driver, including the steps of:

controlling the pressure across the fuel injectors using a temperature compensation strategy based on a function of fuel rail absolute pressure, which determines if the fuel will enter a gaseous state.

2. A method as claimed in claim 1, wherein the step of controlling the pressure across the fuel injectors further includes using an actual switching voltage available to drive the fuel pump.

3. A method as claimed in claim 2, further including the step of:

optimising a desired fuel injection pressure based on fuel mass per injection.

4. A method as claimed in claim 3, further including the step of:

controlling the actual injection pressure as a function of voltage needed at the fuel pump so that controlling the actual injection pressure is less sensitive to the voltage available at the fuel pump power driver.

5. A method as claimed in claim 4, further comprising the step of:

providing feedforward control as a function of desired pump flow, the desired pressure across the fuel pump and fuel pump inlet temperature.

6. A returnless fuel delivery system for an internal combustion engine having fuel injectors supplied by a fuel pump through a fuel rail, the fuel pump being driven by a fuel pump power driver, the returnless fuel delivery system including;

input means to the returnless fuel delivery system for providing engine speed, fuel mass per injection, barometric absolute pressure, manifold absolute pressure, fuel rail temperature, fuel mass per injection, and fuel pump inlet temperature battery voltage, fuel pump current, and ambient temperature;

a means for performing a desired pump flow calculation coupled to receive the engine speed and fuel mass per injection inputs;

a means for performing a desired pump pressure calculation for receiving input of barometric absolute pressure and manifold absolute pressure;

a means for determining a desired injector pressure for receiving fuel rail temperature and fuel mass injection;

said means for determining a desired injector pressure producing an output of desired injector pressure applied to said means for determining a desired pump pressure calculation;

a feedback controller means receiving the desired injection pressure;

a feed forward controller means receiving the fuel pump inlet temperature input and outputs from said means for determining a desired pump flow calculation and means for determining a desired pump pressure calculation;

a summer means for receiving the outputs of said heat forward controller and said feedback controller;

a means for performing an available power driver voltage calculation for receiving inputs of battery voltage, fuel pump current, and ambient temperature;

a means for determining a ratio of voltages having inputs from the output of the means for determining the available power driver voltage calculation and the summer means;

a means for producing an optional protocol for a remote fuel pump power driver receiving an input from the means for producing a ratio of voltages;

said returnless fuel delivery hardware system receiving an input from the means for determining optional protocol for remote fuel pump power driver; and

said feedback controller also receiving an input of the actual injection pressure from said returnless fuel delivery system hardware.

7. A returnless fuel delivery system including:

a fuel pump for providing pumped fuel to the engine;

a fuel rail and fuel line combination coupled to the fuel pump for providing fuel to fuel injectors for the engine;

a fuel rail pressure sensor for determining rail absolute pressure;

a manifold absolute pressure sensor for determining engine intake air manifold pressure;

a summer for receiving manifold absolute pressure as a negative input and the rail absolute pressure as a positive input and producing an output indicating actual injection pressure;

an injection pressure sensor or estimator receiving the input of the actual injection pressure;

a returnless fuel delivery system software processing means receiving an output from the injection pressure sensor means for generating an output to be applied to determine operation of the fuel pump; and

a remote power driver coupled to receive an input from the returnless fuel delivery system software processing means for generating an output to drive said fuel pump.

8. A returnless fuel delivery system as claimed in claim 7, wherein said returnless fuel delivery system software processing means includes means for controlling the pressure across the fuel injectors as a function of a temperature compensation strategy bases on a fuel rail absolute pressure, which determines if the fuel will enter a gaseous state.

9. A returnless fuel delivery system as claimed in claim 8, further including a means for controlling the actual injection pressure as a function of voltage needed at the fuel pump so that controlling the actual injection pressure is less sensitive to the voltage available at the fuel pump power driver.

10. A method for controlling a fuel delivery system of an internal combustion engine substantially as hereinbefore described with reference to the accompanying drawings.

11. A fuel delivery system for an internal combustion engine substantially as hereinbefore described with reference to the accompanying drawings.

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Patents Act 1977 Examiner's report to the Comptroller under Section 17 (The Search report)	Application number GB 9519789.3
Relevant Technical Fields (i) UK Cl (Ed.N) G3N (NGE1, - A, - B NGBB3 NGBX) G3R (RBF, RBE72) (ii) Int Cl (Ed.6) F02D (41/30) F02M (37/08)	Search Examiner MR D A SIMPSON Date of completion of Search 8 NOVEMBER 1995
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) WPI	Documents considered relevant following a search in respect of Claims :- 1 TO 11

Categories of documents

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P: Document published on or after the declared priority date but before the filing date of the present application.

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&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 2272078 A	(FORD) page 5 lines 11 to 19	1, 7 & 8 at least

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