

Sudden Acceleration in Vehicles with Common Rail Diesel Engines

by

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Abstract: An explanation is given for sudden unintended acceleration (SUA) in vehicles with common rail diesel engines. SUA is explained by an increase in the gain of the common rail pressure controller that leads to more fuel being injected into the engine than the throttle map specifies. The gain increase is caused by an erroneous battery voltage compensation coefficient produced by a negative voltage spike occurring while the battery voltage is being sampled. The erroneous battery voltage compensation coefficient increases the fuel injected into the engine, causing an increase in the engine speed, which causes the next iteration of the throttle map to issue a new common rail pressure set-point that is even higher than the previous one. The result is a runaway engine speed without the driver's foot being on the accelerator pedal. No diagnostic trouble code (DTC) is produced because all the engine sensors and actuators are working normally except for the battery voltage compensation coefficient, and this compensation coefficient is not checked for an erroneous value. This explains why a majority of SUA incidents occur while the engine is at idle in a parking lot or at stop sign because this is the only time that the battery voltage can be determined by sampling the supply voltage. It also explains why the high engine speeds go away when the ignition is turned off and the engine is restarted, because a new battery voltage sample is taken after restarting that is not affected by a random negative voltage spike. Finally, the SUA incident rate of 2×10^{-4} incidents per year is explained by the probability that a negative voltage spike occurs while the supply voltage is being sampled.

I. Introduction

Antony Anderson has observed that: 1) black smoke was emitted during two Montero SUA incidents, but 2) was not emitted in Mitsubishi's demonstration of the ability to control the Montero during sudden acceleration or in simulations of SUA by Jake Arello. From these two observations Antony Anderson deduced that the emission of black smoke is a unique symptom associated with Montero SUA. More symptoms associated with Montero SUA are listed in Table 1.

Table 1. Symptoms observed during Montero SUA

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| <ol style="list-style-type: none">1. Black smoke is produced when the engine is under heavy load. This is confirmed by videos of two Montero SUA incidents.2. Black smoke is not produced by the engine during normal operation. This is confirmed by Mitsubishi's demonstration of SUA and by Jake Arello's simulation of SUA.3. Engine runs at an unusually high engine speed – several thousand RPM4. Everything returns to normal when the ignition is turned off and then the engine is restarted.5. SUA often occurs when the transmission is shifted out of PARK and into either DRIVE or REVERSE.6. SUA occurs intermittently. It does not always occur every time engine is started.7. The accelerator pedal does not have to be pressed to cause the engine to run at high speed. Drivers often state that their foot was not on the accelerator pedal. Many claim further that their foot was on the brake pedal.8. No DTC's are found after a SUA incident.9. SUA normally occurs in parking lots and other driving situations like approaching a stop sign, when the engine speed is low or at idle. |
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Black smoke is particulate matter or soot, which means incomplete combustion of fuel. This means that the air-to-fuel ratio during SUA is incorrect. Therefore, during SUA there is either too much fuel or not enough air. If we combine this deduction with the third observation in Table 1 – that the engine runs at an unusually high engine speed of several thousand RPM during SUA – then we can deduce that the black smoke during SUA is caused by too much fuel, and not by the lack of air. Too much fuel can cause a higher engine speed as well as black smoke. But too much air cannot cause a higher engine speed unless it also accompanied by more fuel. And too much air cannot cause black smoke. This means that the cause of Montero SUA is in the fuel injection system and not in the air delivery system, which includes the turbo and EGR systems.

We can also deduce from observation 4) in Table 1 that the fuel injection system problem goes away when the ignition is turned off and the engine is restarted again. This means that the fuel injection problem during SUA is not a permanent fault, because engine operation returns to normal after the ignition is turned off and the engine is restarted. This strongly implies that the fuel injection system problem is not mechanical, but electrical in origin. If the problem were mechanical, then it almost certainly would have set a DTC, because OBD-II regulations require that diagnostic tests must be performed by the engine management system to verify the proper operation of all engine components whose failure can cause higher emissions. But no DTC's are ever found after an SUA incident. This means that every sensor and actuator in the fuel injection system must be operating normally, both during the SUA incident and after the SUA incident when the ignition is turned off and then back on again.

If all the sensors and actuators in the fuel injection system are operating normally both during the SUA incident and after the SUA incident when the ignition is turned off and then back on again, then what could cause the operation of the fuel injection system to be faulty? The answer is: It has got to be a problem in how the data is transferred between these components that causes the sudden acceleration. This data transfer is specified by the design of the engine's fuel injection control system. This means that the problem lies in the ECU, where this control system resides. And this fuel injection control system problem must be intermittent in nature, and not permanent. This means that it can be either a software problem, an EMI problem, or some other problem electronic in origin. The problem cannot be exclusively a random problem because according to observation 5) in Table 1, SUA almost always occurs when the transmission is shifted out of PARK and into either DRIVE or REVERSE. So an exclusively random problem cannot be the cause of SUA because then SUA would occur at any random time, such as while driving at high engine speeds. Somehow, the fuel injection system fault must depend upon the state of the engine control system at a given time. And it must go away when the engine is turned off and then turned back on again. What could cause such a subtle change in the operation of the fuel injection control system? To answer this question we will take a closer look at how the Montero fuel injection system is designed to operate.

II. Montero Common Rail Fuel Injection Control System Design

Figure 1 shows the design of a common rail fuel injection control system. It consists of two engine controllers that control the amount of fuel injected into the engine cylinders¹: 1) a closed-loop negative feedback idle controller that is used in the PARK/NEUTRAL mode to maintain a constant engine RPM, and 2) an open-loop feed-forward engine speed controller without feedback that is used in the DRIVE/REVERSE mode to control the engine torque. The closed-loop negative feedback idle controller maintains a constant engine speed while in PARK/NEUTRAL by decreasing the engine speed when it goes above the normal set-speed (usually 800 RPM) and by increasing the engine speed when it goes

¹ In a Diesel engine, the engine speed is controlled by metering the amount of fuel injected into the engine while the throttle is held nearly wide open at all times. In a gasoline engine, the engine speed is controlled by metering the amount of air entering the engine using an electronic throttle while adjusting the amount of fuel needed to maintain an optimum air-to-fuel ratio.

below the normal set-speed. Since the engine speed does not stay constant while in DRIVE/REVERSE, a different controller must be used in DRIVE/REVERSE that responds to the driver's intent. In DRIVE/REVERSE the amount of torque produced by the engine (which can be anything from zero to the maximum engine torque) is controlled by an open-loop feed-forward controller that gets its instructions from the driver by pressing his foot on the accelerator pedal. The accelerator pedal position (APP) sensor detects how much the driver is pressing on the accelerator pedal, and uses this value (normalized to 0 to 100%) to select a requested torque from the driver demand map, which is a table of torque values versus APP sensor value and engine speed.² The requested torque is then modified by idle-ups that increase the engine torque to offset loads placed on the engine by vehicle accessories such as the air conditioner and the alternator, and the adjusted torque is then used to select a rail pressure set-point value from a map of rail pressure versus engine torque and engine speed. This rail pressure set-point is then used as the input to a PID controller whose output determines the common rail pressure by pulse width modulation (PWM) of the common rail pressure control valve. An increase or decrease in the common rail pressure causes an increase or decrease in the engine speed and torque.

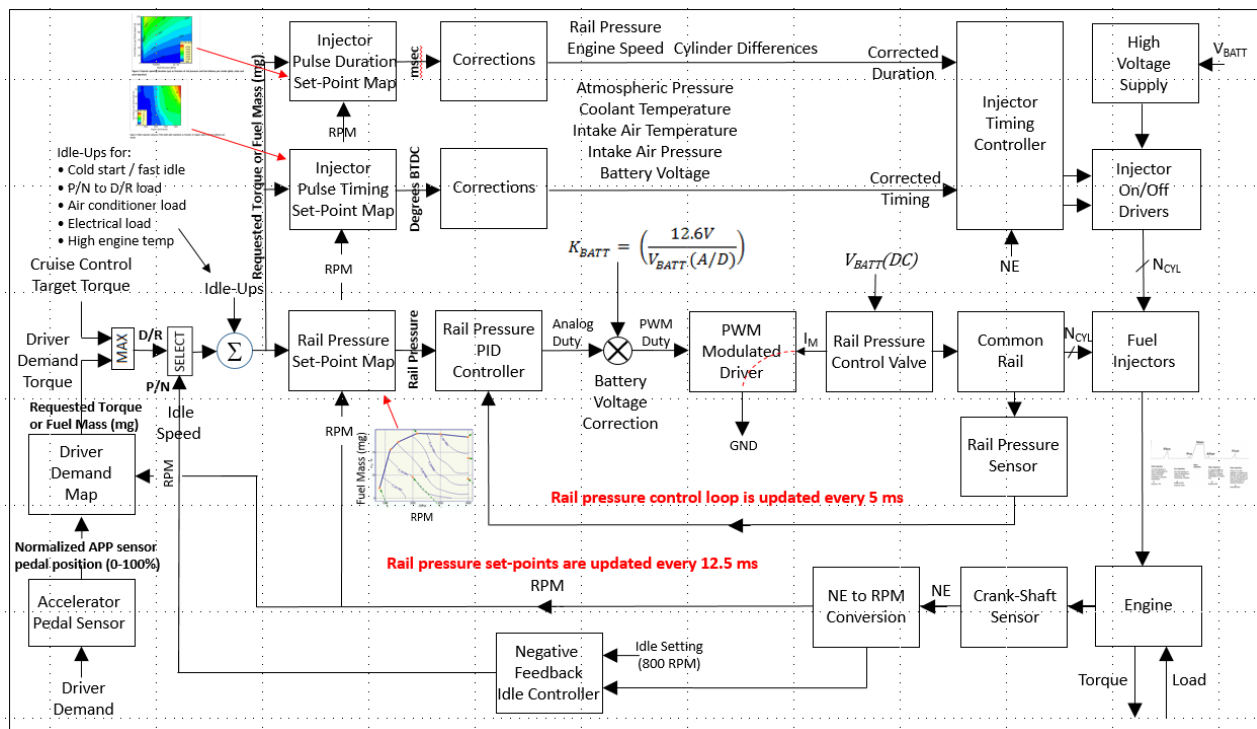


Figure 1. Common rail fuel injection control system design. The control system consists of an open loop feed-forward controller in the D/R mode and a closed loop negative feedback controller in the P/N mode. The figure is based on information from a variety of sources, including Denso common rail brochures, Mitsubishi repair manuals, control system research papers, auto maker's patents, and auto industry educational material. It is more informative than the ECU software because it provides an overview of how the engine is controlled all the way from the accelerator pedal to the engine output.

In parallel with controlling the rail pressure of the fuel injection pulse, two other controllers determine the timing and duration of the fuel injection pulse. These values must be synchronized with the opening and

² Maps, or look-up tables, are used as a speedier alternative to calculating outputs by substituting inputs into complex formulas. Two maps are used because they allow tailoring the engine response to accelerator pedal input to achieve faster or slower response as driving conditions require. Instead of torque, the two maps can use the value of fuel mass in milligrams, since torque is almost linearly proportional to the fuel mass in milligrams. Older control systems use fuel mass, while newer control systems use torque, which provides more insight into engine operation and which simplifies the design of the control system.

closing of the cylinder valves, which depend upon the engine speed. In a common rail engine this control is done electronically by turning the fuel injectors on and off at the appropriate times relative to the top dead center position of the moving pistons as determined by look-up tables of timing and duration versus requested torque and engine speed. In older fuel injection systems, like Volkswagen's TDI injection system, the timing and duration of the fuel injection pulses was controlled mechanically by cam-operated injector valves. The change to electronically controlled timing and duration allows more precise control over the fuel injection pulses, which allows the use of multiple pulses to aid in the control of smoke, NO_x and engine noise. Newer common rail controllers provide up to five pulses per fuel injection event as shown in Figure 2. The main injection pulse controls the engine speed and torque while the smaller pulses control the smoke (particulate matter or PM), NO_x, and engine noise.

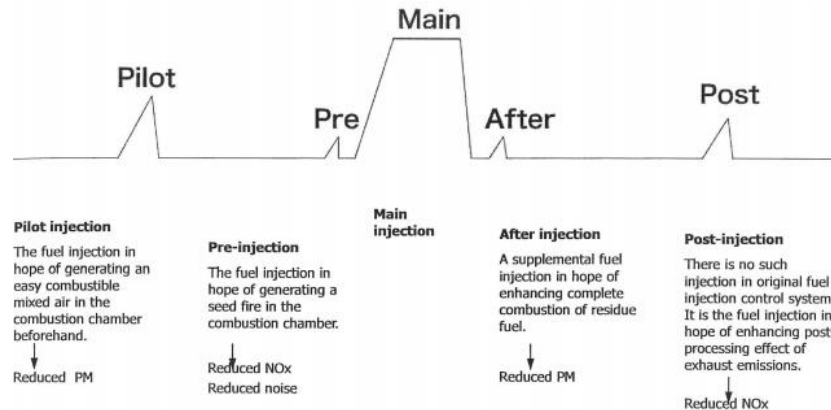


Figure 2. Modern common rail controllers provide up to five injection pulses per injection event. The duration of the smaller pulses can be as short as 250 microseconds, while the duration of the main pulse can vary from 500 microseconds to five milliseconds. Only the main pulse controls the engine torque and speed.

One can see that maps or look-up tables are used to control the pressure, timing, and duration of the fuel injection pulses. These maps are all a function of the desired engine torque and the current engine speed. The map for the common rail pressure is shown in Figure 3, and the maps for the timing and duration are similar. Values of pressure, timing, and duration for engine speeds and torques lying in between the values on the map axes are determined by two-dimensional interpolation. The values in the maps are determined by a process called map calibration, which is done by an engineer during engine design and again for each model vehicle using the same engine design. This tuning is done with such care that the map values are sensitive to the battery voltage used for the actuators unless the actuators are compensated for the battery voltage as shown in Figure 1. This is because the rail pressure control valve opening depends upon the current through the control solenoid, which varies with the battery voltage. A higher current means a higher rail pressure and thus a higher engine torque and speed. Therefore, one must compensate for variations in the battery voltage by multiplying the PWM duty cycle of the control valve by the inverse of the battery voltage normalized to some constant battery voltage, such as 12.6 volts. Similarly, the injector timing and duration can change with battery voltage because the start of injection and the pulse duration vary with battery voltage. These can be compensated by starting the injection at an earlier or later time or by changing the pulse duration as determined by a look-up tables of timing or duration compensation values versus battery voltage.

One might wonder why the actuators are sensitive to changes in the battery voltage, when the supply voltage that powers them while the engine is running is set by the alternator voltage to a constant between 13.6V to 14.4V and not by the battery voltage, which is 12.6V or lower. Is this just a sloppy use of the term “battery voltage” instead of “alternator voltage”? The answer is no. All auto makers specifically

mean that the actuators are sensitive to the battery voltage. This is because the response time of the actuators must be very fast, on the order of one millisecond, in order to control the fuel injectors properly at all engine speeds. This means that the current through the actuators must change very rapidly, or within about one millisecond. But the alternator cannot change its output current this rapidly because to do so it must first change the magnetic field through which the output coil rotates, and the response time of the magnetic field is limited to 150 milliseconds or longer by the resistance/inductance (R/L) ratio of the field current windings. Therefore, when the actuators need a larger current within one millisecond, they cannot get the larger current they need from the alternator, and so must draw the larger current from the battery. When this happens, the battery is setting the voltage through the actuator. So the actuators are indeed sensitive to battery voltage just as stated by the auto manufacturers.

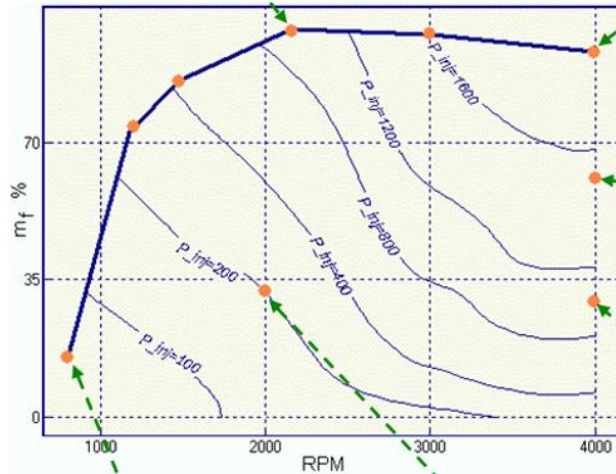


Figure 3. Map of common rail pressure versus requested fuel mass (or torque) and engine speed. The heavy curve of maximum torque (or fuel mass) for any given RPM is identical to the engine torque curve advertised by the auto manufacturer. This map is sometimes referred to as an inverse engine map because it is used to obtain the rail pressure from the requested engine torque, while the engine map is used to obtain the engine torque from the applied rail pressure. But they are the same map, just used differently.

This raises an interesting question about how to measure the battery voltage in order to compensate the actuators for changes in the battery voltage. If the supply voltage is set by the alternator while the engine is running, then merely taking an analog-to-digital (A/D) sample of the supply voltage at any time will yield the alternator voltage and not the battery voltage. To get the battery voltage, one must use the fact that the alternator output current varies with engine RPM. One can then sample the supply voltage while the alternator is running at a low enough RPM that the alternator cannot supply all the DC current required by the vehicle at the time. In this case, the battery must provide the required current, and the supply voltage is set by the battery voltage, allowing the sampling of the supply voltage to yield the battery voltage. Now this gets very interesting, because this means that one can sample the battery voltage only while the engine is at idle. One cannot sample the battery voltage while the engine is running at a higher speed because then one gets the alternator voltage instead of the battery voltage. Therefore, to make battery voltage corrections at higher engine speeds one must store the battery voltage measured while the engine is at idle and continue to use this battery voltage until the engine is once more at idle, when the supply voltage can again be sampled to yield the battery voltage. This provides an explanation for why most SUA incidents occur in a parking lot or at a stop sign while the engine is at idle, yet why SUA incidents can occur for very long times at high engine speeds. It is impossible to continuously measure the battery voltage. The best one can do is measure it at low engine speed and then store the measured value so it can be used at higher engine speeds.

So, what can go wrong when the battery voltage is being sampled while the engine is at idle? Well, there is a lot of noise on the “12V” power supply line while the battery is being sampled. The largest supply voltage variations are caused by negative-going voltage spikes produced by the inrush currents of electric motors turning on, such as air conditioner compressors, power brake accumulator air compressors, electric power steering motors, and radiator fan motors. When these motors turn on, they produce a temporary short to ground that lasts approximately 100 microseconds and that pulls the battery supply line down as low as 6 volts or even as low as 2 volts or less in some cases. When the battery state of charge is low, these negative voltage spikes can be even lower. If one of these voltage spikes occurs while the supply voltage is being sampled by an A/D converter in the ECU (sample time is ~50 microseconds), then the A/D converter will read the value of the negative voltage spike instead of the true battery voltage. The battery voltage compensation coefficient obtained from this incorrect battery voltage will therefore be the erroneous value of $12.6/V_{\text{negative voltage spike}}$ instead of the normal $12.6/V_{\text{BATT}}$, causing the battery voltage compensation coefficient to be increased by a factor of $V_{\text{BATT}}/V_{\text{negative voltage spike}} = 2$ to 6 times. To make matters worse, this larger erroneous battery voltage compensation coefficient multiplies the actuator output corresponding to the normal battery voltage of 12.6 volts because the DC voltage to the actuator does not change as a result of a short 100 microsecond negative voltage spike. This means that the actuator output is increased by 2 to 6 times its normal amount. And since the same battery voltage compensation coefficient must be used while the engine speed remains high, this 2 to 6 times increase in the actuator output can last a long time.

So here we have a mechanism that increases actuator outputs by a factor of 2 to 6 without causing an actuator fault. Specifically, this mechanism can cause an increase in the gain of the rail pressure control actuator, which increases the rail pressure, and thus the engine torque and speed, producing SUA. This gain increase is caused by an erroneous battery voltage compensation coefficient which is not the subject of a diagnostic test of the vehicle actuators, corresponding to the failure to register a DTC. And the mechanism producing the erroneous battery voltage compensation coefficient starts while the engine is at idle by the erroneous sampling of the battery voltage during a negative voltage spike. This corresponds to the SUA starting at low engine speeds while the engine is at idle in parking lots or at stop signs. The erroneous battery voltage compensation coefficient resulting from this incorrect voltage lasts until the engine is turned off and the engine is restarted again. When the engine is restarted, a new sample of the battery voltage is taken that may not be affected by a negative voltage spike. Therefore, the engine runs normally once more. This corresponds to the failure of auto dealers to reproduce the SUA in their auto repair shops.

This mechanism is consistent with SUA occurring simultaneously with shifting out of PARK or NEUTRAL and into either DRIVE or REVERSE because the higher gain of the rail pressure controller is offset by the negative feedback of the closed loop idle controller while in PARK or NEUTRAL. But when the transmission is shifted out of PARK or NEUTRAL and into either DRIVE or REVERSE, then a new open-loop feed-forward controller takes control that does not have any negative feedback capability. If the open-loop controller gain is erroneously larger than normal, then the engine speed is higher than that expected by the rail pressure set-point map. The higher engine speed then acts like a parasitic positive feedback to the map which causes an even larger rail pressure set-point to be selected on the next iteration of the map. This happens with each 12.5 millisecond iteration of the set-point map, causing the rail pressure control set-point to run away to the largest value in the set-point map in less than one second (80 iterations). This produces the high engine speed that surprises even the driver during an SUA incident. This all happens without the driver touching the accelerator pedal.³

³ Control theory experts know that when an open-loop feed-forward controller uses an inverse map, then the inverse map must be the exact inverse of the process being controlled, or the controller will not provide the proper control. This means that the once the map has been calibrated, then the process being controlled must not change. But in the case of SUA, the process being controlled changes when an erroneous battery voltage compensation coefficient causes the process gain to increase. Therefore, the inverse

The process causing a runaway of the engine speed is explained more clearly in Figures 3 and 4. Figure 3 shows the normal operation of the set-point map in the open-loop feed-forward engine controller. Normally, when the driver requests a higher engine torque via pressing on the accelerator pedal, the rail pressure set-points are selected from the dark blue envelope curve based on driver's request for torque and the current engine speed, producing the upward-going trajectory A-B. When the driver releases the accelerator pedal, the rail pressure set-points are selected from the downward-going curve B-A to allow the engine speed to slowly decline instead of going back to idle abruptly. Figure 4 shows what happens during a sudden acceleration incident. During a sudden acceleration incident the rail pressure set-points follow the horizontal curve A-B to cause the engine speed to increase to the maximum speed in the map in less than one second without the driver pressing on the accelerator pedal. When a load is placed on the engine by the vehicle encountering an obstacle or by the brakes, the engine speed decreases and the engine torque increases along the constant pressure curve B-C causing the vehicle to jump over obstacles and causing the driver to feel that the brakes are acting like an accelerator.

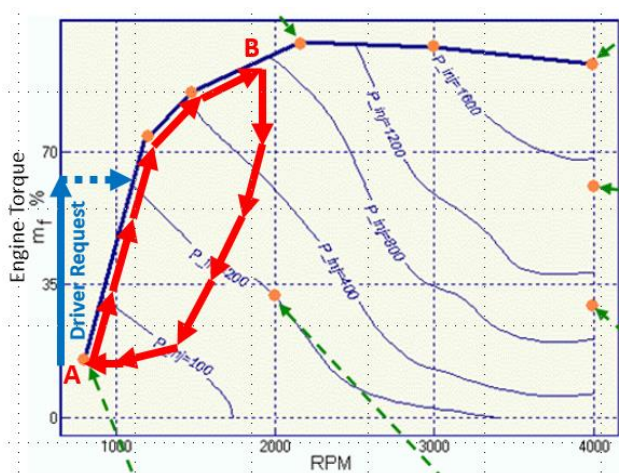


Fig 3. During normal operation of the rail pressure map the pressure set-points are obtained from the upward-going dark envelope curve A-B during acceleration according to the driver's request for torque via pressing the accelerator pedal, and from the downward-going curve B-A during deceleration when the accelerator pedal is released.

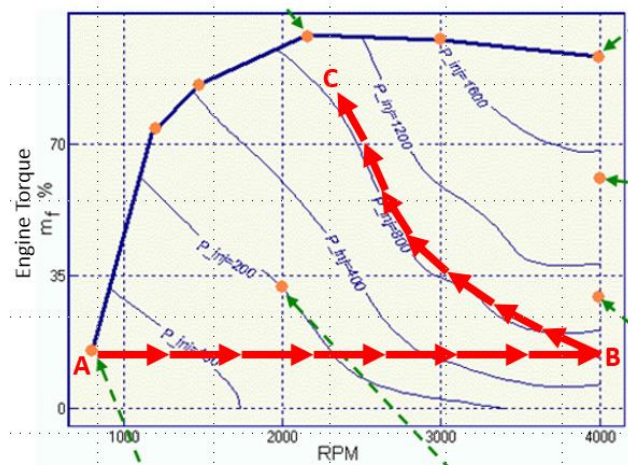


Fig 4. During sudden acceleration the pressure set-points follow the horizontal curve A-B to cause the engine speed to increase to the maximum speed in the map in less than one second without the driver pressing on the accelerator pedal. When a load is placed on the engine by the vehicle encountering an obstacle or by the brakes, the engine speed decreases and the engine torque increases along the constant pressure curve B-C causing the driver to feel that the brakes are acting like an accelerator.

This SUA mechanism can even explain the SUA incident rate observed in a population of vehicles over a given time. If the battery voltage is sampled one to two minutes after the engine is started, as shown in Figure 5, then the probability of sudden acceleration occurring is related to the likelihood that a randomly occurring negative voltage spike occurs during the 50 microsecond long sampling time. We can estimate this probability by counting how many 50 microsecond sampling times occur during an interval of one to two minutes, and then multiplying this result by the number of times the vehicle is started in one year, which we can assume to be once a day. The result is:

map is no longer the exact inverse of the process being controlled, and the open-loop feed-forward controller gives an incorrect output, which causes the engine speed to run away to the maximum speed in the map.

$$\frac{50 \text{ us}}{120 \text{ sec}} \left(\frac{365 \text{ events}}{\text{year}} \right) = 1.5 \times 10^{-4} \text{ events/year-vehicle, or } 0.015\% \text{ events/year-vehicle.}$$

This result can be compared to the incident rate for sudden acceleration in Mitsubishi Montero's, which show that approximately 97 Montero SUA incidents have occurred over the past six years from 2010 to 2015:

$$\frac{97 \text{ events}}{60,000 \text{ vehicles}} \left(\frac{1}{6 \text{ years}} \right) = 2.7 \times 10^{-4} \text{ events/year-vehicle, or } 0.027\% \text{ events/year-vehicle.}^4$$

Both of these estimates can be compared to the statistics¹ for sudden acceleration events found for most gasoline-powered vehicles, which show that sudden acceleration occurs in about 10 vehicles in 100,000 of the same vehicle type each year, which gives a probability of:

$$\frac{10 \text{ events/year}}{100,000 \text{ vehicles}} = 1 \times 10^{-4} \text{ events/year-vehicle, or } 0.010\% \text{ events/year-vehicle.}$$

Therefore, the SUA incident rate calculated using this theory agrees closely with the actual SUA incident rate for Montero vehicles, and both agree closely with the SUA incident rate for gasoline-powered vehicles. This implies that the theory is correct. It also implies that the mechanisms causing sudden acceleration in Montero's is the same as that found in gasoline-powered vehicles; namely, an erroneous battery voltage compensation coefficient changing the gain of the engine speed/torque control system.

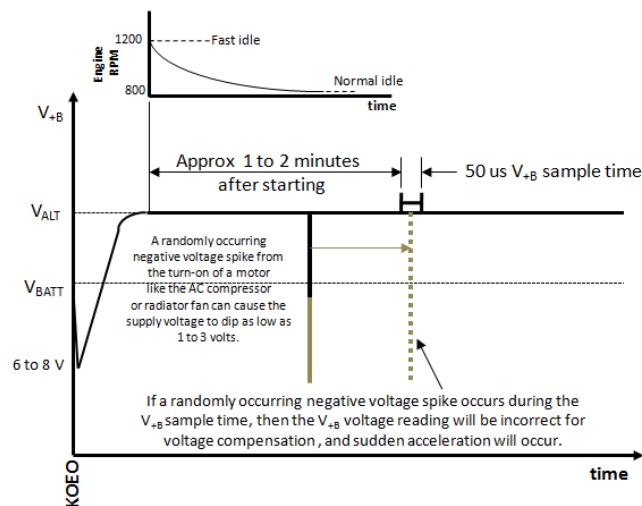


Fig 5. The +B battery voltage is sampled 1 to 2 minutes after the engine is started when the engine is at the normal idle speed of 800 RPM. If a randomly occurring negative voltage spike occurs during this sample time, then the +B battery voltage compensation applied using this incorrect battery voltage reading will cause sudden acceleration.

⁴ The total number of Montero vehicles used (60,000) is the total number of Montero's with automatic transmissions. If one includes Montero's with standard transmissions (which can also have sudden acceleration), then the total number of vehicles increases to 88,000 units, which gives an SUA incident rate of 1.8×10^{-4} . This is even closer to the estimated value of 1.5×10^{-4} above. Note that the Montero incident rates of 0.11% for 88,000 vehicles and 0.16% for 60,000 vehicles provided earlier by Dr. Belt were for a five-year period. Therefore, they must be divided by 6 years to get a yearly SUA incident rate of 2.7×10^{-4} for 60,000 vehicles or 1.8×10^{-4} for 88,000 vehicles, which agrees with the yearly estimates calculated here.

This theory provides an explanation for the cause of sudden acceleration, and is able to explain all the observed symptoms listed in Table 1. One would think that this success would be sufficient to cause government officials and auto manufacturers to want to test the theory by applying negative voltage spikes to the supply voltage while the supply voltage is being sampled to obtain the battery voltage compensation coefficient. After all, this 50 microsecond interval is the only time when the vehicle is susceptible to negative voltage spikes causing sudden acceleration. At all other times the vehicle is immune to negative voltage spikes because the A/D sampling process used to obtain the battery voltage is not active. But government officials seem to ignore the fact that the vehicle is susceptible to negative voltage spikes only during a 50 microsecond interval. This is because the standard EMI tests that they want to perform will not stimulate the entire vehicle during this 50 microsecond period of susceptibility. And standard EMI tests of the rail pressure PID loop subsystem will not stimulate changes in the open-loop rail pressure control map providing set-points to the PID loop, which is what causes the runaway of the set-points. Therefore, one can predict ahead of time that the standard EMI tests will be unsuccessful in causing SUA.

It is not known whether this failure of the standard tests to cause sudden acceleration is understood by the government officials. Their failure to understand this issue may be the result of ignorance, or it may be because they are being misled by the auto manufacturers. However, auto manufacturers should clearly understand the cause of the problem as explained above, and should clearly understand that the standard EMI tests will not stimulate the mechanism causing sudden acceleration. The fact that auto manufacturers still recommend using standard EMI tests, and that they continue to claim that sudden acceleration is caused by the driver pressing on the accelerator pedal, may be regarded by some as evidence that they are trying to mislead the public and are trying to avoid legal liability for a faulty vehicle design. The public should demand that any SUA tests must stimulate the vehicle while the battery voltage is being sampled. And this stimulation must be done using negative voltage spikes as low as 2 volts and applied to the correct node being sampled by the A/D to get the battery voltage. It is believed that this node is the power input to the engine ECU coming from the main ignition-switched power relay, although it may be the power input to the keep-alive memory coming directly from the battery.

III. PID Controller Behavior

Skeptics of this theory may argue that the gain of the rail pressure controller cannot change because the PID loop always converges to the pressure set-point. Therefore, the battery voltage compensation coefficient cannot change the rail pressure unless the PID loop fails to converge, which never happens because there are large margins on the gain and phase of the PID loop. This argument, however, fails to consider that new pressure set-points are issued every 12.5 milliseconds, which is faster than the convergence time of the PID loop, which is approximately 150 milliseconds. This is because it is impossible to design a PID controller for this application that will converge in less than 12.5 milliseconds. Yet, the sample rate of 12.5 milliseconds, or 80 Hz, is needed for other real-time control reasons. Therefore, auto manufacturers have no choice but to use the PID output before the PID loop converges to the pressure set-point.

Table 2 shows the specifications for the rail pressure PID controller. Note that convergence to 2% of the set-point value is required in less than 150 milliseconds, and the PID sample rate is only 5 milliseconds. But PID set-points are issued every 12.5 milliseconds. The auto manufacturers get away with this faster set-point operation by placing a specification of <3% on the maximum overshoot of the PID waveform. This is practically the same as no overshoot, which means that the samples obtained before convergence have an amplitude that is some constant fraction of the set-point value with the fraction being less than one. Therefore, the PID output is always bounded by the set-point value, and eventually converges to the current set-point as desired. This all assumes that the PID loop gain remains constant, which is assured by

applying a battery voltage compensation coefficient to the PID PWM output to make up for changes in the actuator gain due to drops in the battery voltage.

Table 2. Rail pressure PID controller specifications

Steady state error	$p_{rail}(\infty) - p_{set-point} < 30 \text{ bar (2\%)}$
Maximum overshoot	$< 50 \text{ bar (3\%)}$ for 0 to 800 bar/sec at 1000 RPM
PID settling time	$< 150 \text{ msec}$
PID sample rate	5 msec
Set-point sample rate	12.5 msec
Maximum rail pressure	$p_{railMAX} < 1600 \text{ bar}$
Disturbance rejection	Reject all disturbances
Amplification of harmonic components	No amplification
Compensation of dependent variables	Battery voltage

Figure 6 shows the PID output for different values of the battery voltage compensation coefficient. The red curve is the normal output that satisfies the PID specifications of Table 2. If the battery voltage drops because the battery is temporarily discharged, then PID output changes to the violet curve, and the engine response becomes more sluggish if the PID output is not compensated for battery voltage. However, if battery voltage compensation is applied, then the violet curve is raised back up to the red curve, and the engine maintains its normal operation. This achieves the desired constant operation of the PID controller.

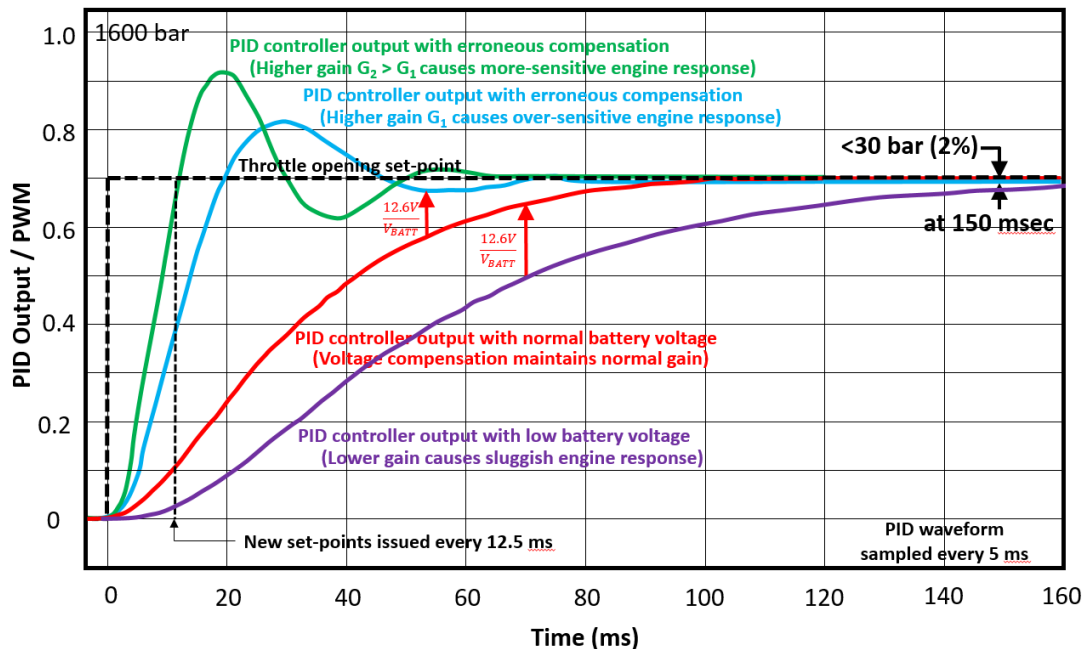


Figure 6. Output waveforms for the rail pressure PID controller for different values of the battery voltage compensation coefficient.

Consider, now what happens when an erroneous battery voltage compensation coefficient arises as a result of the battery voltage being sampled during a negative voltage spike. In this case, the erroneous battery voltage compensation coefficient is applied to the normal red curve, resulting in a curve that has overshoot like the blue or the green curve. A larger erroneous battery voltage compensation coefficient means more overshoot, causing the engine to have a more sensitive response and a higher engine speed. This means

that the gain of the PID controller effectively changes, because the PID waveform is sampled while overshoot is occurring before the PID waveform converges to its set-point value. If the erroneous battery voltage compensation coefficient is large enough, then gain of the PID controller can increase enough so that the PID waveform saturates at the maximum rail pressure during the overshoot. But saturation of the PID waveform is not necessary to produce sudden acceleration. One only needs an increase in the gain of the pressure controller over the gain that was assumed when the set-point map was calibrated. If this pressure controller gain increases, then the engine speed will increase, causing a higher set-point to be issued on the next iteration through the map. Since these map iterations occur every 12.5 milliseconds, one can have 80 iterations in one second, causing the engine speed to run away in less than one second.

It is easy to see that the PID output changes with changes in the battery voltage compensation coefficient if one is aware that the rail pressure PID controller is not just a simple PID controller, but has a feed-forward component as shown in Figure 7. The feed-forward component is used to speed up the convergence of the PID controller as well as account for any non-linearity in the transfer function of the rail pressure control valve. The idea is to use one's *a priori* knowledge of the valve operation to provide a quick estimate of the PID controller output, to which the normal PID controller makes the output converge. This works well if the controller gain doesn't change, which is normally assured by a proper battery voltage compensation coefficient. But if the battery voltage compensation coefficient is erroneous, then the *a priori* PID output estimate as well as the simple PID output gets multiplied by the erroneous battery voltage compensation coefficient. The result is a change in the gain of the control valve by the value of the battery voltage compensation coefficient, which can be anywhere from 1 to 6 or more. At some value of the battery voltage compensation coefficient this will cause sudden acceleration.

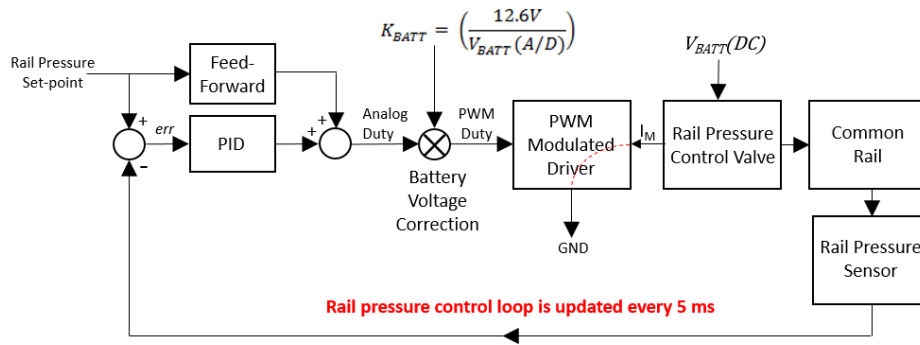


Figure 7. The rail pressure PID controller uses a feed-forward controller to speed up the convergence of the PID controller.

IV. Conclusion

An explanation has been given for sudden unintended acceleration in Mitsubishi Montero Sport vehicles with common rail Diesel engines. Sudden acceleration is caused by an increase in the gain of the common rail pressure controller that leads to more fuel being injected into the engine than the throttle map specifies. The gain increase originates with an erroneous battery voltage compensation coefficient produced by a negative voltage spike occurring while the battery voltage is being sampled. The erroneous battery voltage compensation coefficient increases the fuel injected into the engine, causing an increase in the engine speed, which causes the next iteration of the throttle map to issue a new common rail pressure set-point that is even higher than the previous one. The result is a runaway engine speed without the driver's foot being on the accelerator pedal. This explanation explains the origin of all the SUA symptoms occurring in Montero sudden acceleration incidents, including why a majority of SUA incidents occur while the engine is at idle in a parking lot or at stop sign, why the high engine speeds go away when the ignition is turned off and the engine is restarted again, and the lack of a diagnostic trouble code (DTC) after the sudden

acceleration incident. It also explains why the SUA incident rate is 2×10^{-4} incidents per year. It is believed that the success of this explanation should be sufficient to justify a test the theory by applying negative voltage spikes to the supply voltage of a vehicle while the supply voltage is being sampled to obtain the battery voltage compensation coefficient. If the test is not done during the 50 microsecond interval while the supply voltage is being sampled, then the test will be unsuccessful as a test of sudden acceleration because this is the only time that the vehicle is susceptible to sudden acceleration. This rules out the use of standard EMI tests as a test for sudden acceleration.

V. References
