A Second Possible Cause of SUA
In Mitsubishi Montero Sport Vehicles

by

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Abstract: A new cause of sudden unintended acceleration (SUA) has been found in Mitsubishi Montero Sport vehicles. The new cause arises from a known sticking defect in the Denso suction control valve used to meter fuel to the common rail and from a known ECU learning operation used on the Mitsubishi vehicle assembly line to correct for manufacturing variations in the fuel system components. These known vehicle features cause sudden unintended acceleration during engine idling in much the same manner as a negative voltage spike affects the battery voltage compensation function, leading to the same vehicle behavior relative to the idle and cruise engine controllers and the shifting of the transmission out of PARK and into DRIVE. Therefore, everything discussed to date about how the battery voltage compensation function causes sudden unintended acceleration during engine idling applies as well to this new cause of SUA. However, the two causes of sudden acceleration are independent, leading to an increase in the incident rate for sudden unintended acceleration. This may help explain the higher SUA incident rate of Montero Sport vehicles with diesel engines compared to vehicles with gasoline engines. This only affects Mitsubishi Monterey Sport vehicles with model years from 2010 to 2014. Model years 2015 and later are unaffected.

I. Introduction

Negative voltage spikes disrupting the operation of battery voltage compensation have been identified as a potential cause of sudden unintended acceleration (SUA) in Mitsubishi Montero Sport vehicles. If a negative voltage spike occurs while the battery voltage is being sampled, it makes the battery voltage appear to be low when the DC battery voltage to the injectors, the high pressure fuel pump metering valve, and the variable geometry turbo actuator remain unchanged at the normal supply voltage. Therefore, the battery voltage compensation function increases the outputs of these actuators above their normal values associated with the DC supply voltage, which remains unchanged. This causes the amount of fuel and air injected into the engine to increase above the normal value, resulting in sudden unintended acceleration.

A second possible cause of sudden acceleration in Montero Sport vehicles has recently been identified. This new mechanism is found in all Mitsubishi vehicles with common rail diesel engines, and operates independently of the battery voltage compensation function. Therefore, it further increases the probability of sudden unintended acceleration. The second mechanism consists of a learning function in the ECU which corrects for variations in the fuel rail pressure as a result of manufacturing variations and wear variations in the fuel system components like the high pressure pump, the flow control valve, and the injectors. The learning function checks whether a difference exists between the actual rail pressure and the target rail pressure as a result of these variations, and increases the actual rail pressure if it is lower than the target pressure or decreases it if it is higher. The learning function is intended to correct for slowly varying changes in the fuel system components as a result of aging. But if an abrupt change occurs during the learning process to cause a lower fuel rail pressure, but then disappears immediately afterward, then the result of the learning compensation function is to increase the fuel rail pressure over and above its normal value, causing a higher engine speed without the driver pressing on the accelerator pedal. The result is sudden acceleration.

The effect is similar to the increase in fuel rail pressure caused by an error in battery voltage compensation affecting the high pressure pump output, with the learning function being analogous to the battery voltage compensation function, and the sudden lowering of fuel rail pressure being analogous to the sudden lowering of the pump actuator supply voltage by a negative voltage spike. In both cases the correction function is intended to correct only for slowly varying changes in the values to be corrected, and not for abrupt temporary changes occurring during the acquisition of the data used to determine the correction amounts. The result of an abrupt temporary reduction in the rail pressure during the acquisition of the data, followed by applying the correction to the fuel pump output when the abrupt temporary reduction is no longer present, is an increase in the fuel rail pressure. The result is sudden unintended acceleration without the driver pressing on the accelerator pedal.

So, what can cause an abrupt and temporary reduction of the fuel rail pressure during the learning process that is analogous to the abrupt and temporary lowering of pump actuator supply voltage produced by a negative voltage spike during the battery voltage compensation process? The answer is a sticking fuel flow control valve, otherwise known as a suction control valve, or SCV. We will now provide a discussion of suction control valves in Mitsubishi common rail vehicles and how they can stick to cause the rail pressure to be temporarily lower than the normal rail pressure.

II. Denso SCV Valves and Sticking

The Denso common rail fuel injection system used in all Mitsubishi vehicles is shown in Figure 1. This system uses a high pressure fuel pump to supply fuel to the rail at a pressure up to 1800 times higher than atmospheric pressure. The injectors at each cylinder then squirt the fuel into the cylinders, with their opening times adjusted to be near the top dead center of each cylinder when combustion begins, and with their opening durations adjusted to regulate the amount of fuel based on the driver's demand. More fuel injected implies a higher engine acceleration and a higher engine speed. Clearly, the amount of fuel injected into the cylinders depends strongly on the pressure of the fuel in the rail.

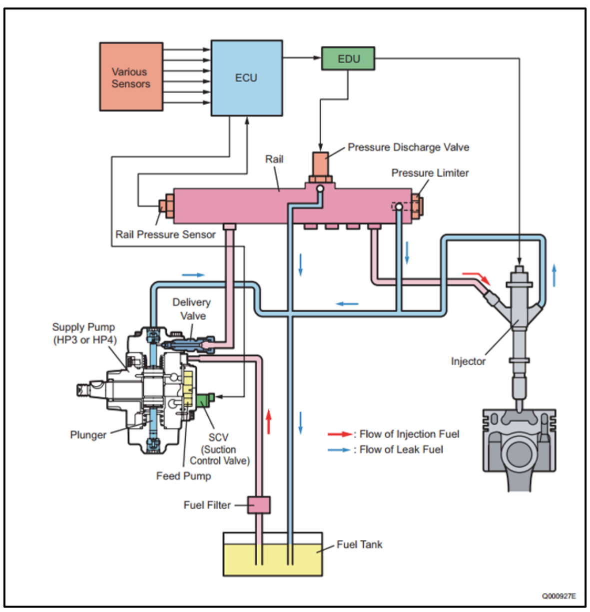

Fig 1. Denso common rail system diagram

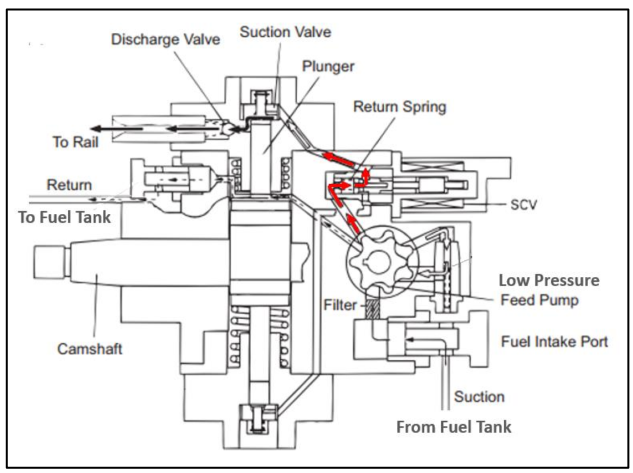

Fig 2. Denso high pressure fuel pump showing fuel flow through the SCV

The fuel pressure in the rail is regulated by a flow control valve (also called a suction control valve or SCV) at the input of the high pressure pump, which operates at a low pressure that is easier to control. The valve is controlled by a PID controller that adjusts the actual rail pressure, as sensed by a pressure sensor at the end of the rail, to be equal to a target rail pressure provided by a table in the ECU. In early common rail systems, where rail pressures of 350 bar or so were used, the target rail pressures varied with engine speed and the driver's depression of the accelerator pedal. In more recent common rail systems, where the target pressures can approach 1800 bar or higher, the target rail pressures are held practically constant except at very low engine speeds. If the actual rail pressure rises above the target value, then more fuel is squirted into the engine cylinders, causing the engine RPM to rise above the desired target RPM value. If the actual rail pressure becomes too high, then a mechanical pressure limiter safety valve opens to relieve the pressure, sending the excess fuel back to the fuel tank. Older common rail systems used an electrically operated pressure control valve (PCV) between the high pressure pump and the common rail to regulate the common rail pressure. But an electrically operated pressure control valve could not provide a fine enough control of the rail pressure to keep it constant as it was continuously being changed by the operation of the fuel injector valves. On the other hand, a flow control valve on the input of the high pressure pump can provide a much finer control of the rail pressure because it can supply exactly the same amount of fuel to the rail that the injectors draw from the rail during fuel injection, thereby keeping the rail pressure constant.

Figure 2 shows how the fuel flows through the high pressure pump in the Denso system. The fuel is sucked from the fuel tank by a low pressure feed pump, and then sent through a suction control valve (SCV) on its way to the compression chamber of the high pressure pump. The suction control valve contains a needle valve that is opened and closed by a solenoid activated by an electrical current supplied by the ECU. After the fuel is compressed by a plunger in the high pressure pump, it is sent to the common rail through a one-way valve called a discharge valve.

Figure 3 shows a cross section of Denso's HP3 high pressure pump. It consists of two compression chambers alternately activated by a rotating cam that is driven in synchronism with the engine rotation, allowing it to change its throughput in step with the engine speed. Both compression chambers are fed by a single suction control valve (SCV) that regulates the rail pressure by varying the amount of fuel input to the rail in response to the amount of fuel discharged by the fuel injectors. A pictorial diagram of the HP3 pump with its SCV is shown in Figure 4. The SCV valve is easily observed on the pump by looking into the engine under the hood from above. Denso also has a newer HP4 pump that has three compression chambers instead of two, allowing it to supply 50% more fuel at the same rail pressure to larger engines having larger combustion chambers that burn more fuel.

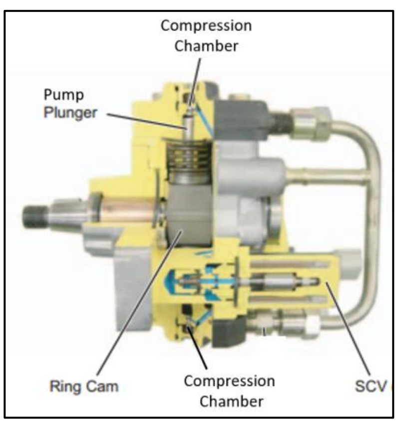

Fig 3. Denso HP3 pump cross section

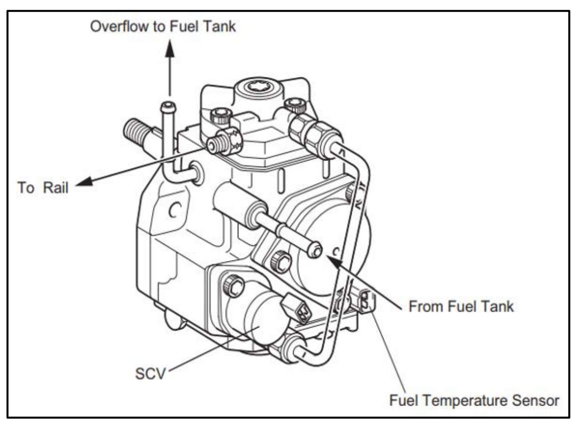

Fig 4. Denso HP3 pump pictorial diagram

Denso SCV valves come in two versions, an older long version and a newer compact version. A cross section of an older SCV valve is shown in Figure 5. This valve has a compression spring on the left that pushes to the right a hollow armature containing a groove for a needle valve. Meanwhile, an electric solenoid pushes the same armature to the left against the spring. By properly locating a groove in the armature (or spool) relative to a fixed keyhole-shaped hole in the valve body[1], a needle valve can be made that is either normally open or normally closed. By varying the amount of current through the solenoid, the amount of overlap between the groove in the moving armature and the hole in the valve body can be linearly varied, allowing a precise flow of fuel to the high pressure pump. Figure 6 shows the newer and more compact Denso SCV valve. It has a spring on the right that pushes the armature to the left. Meanwhile, an electric solenoid pulls the armature to the right against the spring. The valve can be made into either a normally open valve or normally closed valve by properly locating the moving groove in the armature relative to the fixed keyhole-shaped hole in the valve body in a manner similar to the older version. The SCV valves in all Mitsubishi vehicles are of the normally open type, with newer vehicles using the compact version.

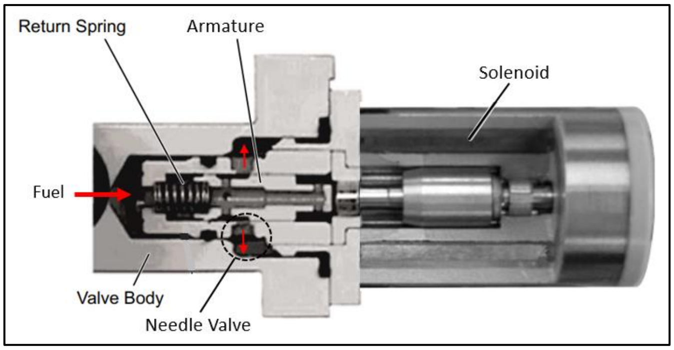

Fig 5. Conventional type of Denso SCV
(Type SV1)

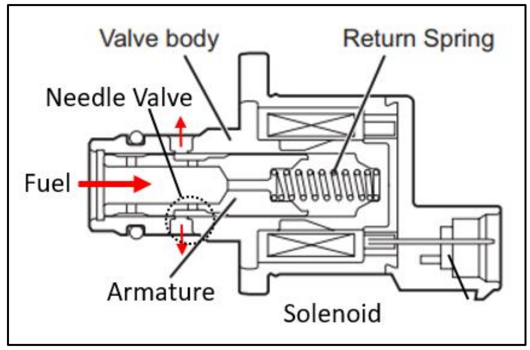

Fig 6. Compact type of Denso SCV
(Type SV2)

Figure 7 shows how a normally closed SCV valve operates. When there is no current to the valve, the valve opening is fully closed. A 100% duty cycle corresponds to a fully open valve, while a duty cycle less than 100% corresponds to a partially open state that provides the normal rail pressure. To increase the rail pressure, a higher duty cycle input is applied. To decrease the rail pressure, a lower duty cycle input is applied. When the standard 12V supply voltage to the solenoid is multiplied by the duty cycle, one obtains the average voltage applied to the solenoid, which varies from 0V to 12V. If the 12V supply voltage changes, then the current through the solenoid changes in proportion to the supply voltage, causing a larger or smaller valve opening corresponding to a higher or lower rail pressure.[2] Therefore, higher supply voltages imply higher rail pressures. Consequently, it is important to compensate the duty cycle for changes in supply voltage.

Figure 8 shows how a normally open SCV valve operates. When there is no current to the valve, the valve opening is fully open. As soon as the ignition is turned ON, a maximum DC current (duty cycle = 100%) is applied to the valve solenoid that puts the valve in its fully closed position. A 0% duty cycle corresponds to a fully open valve, while a duty cycle less than 100% corresponds to the normal rail pressure. To increase the rail pressure, a lower duty cycle input is applied. When the standard 12V supply voltage to the solenoid is multiplied by the duty cycle, one obtains the average voltage applied to the solenoid, which varies from 0V to 12V. If the 12V supply voltage changes, then the current through the solenoid changes in proportion to the supply voltage, causing a larger or smaller valve opening corresponding to a higher or lower rail pressure.[2] Therefore, higher supply voltages imply lower rail pressures. This means that a normally open SCV operates exactly like a normally closed SCV except that the input voltages have a different sign. Pressure always increases in proportion to the valve opening.

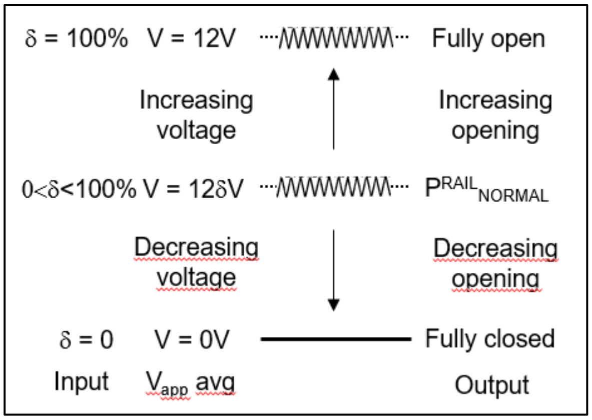

Fig 7. Normally closed SCV operation[2]

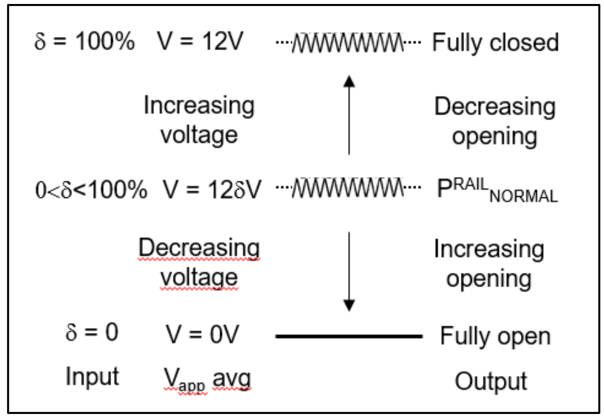

Fig 8. Normally open SCV operation[2]

Table 1 shows the four suppliers of common rail fuel injection systems and the vehicles in which they appear. Denso supplies to nearly all the Asian manufacturers, Bosch to nearly all the European manufacturers, and Delphi to nearly all the American manufacturers, with each having a small foothold in the other's markets. It is interesting that the SCV valves in all of Denso's customer's vehicles are of the normally open type except for Toyota, which uses only normally closed SCV's. The input metering valves (IMV's) used by Bosch and Delphi to accomplish the same purpose as Denso's SCV's are all of the normally open type, which correspond to Denso's normally closed SCV's, because Bosch and Delphi use the valves as bypass/dump valves to channel the fuel away from the inlet of the high pressure pump. This makes the use of normally open Denso SCV's in Mitsubishi and other non-Toyota vehicles an exception among the three major suppliers.

Table 1. Common Rail Fuel Injection System Suppliers

Common Rail System Suppliers			
Denso[1]	Bosch[2]	Delphi[3]	Siemens/Vdo[4]
Toyota	BMW	GM	
Mitsubishi	Volkswagen/Audi	Renault	
Nissan	Mercedes Benz	Citroen	
Isuzu	Renault	Hyundai/Kia	
Hino	Peugeot	Ford	
Hyundai	Hyundai/Kia	Ssangyong	
Opel/Vauxhall	Volvo	Jaguar	
Land Rover	Land Rover	Tata	
Ford			
Kubota			
John Deere			

1. Denso SCV's pass fuel through the SCV to the inlet of the high pressure pump.
   All Toyota Denso SCV's are normally closed. All other vehicle SCV's are normally open.
2. Bosch IMV's bypass/dump fuel away from the inlet of the high pressure pump.
   All Bosch IMV's are normally open. This corresponds to normally closed Denso SCV's.
3. Delphi IMV's operate similarly to Bosch IMV's.
4. Siemens/Vdo is now Continental.

Many owners of vehicles having Denso common rail systems have found that their vehicles occasionally experience a lagging behavior with poor acceleration followed by surges in engine speed. The following references contain descriptions of these incidents, which the reader is encouraged to read, especially reference eight.[3,4,5,6,7,8,9,10] When owners take their vehicles to the dealer for repair, the dealer frequently mentions that the SCV valve is dirty and needs either cleaning or replacement at a cost of several hundred dollars. The explanation is given that dirty fuel has caused the valve to stick, and that the valve must be cleaned or replaced to eliminate the cause of the sticking. This explanation applies even though there is a fuel filter between the fuel tank and the SCV valve at the input of the high pressure pump. The dealer sometimes adds that even if the fuel is refined adequately, it may be stored in a local vendor's dirty tanks or in an owner's private tanks, and that these tanks are not maintained adequately to prevent dirt and/or water from getting into the fuel. Some owners have found that their SCV valves must be either cleaned or replaced every 50,000 km in order to eliminate this problem. It is interesting that many diesel repair technicians have noticed that this surging problem happens most often with Denso common rail systems[11], but rarely with Bosch or Delphi common rail systems.[12] This may have something to do with the design of Denso's SCV valves versus the IMV valves of Bosch and Delphi[13].

Isuzu has studied this sticking problem and has discussed their findings in several US patents. In US patent 6,792,916[14], Isuzu discusses the case of a normally open SCV valve having a duty cycle command frequency set to a constant value of 180 Hz. With this fixed duty cycle frequency, the so-called stick/slip problem of the SCV valve is produced, leading to the SCV valve becoming stuck. Sticking of the SCV valve occurs during idling when the SCV is just slightly opened, and/or during a non-injection (fuel cut off) condition like engine braking when the SCV valve is fully closed.

When the engine is idling, the rail pressure changes very little because only a small amount of fuel is being used. So the SCV valve stays in a fixed position with only a slight degree of opening. Similarly, the SCV valve stays in a fixed position during the fuel cutoff condition where the SCV is completely closed. Under these conditions, one would expect that the valve armature would vibrate slightly due to the applied current. But, with the normal duty cycle command frequency of 180 Hz, the amplitude of the vibration is very small. Sufficient energy cannot be supplied with these minute vibrations of the valve armature. Consequently, the valve armature becomes stuck. In other words, since the energy per cycle of the current is small, when frictional force is present due to the viscous resistance and/or coefficient of friction of the fuel on the sliding section of valve body, the valve armature cannot achieve strong enough vibrations and sticking of the valve armature occurs.

This tendency to stick is even more pronounced if fuel having a higher coefficient of friction is used. Such fuel corresponds to fuel which has been desulfurized as a counter-measure against particulate matter (PM). It has been found that desulfurized fuel tends to have a coefficient of friction about twice that of conventional fuel. This increases the probability of sticking by about a factor of two.

If the valve armature gets into a stuck condition, even though it tries to move in response to a change of operating condition, since the static frictional force that acts on valve armature is larger than the dynamic frictional force, the drive energy of the valve armature (provided by the return spring) cannot overcome the static frictional force. The result is that there is a possibility of encountering a momentary delay in actuation of the valve armature. The static frictional force is larger if fuel of high coefficient of friction is employed. In the worst case, this friction results in the valve armature being temporarily incapable of actuation. To overcome this sticking condition, one may be tempted to apply a sudden higher voltage input to try to trigger the actuation of the valve. However, if this is done, then the average current also becomes high, resulting in a large change in the valve opening, causing a sudden lurching movement. So this method cannot be adopted.

In order to eliminate this sticking problem, Isuzu proposes changing the frequency of the control duty signal to a lower frequency when the opening of metering valve becomes constant. This lower frequency causes the oscillations of the armature to become higher in amplitude. In this way, good tracking performance of the actuator under high-speed operation can be ensured by means of a higher control frequency, while stability of control during an idling operation can be ensured by a lower control frequency. Normally, the control frequency is changed to a lower frequency only during idling and under non-ignition conditions like engine braking.

Specifically, the frequency of the duty signal is altered from a higher frequency to a lower frequency only if the following three conditions are satisfied: 1) the engine speed is at idling speed, 2) the transmission is in neutral, and 3) the accelerator pedal is in the idling position i.e. fully returned. In these three conditions, the idling condition includes not merely the ordinary case where the vehicle is idling while stationary, but also the case where the vehicle is moving slowly or decelerating with the accelerator released and the transmission engaged. A waiting time or delay time Δt may also be provided before the control frequency is changed. This delay helps maintain control stability by avoiding a frequency change if the conditions are present only momentarily. Δt is approximately 0.2 seconds.

In Isuzu's solution, the SCV duty control frequency on the high frequency side is normally set to a value between 170 Hz and 190 Hz (for example 185 Hz). The duty control frequency on the low frequency side is normally set to a value between 120 Hz and 170 Hz (for example 166 Hz). Table 2 shows the results of actual experiments to assess the merits of this solution on reducing valve sticking. It was found that the results depend upon the SCV supply voltage. The ability to eliminate sticking by lowering the control frequency to 166 Hz diminishes as the supply voltage is decreased. As shown in Table 2, under idling conditions, sticking occurred at all supply voltages with a duty frequency of 185 Hz. But when the duty frequency was lowered to 166 Hz, no sticking occurred until the supply voltage was lowered to 8V.

Table 2: Effect of Frequency Variation and Voltage on SCV Valve Sticking

	Supply Voltage			
Control Frequency	13.5V	12V	10V	8V
High (185 Hz)	Sticking	Sticking	Sticking	Sticking
Low (166 Hz)	OK	OK	OK	Sticking

Isuzu developed this idea further in US patent 6840220[15], where they proposed to use a controller to impose an oscillation or dither frequency on the duty drive signal in which the frequency of the oscillation can be changed according to the engine operational state. The controller obtains a duty frequency correction coefficient from a table based on the engine operational state and then multiplies the value of the base duty frequency by the correction coefficient to obtain a duty frequency correction value. The final duty frequency value is obtained by adding the duty frequency correction value to the base duty frequency.

This solution solves the problem of a valve sticking when the engine is in a stationary state (for example, while idling). When the valve opening is held stationary, the static friction requires a larger force in order to move the valve out of the stationary state, requiring comparatively large changes in electric current to be induced. In addition, if the stationary state is maintained for a certain time, lubrication in the sliding parts of the valve is further degraded and the tendency to stick is further increased (the static friction force increases). As a result, the responsiveness of the valve to changes in current is degraded, and sticking can occur.

Valve sticking usually occurs when the pumping frequency is low, which can happen: 1) at a time of low engine RPM, when the quantity of fuel flowing into the metering valve is comparatively small, 2) at a time of low engine load, and 3) during idling when the engine operational state is constant. Under these conditions, an oscillation or dither frequency can effectively prevent the valve from sticking. Conversely, when engine RPM and load are high, the pumping frequency is high, the valve vibrates by itself, and the quantity of fuel flowing into the metering valve is comparatively large. As a result, valve sticking is less likely to occur even without specially induced oscillations. Conversely, because in this case the sensitivity of the metering valve is high, creating the oscillations can cause common rail pressure hunting. Accordingly, it is desirable not to cause any oscillations when the engine RPM and load are causing the pumping frequency to be high.

Further insight into the cause of sticking is provided by Denso Mori US patent 7730875[16]. This patent mentions that sticking is caused by minute particles getting lodged between the sliding surfaces inside the SCV valve. It then discusses several measures that can be taken to prevent sticking, namely:

1) Hardening the sliding surfaces by plating a metal onto them that is harder than the soft magnetic material of which they are made
2) Machining circular grooves around the circumference of the armature to form an oil film for lubricating the sliding surfaces,
3) Machining longitudinal grooves and drilling longitudinal passages parallel to the axis of the armature to channel foreign particles away from inside the armature and the spring area where they collect in order to create a differential pressure that keeps the particles away from the sliding surfaces,
4) Drilling non-radial holes into the armature to cause the armature to rotate with time,
5) Applying an oscillatory or dither motion to the armature to prevent it from sticking as a result of remaining stationary for a long time (Isuzu).

These measures show that SCV valve design is extremely important to the valve's ability to operate without sticking when particles are present in the fuel. Denso uses the same soft magnetic material for both the armature and the valve aperture surfaces, creating a large sliding surface area that gets exposed to the fuel. The valves used by Bosch and Delphi, however, solve the same problems by minimizing the area of the sliding surfaces exposed to the fuel and by using metals for the sliding surfaces inside that smaller area that are substantially harder than the soft magnetic material used for the solenoid armature.

In summary, the discussion to this point reveals the following facts about sticking in SCV valves:

1) Sticking of the SCV valve usually occurs:
   a) at idling (when the SCV is fixed with a slight degree of opening) and/or
   b) during the non-injection condition (fuel cut off), as in the case of engine braking (when the SCV valve is fixed in the fully closed position).
2) Sticking usually occurs when the pumping frequency is low, as:
   a) during idling when the engine operational state is constant,
   b) at a time of low engine RPM, when the quantity of fuel flowing into the metering valve is comparatively small,
   c) at a time of low engine load.
3) Sticking occurs intermittently and without warning.
4) Sticking is more likely if desulfurized fuel having a higher coefficient of friction is used.
5) Sticking is more likely if the battery voltage is low.
6) Sticking is stopped when the ignition is turned off. When the engine is restarted, the sticking is usually removed because the SCV valve opening is changed to a wide open position during engine starting, after which it goes to a partially closed position during idling.
7) Sticking can cause a change in valve operation leading to either a rail pressure shortage or a rail pressure surplus, depending upon what state the valve is in when the sticking occurs relative to the desired state of operation. Usually, the valve sticks in a state of lower opening relative to the desired opening state.
8) Sticking can cause sub-par engine response followed by surging. Surging is a temporary increase in the engine RPM's, usually without an accompanying engine torque. Sometimes the surging RPM's get so high that the engine goes into the limp home mode.
9) Denso SCV's stick more often than any other common rail manufacturer. Bosch and Delphi IMV's rarely stick.

To understand how sticking can cause sub-par engine performance followed by surging, take a look at Figure 9. At some point in time, while the engine RPM is low, sticking of the SCV valve occurs, causing the actual rail pressure to drop below the target value. This causes sub-par engine performance with lower engine RPMs. It also causes the SCV PID controller to increase its integral I-term in order to adjust for the inability of the actual rail pressure to reach the target pressure. This can take several seconds. With an increased I-term, the controller increases the SCV valve opening, causing the actual rail pressure to increase to compensate for the perceived mismatch between the actual rail pressure and the target pressure caused by the sticking. This causes the sub-par engine performance to disappear. Then, when sticking ends as the SCV is opened in response to either an engine idle-up or the driver nudging the accelerator pedal, the actual rail pressure suddenly exceeds the target value because the integral I-term overcompensates the actual rail pressure as a result of the sticking being absent. The result is a temporary increase in the actual rail pressure that exceeds the amount normally associated with the small increase in SCV opening caused by either an engine idle-up or the accelerator pedal being pressed slightly by the driver. This increase in actual rail pressure causes more fuel to be injected into the engine, causing a temporary surge in the engine RPMs. The surge ends after a second or two because the I-term decreases again as the actual rail pressure falls back to the target value as the injectors deplete the excess fuel in the rail. But sometimes the rail pressure can become so high that it exceeds the maximum pressure that the rail can withstand, triggering the opening of a pressure relief valve and the switching of the engine to the limp home mode in which the engine RPM's are limited to a very low value. Drivers rarely refer to this surging in RPMs as sudden unintended acceleration because it is usually short in duration and is usually not accompanied by a higher engine torque, or acceleration.

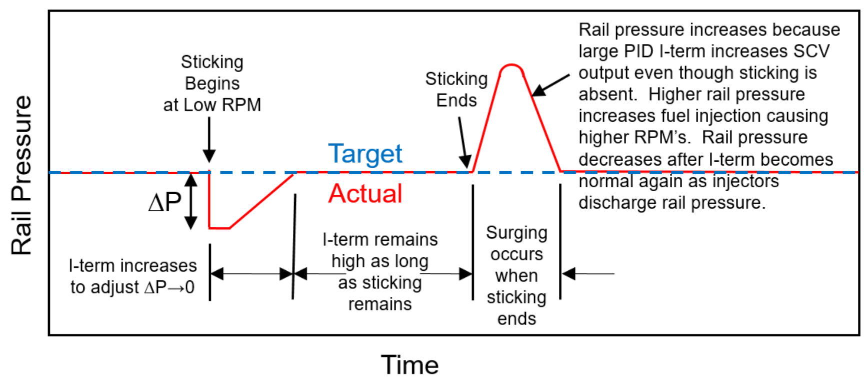

Figure 9. Rail pressure time behavior during surging[17]

It has been found that air in the fuel system can also cause surging similar to the sticking of an SCV valve[18]. When air enters the fuel system, the actual rail pressure drops. The drop in actual rail pressure causes the I-term in the PID controller to become excessive, just like SCV valve sticking. This, in turn, causes the SCV valve opening to become excessively large. Sometimes the SCV valve can even become fully open. This may cause the rail pressure to become so high that it exceeds the maximum pressure that the rail can withstand, triggering the opening of a pressure relief valve and the switching of the engine to the limp home mode in which the engine RPM's are limited to a very low value.

Air in the fuel system differs from SCV sticking in that air can only cause a shortage of fuel to the rail[19,20] while SCV sticking can cause either a shortage of fuel to the rail or an excess depending upon when sticking occurs relative to the change in SCV opening (although SCV sticking usually causes a shortage of fuel because it occurs most often at low engine RPM's when the SCV opening is stationary for a long time). Other differences are that air in the fuel system can cause surging to begin at either high or low engine RPM's, and air in the fuel system usually causes a more repetitive surging problem than sticking, because air in the fuel is usually caused by a persistent leak in a fuel hose, fuel tank, or connection, while sticking is a more probabilistic event.

There is one more reason why the actual rail pressure may not follow the target rail pressure exactly. This is because of manufacturing variations in the fuel system components, like the inlet metering valve (SCV) and the high pressure pump, that must be eliminated before the vehicle is delivered to the customer. There are also aging variations in these same components, as well as variations in the temperature characteristics of the fuel (e.g., viscosity) and SCV valve solenoid, that must be eliminated as the vehicle continues to be used by the customer. These variations are of a long-term nature that can cause changes in the actual rail fuel pressure that lie outside the range of the I-term function in the PID controller. Therefore, they are very noticeable to the driver. The effects of these long-term variations are eliminated by a learning function in the vehicle's engine control unit, or ECU.

III. Fuel System Learning Function

Denso Takahashi patent US7320312[21] discusses this learning function. It is performed on all vehicles as they come off the assembly line. At that time, only a partial learning is done because complete learning requires that the engine be fully warmed up, which requires about eight minutes of engine operation. This is too long to be done on the assembly line, so it must be done after the vehicle rolls off the assembly line, which is very expensive. Therefore, a so-called tentative learning is done on the assembly line which learns all the manufacturing variations in the fuel system except for the variations in temperature. Then, after the vehicle is delivered to the dealer, a more complete learning is done at the full engine temperature. This same learning function then continues to operate during the lifetime of the vehicle to eliminate aging variations.

The way this learning is done is shown in Figure 10. Any difference ΔP between the actual rail pressure and the target rail pressure that persists after the engine speed has remained constant for a given period of time is detected by the learning function and stored in a memory inside the ECU. This difference is then added to the target rail pressure obtained from the vehicle's rail pressure map to either increase or decrease the target rail pressure as needed to make the actual rail pressure become equal to the compensated target rail pressure. The ΔP difference is applied only to the I-term in the PID controller, with the other two PID terms remaining unaffected[22].

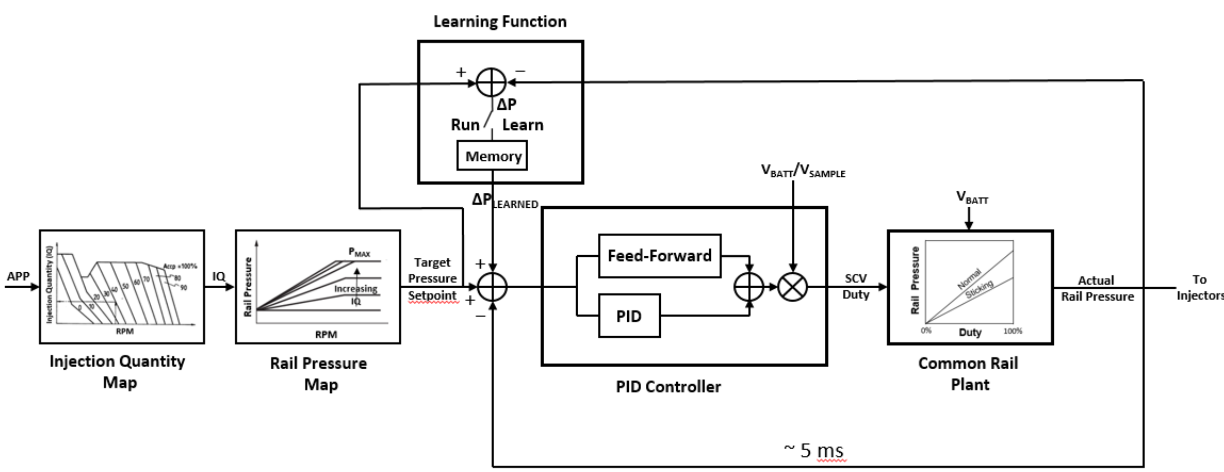

Figure 10. Rail pressure control system showing a learning function
to eliminate manufacturing variations and aging variations
represented by different transfer functions in the common rail plant.

When tentative learning is done during manufacturing, the following conditions must be satisfied:

1) A deviation between the engine rotation speed NE and target idling rotation speed is equal to or lower than a predetermined value.
2) The engine rotation speed NE is within a predetermined range (for example, 800 to 1000 rpm).
3) The accelerator position ACCP is equal to or lower than a predetermined value (for example, 1%).

4) A pressure deviation ΔP between the actual common rail pressure PC and the target common rail pressure PFIN is equal to or lower than a predetermined value (for example 30 MPa).
5) The actual common rail pressure PC is within a predetermined range (for example, 30 to 40 MPa).
6) The command injection amount QFIN is within a predetermined range (for example, 1 to 5 mm^3/st).
7) There is no system abnormality such as fuel leakage or exhaust emission abnormality.
8) The starter is OFF.
9) The vehicle running speed (vehicle speed) is equal to or lower than a predetermined value (for example, 0 km/h).

When main learning is done by the dealer, the following additional conditions must be satisfied:

10) The fuel temperature THF is within a predetermined range (for example, 40 to 70°C).
11) The engine cooling water temperature THW is within a predetermined range (for example, 60 to 90°C). (It usually requires about 8 minutes for the engine to warm up to this temperature).
12) The battery voltage is within a predetermined range (for example, 24V or 12V).

These same conditions (1 through 12) must then be satisfied each time the learning function is executed during the life of the vehicle. Learning is not repeated continuously while the engine is being run because it requires too much CPU time at higher engine speeds. Learning is usually performed each time the ignition switch is turned on, and after some predetermined time elapses or mileage is run after the last learning session if the ignition switch has not been turned off in the meantime.

These learning conditions should sound familiar to people interested in sudden unintended acceleration. Learning is usually done:

1) each time the ignition is turned on, or after some predetermined time has elapsed after the ignition has remained on,
2) while the vehicle is stationary,
3) while the engine speed is at idle,
4) while the accelerator pedal is not pressed, and
5) while the engine is running at normal temperature (about 8 minutes after starting).

Under these conditions learning can cause sudden unintended acceleration to occur if SCV sticking happens during the learning function. This is shown more clearly in Figure 11.

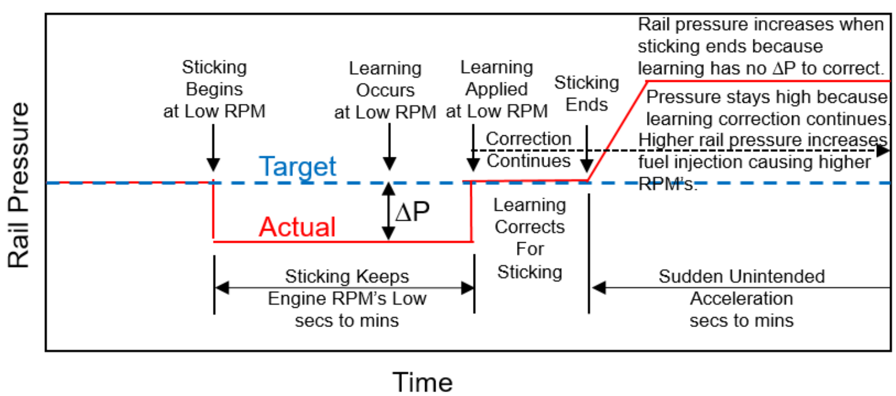

Figure 11. Sticking during learning can cause sudden unintended acceleration when the sticking ceases and the learning correction is applied to the normal target pressure without sticking being present.[23]

Figure 11 shows that SCV sticking can cause the rail pressure to become lower than the target pressure by an amount ΔP when it occurs at a low engine RPM such as when the engine is idling. At some time after SCV sticking occurs, learning happens after the engine is warmed up and while the sticking is still present. The learning corrects for the pressure difference ΔP and makes the actual rail pressure equal to the compensated target pressure while the sticking is still present. Then, the sticking ends because perhaps an increase in SCV opening occurs to cause an engine idle-up, as a result of either the air conditioner turning on or the radiator fan turning on. When the sticking ends, the actual rail pressure increases because the learning correction is still being applied while the cause of the learned compensation value has disappeared. When the actual rail pressure increases, more fuel is injected into the engine even though the target rail pressure, the injector opening time, and the injector opening duration do not change. The result is sudden unintended acceleration without the driver pressing on the accelerator pedal. And no diagnostic code is produced because nothing in the engine is working incorrectly, except that the learning function has obtained an incorrect value, which it continues to apply as designed.

There is one more consequence of the actual rail pressure increasing as a result of a learning correction being applied to the target rail pressure. Notice in Figure 10 that the target rail pressure is obtained from a pressure map that has the engine RPM as one of its axes and the injection quantity as the other axis. Note also that this map is fed by an injection quantity map that has the engine RPM as one of its axes and the accelerator pedal depression on the other axis. Therefore, if the engine speed increases for some reason, the injection quantity selected from the injection quantity map can increase, mimicking an increase in accelerator sensor input, even though the accelerator pedal sensor input remains unchanged. This can cause the target rail pressure to increase. But we have just discussed how the actual rail pressure can increase even though the target pressure remains the same, and we know that increasing the actual rail pressure causes the engine RPM to increase. Therefore, it is possible for a runaway condition to exist whereby the actual rail pressure increases because of an incorrect learning value even though the target pressure remains the same, causing the engine RPM to increase, causing the injection quantity to increase, and causing the target pressure to increase. Since this loop takes only about 15 milliseconds to traverse, one can traverse it over 66 times in one second, causing a small increase in the learning correction value to suddenly produce a large change in actual rail pressure, leading to runaway engine RPM.

Even worse, notice in Figure 10 that the slope of the curves for a fixed accelerator opening in the injection quantity map are all in the downward direction. This means that if the engine speed is reduced by some load on the engine, such as applying the brakes or the vehicle running into some movable object, then the injection quantity increases to cause the engine torque to increase even though the accelerator position sensor input does not change. The sensation the driver gets is that the harder he/she applies the brakes the more torque the engine produces, much the same as the engine torque increases when a vehicle goes up a hill with the cruise control on. This may be the reason that some drivers who have experienced sudden acceleration state that pressing harder on the brakes caused the engine to accelerate more forcefully.

So, what has caused this problem and who is at fault? The answer is that the design of the learning function assumes that the variations to be corrected by the learning operation are caused by <u>long-term</u> changes in pressure system operation that remain in effect after learning takes place. The design is not capable of correcting for <u>short-term</u> changes in the actual rail pressure caused by SCV sticking, where the sticking ceases after the learning is done but the learning correction continues as if the sticking is still present. The result is that the learning correction value is too high when the actual rail pressure is sampled while the SCV valve is sticking, but later changes, similar (but not the same) to what Denso refers to as excessive learning.[24] The presence of sticking in the Denso SCV is also a design flaw that is not present in other manufacturer's flow control valves. These are engineering design flaws in the Denso common rail system that both companies have failed to correct. So one might expect that both companies are at fault. However, these defects should be covered by a manufacturer's warranty, which in this case may be provided only by Mitsubishi. What is clear from this paper is that these defects lead to sudden unintended acceleration without the driver pressing on the accelerator pedal. Therefore, SUA is not a problem caused by the driver, but a problem caused by manufacturing design defects.

This new cause of sudden acceleration provides a new avenue to search for why Montero Sport vehicles with model years from 2010 and 2014 experience sudden unintended acceleration while Montero vehicles with model years 2015 and later do not. The new avenue is that maybe there is a difference in the SCV valves used by Montero vehicles compared to other Mitsubishi vehicles that makes the valves in 2010 to 2014 Montero vehicles more susceptible to sticking. Model years 2015 and later are unaffected.

A search for SCV part numbers used on different Mitsubishi vehicles has found a Denso document that appears to support this assumption[25]. Figure 12 shows an excerpt from this document listing the part numbers for the high pressure supply pumps used on all versions of the Pajero Sport, which is similar to the Montero Sport vehicle. The excerpt shows that the Pajero Sport has used three different high pressure pumps at various times, with one having a start of sale (SOS) before 2010/01 experiencing no SUA (green), a second with a start of sale after 2010/06 certainly experiencing SUA (red), and a third with a start of sale between 2010/01 and 2010/06 uncertain as to whether it experiences SUA (yellow). A further search has found that the part numbers of the SCV's on these pumps varies with the part number for the pump, implying that the same basic pump is used with different SCV's. More explicitly, the SCV's on all the red pumps had the same part number and type (P/N 294200-2760, long SV1 type), on all the yellow pumps had the same part number and type (P/N 294200-0360, short SV2 type), and on all the green pumps had the same part number and type (P/N 294200-0260, short SV2 type). What stood out after finding this information was that the SCV part numbers had changed for the model year 2010, just when SUA began to be observed in Montero Sport vehicles. Even more interesting is that the change was made from a <u>newer</u> SCV type (SV2 short type), which produced no sudden acceleration, to an <u>older</u> SCV type (SV1 long type) in 2010/06, which clearly produced sudden acceleration. Could the older SCV type (SV1 long type) be more susceptible to sticking than the newer type (SV2 short type)? If so, then why was it still used? Was this change made for some other reason, like a difference in the flow rates of the two valves? It may be noted that the Gen 3 Montero Sport uses a completely different engine type (4N15) than the Gen 2 Montero Sport (4D56 mostly with some 4M41), with the Gen 3 using a newer type of SCV than the Gen 2 Montero Sport. This is consistent with the difference in SUA behavior relative to the Gen 2 Montero Sport.

Model	Engine Type	Details	SOS	Supplypump		Injec	
				Car Maker	DENSO	Car Maker W/O gasket	Car Maker With gasket
Pajero Sport sedan with mostly automatic transmission	4M41 small number of SUA's have this engine		2009/01	1460A022	SM294000-066#	1465A307	-
			2010/01	1460A058	SM294000-125#		
			2010/06	1460A052	SM294000-136#		
	DI-D 4D56 most SUA's have this engine	Euro4	2006/02	1460A001	SM294000-033# no SUA	294009-0260 SCV	Also used on Nissan Navara, Nissan Pathfinder
			2010/01	1460A057	SM294000-124#	1465A041 294200-0360 (short SV2)	-
			2010/06	1460A053	SM294000-137# SUA	294200-2760 (long SV1)	
		Euro5	2011/08	1460A053	SM294000-137# SUA	1465A367	-
		Euro3	2007/03	1460A019	SM294000-064# no SUA		
			2010/01	1460A057	SM294000-124#	1465A041 294200-0360 (short SV2)	-
			2010/06	1460A053	SM294000-137# SUA	294200-2760 (long SV1)	
	4D56 DI-DC most SUA's have this engine	High Power	2009/01	1460A047	SM294000-0333 no SUA	294009-0260 SCV 1465A297	-
			2010/06	1460A053	SM294000-137# SUA		
			2011/10			1465A257 294200-2760 (long SV1)	-

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Montero Sport 3rd gen	4N15		>2015		No SUA SM294000-2330 (SCV 294200-2960)

Figure 12. Excerpt from a Denso catalog of high pressure pump part numbers[25]

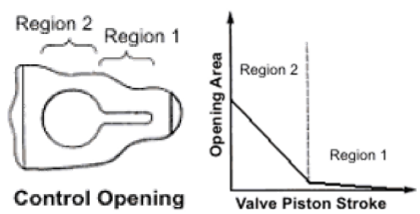
Admittedly, this study of SCV part numbers, and their correlation to Montero's with and without sudden acceleration, is not complete at this time. It should be continued to verify the above information and possibly reveal new information that might explain the difference in SUA behavior between Montero vehicles.

IV. Conclusion

A new cause of sudden unintended acceleration has been found in Mitsubishi Montero Sport vehicles. The new cause arises from a known sticking defect in the Denso suction control valve used to meter fuel to the common rail and from a known ECU learning operation used on the Mitsubishi vehicle assembly line to correct for manufacturing variations in the fuel system components. These known vehicle features cause sudden unintended acceleration during engine idling in much the same manner as a negative voltage spike affects the battery voltage compensation function, leading to the same vehicle behavior relative to the idle and driving engine controllers and the shifting of the transmission out of PARK and into DRIVE. Therefore, everything discussed to date about how the battery voltage compensation function causes sudden unintended acceleration during engine idling still applies. However, the two causes of sudden acceleration are independent, leading to an increase in the incident rate for sudden unintended acceleration. This may help explain the higher incident rate of Montero Sport vehicles with diesel engines compared to vehicles with gasoline engines. This only affects Mitsubishi Monterey Sport vehicles with model years from 2010 to 2014. Model years 2015 and later remain unaffected.

V. References

[1] A keyhole-shaped slot allows a higher fuel flow when the fuel pressure and engine RPM are changing rapidly (region 2), yet finer control over the fuel flow at low fuel flows when the fuel pressure and engine RPM are nearly constant, such as during idling (region 1).



[2] A controller which performs these functions is discussed in US patent 9653200B2, "*Electromagnetic Valve Controller*", Denso Corporation, Ito et. al., May 16, 2017.

[3] https://forums.whirlpool.net.au/archive/2489715. Posting by ribreef6: "I suspect the suction control valve in my NS Diesel Pajero may be faulty as the engine is experiencing some surging. Mechanic got the Pajero to surge several times during a drive. Electronic diagnosis connected to the car's computer showed the fuel pressure fluctuating erratically. He pointed toward the SCV. He removed it and gave it a good clean before installing again. All good so far. If it happens again, though, it will need replacing."

[4] https://www2.pajeroclub.com.au/forum/showthread.php?t=20639. Posting by pajmobil (#1): "Had some problems with the NS DID auto recently. The engine on steady acceleration would surge up and down, mostly an audible sound. The engine also felt tired and unresponsive when the accelerator was pressed hard. It was nailed down to the suction control valve (SCV) on the high pressure diesel pump. This could be a regular maintenance item (mine lasted only 56000 km). According to the guy at MM parts it is a regular moving item ($472)."

[5] https://www2.pajeroclub.com.au/forum/showthread.php?t=20639. Posting by Esteban (#5): "I have just recently begun experiencing an annoying surging when using light or moderate accelerator use. The surging was intermittent and sometimes only light, but every now and then a bout of serious surging would occur. After a significant series of surging at moderate throttle, the engine gave a shudder and the ASC off, stability light, and engine check lights came on. The vehicle went into limp mode. Shut the engine down and looked at my scan gauge. The stored error code was a P0089. This apparently for a Mitsubishi is a suction control valve stuck error condition."

[6] https://www.tsikot.com/forums/mitsubishi-cars-talk-94/scv-suction-control-valve-75137/index8.html.

See several postings by *arsen*: “So, with a failed SCV, a sign of Strada SCV failure is an increase of engine power due to abnormal high rail pressure. This is followed by a power loss when the failsafe device called a pressure limiter cracks open, causing the rail pressure to drop from 220 MPa to 50 MPa. Power returns when the rail pressure rises back to the 150MPa to 180MPa operating pressure. An SCV failure occurs only occasionally (for example, because of a stuck valve or some loose wiring). If an SCV does fail, it will be annoying to drive the vehicle, but it is not prone to stalling.”

[7] https://www.youtube.com/watch?v=nNmwuyAiG1o. A youtube video by *monteroguy* describes the surging problem and demonstrates how to clean the SCV.

[8] http://chiptuning.com.au/products-page/standard-suction-control-valve-scv/. The company Chiptuning states: “When the suction control valve is contaminated or worn it will cause the common rail pump to deliver an inconsistent fuel pressure to what is being demanded by the factory ECU. When the fuel pressure at the injectors jumps around by many thousands of PSI the vehicle driver will experience surging as the ECU tries (and fails) to find the correct operating rail fuel pressure. This is seen diagnostically when viewed via live data. If the problem of varying fuel pressure moves past a preset limit that the manufacturer states should be the normal range for a certain RPM, then the vehicle will go into limp mode. You can reset the normal operating condition by stopping and re-starting the engine. The problem will re-appear in a short while however. This problem occurs consistently in Mitsubishi Pajero, Triton, and Challenger, Nissan Navara, and early and late model Toyota Hilux with the D4D engines. Cleaning and re-installing the suction control valve rotated 90 degrees may fix the problem short term. However, sooner or later the suction control valve will need to be replaced. A relearn of the factory ECU will also need to be conducted”.

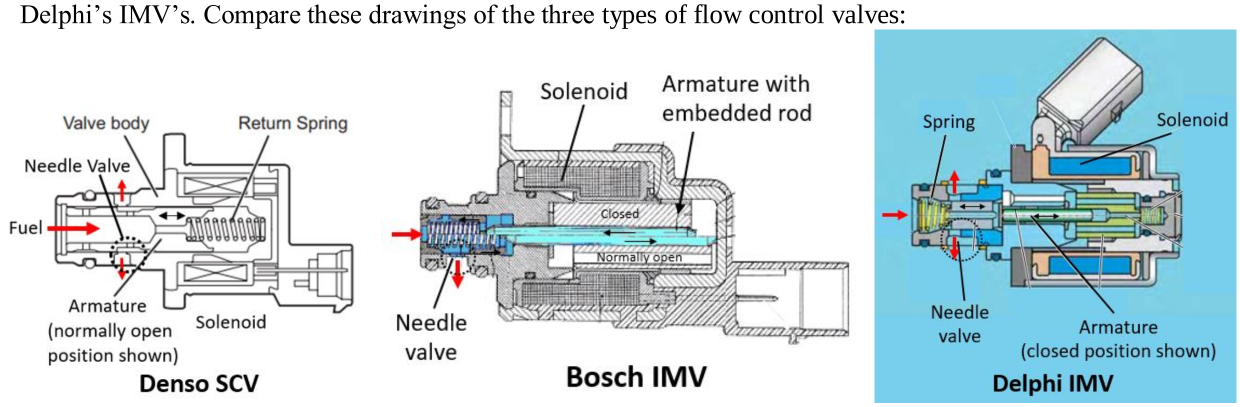
[9] https://www.autosceneuk.co.uk/denso-hp2-fuel-pump-explained/. Blue Print Magazine states: “This article looks at the Denso HP2 fuel system, the way in which it operates and the common problems associated with it. This particular system was fitted to Toyotas, Nissans, Renaults, Vauxhalls/Opels, and Isuzu vehicles from around 1999 to 2007. The most common symptoms are a lack of power or rough idling; both these faults may be intermittent. DTCs P1229 and P0093 relate to excessive pressure in the system caused by the SCV sticking open longer than it should and will cause the engine to go into failsafe mode where the engine power is restricted. DTC P0627 relates to the SCV circuit, this could be caused by an open or short circuit in the SCV field coil or in the wiring.”

[10] https://www.tat.net.au/tatarticles/Issue52_aug2016_p11.pdf. This article in the trade magazine *The Automotive Technician* describes surging in China’s Great Wall V200 pickup truck: “A small but noticeable surge could be felt while cruising or while applying throttle at a standstill. Idle and wide open throttle were OK. No fault codes. With the scan tool connected while driving, I could feel a small surge and could see the fuel pressure dropping on average 500psi to 1000psi on each surge pulse while steadily cruising. Initially this felt and looked very similar to common suction control valve faults.”

[11] http://chiptuning.com.au/products-page/standard-suction-control-valve-scv/. “This (surging) problem occurs consistently in Mitsubishi Pajero, Triton and Challenger, Nissan Navara, and early and late model Toyota Hilux with the D4D engines.”

[12] https://www.landcruiserclub.net/community/threads/90-series-d4d-common-rail-low-fuel-pressure.143321/ See remarks by StarCruiser: “When I brought the vehicle in, the repair technician mentioned that suction control valves often go faulty causing low fuel pressure, and they regularly change them. He thought the engine would have a Denso pump. When he found it to be a Bosch system he said their SCVs just don't give trouble.”

[13] Denso’s SCV’s have a much greater sliding area in contact with the fuel containing particles than Bosch and Delphi’s IMV’s. Compare these drawings of the three types of flow control valves:



[14] US patent 6792916B2, "*Control Device of Common Rail Fuel Injection System of an Engine*", Isuzu Motors Limited, Sept. 21, 2004.
[15] US patent 6840220B2, "*Common Rail Fuel Injection Control Device*", Isuzu Motors Limited, Jan. 11, 2005.
[16] US patent 7730875B2, "*Flow Control Valve*", Denso Corporation, Jun. 8, 2010.
[17] This figure attempts to show only the time sequence of events and the corresponding changes in the actual rail pressure. It is not intended to show the actual pressure waveform.
[18] US patent 7216628B2, "*Fuel Injection Apparatus Having Common Rail and Subject Device Control System*", Denso Corporation, May 15, 2007.
[19] US patent 6971368B2, "*Fuel Injection System for an Internal Combustion Engine*", Denso Corporation, Ken Uchiyama, Dec. 6, 2005.
[20] US patent 6374800B2, "*Engine Operation Control Device*", Isuzu Motors Limited, Apr. 23, 2002.
[21] US patent 7320312B2, "*Fuel Injection Device for Internal Combustion Engine*", Tomohiro Takahashi, Denso Corporation, Jan. 22, 2008.
[22] Denso patent US7320312B2 (Takahashi) states that this learning value is applied to the PID integral I-term. However, the author believes that the difference ΔP should be applied to the feed-forward term instead of the integral I-term, which would shorten the time that common rail pressure output of the PID controller converges to the target value. Both the integral I-term and the feed-forward term in the controller adjust the offset between the target value and the actual rail value. However, the range of adjustment of the feed-forward term is much greater than the PID I-term and it allows for faster convergence.
[23] This figure attempts to show only the time sequence of events and the corresponding changes in the actual rail pressure. It is not intended to show the actual pressure waveform.
[24] US patent 6971368B2, "*Fuel Injection System for an Internal Combustion Engine*", Denso Corporation, Ken Uchiyama, Dec. 6, 2005.
[25] Denso Europe B.V., "*Service Bulletin Fuel Injection Pump*", Subtitle: "*ECD Application List, March 2015*", DE00400107E, March 2015. p.18. http://www.bgdiesel.dk/otherfiles/dk/denso/applikationsliste.pdf