# EDR Accelerator Pedal Data Can Be Wrong With This Cause of Sudden Acceleration

by

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**Abstract:** Before the accelerator pedal sensor outputs can be used by the vehicle's control system they must first be digitized by analog-to-digital converters (ADC's) in the ECU. This digitization process requires calibration of each ADC with the same known reference voltage, which requires digitizing the same calibration voltage by both ADC's to determine the ratio of input voltage to output count for each ADC. These calibration ratios are then used to multiply the digitized output counts of the accelerator pedal sensors from each ADC, which gives the inferred ADC input voltages of the two pedal sensors. Calibration is done periodically during vehicle operation, with the same calibration values being used for all subsequent pedal sensor outputs (i.e., analog ADC inputs) until the next calibration operation is performed, which may be minutes later. If the calibration reference voltage dips suddenly while it is being digitized, causing the digitized calibration output counts to be less than normal, then the calibration ratio for each ADC increases. This causes all the subsequent digitized accelerator pedal sensor outputs from each ADC to increase even though the analog values of the two pedal sensors remain unchanged. These increases in the digitized accelerator pedal sensor outputs are identical in every way to the increases caused by the driver stepping on the accelerator pedal of a pedal assembly having two sensors with outputs A = 2B. Therefore, the increased accelerator pedal sensor values pass all tests performed on the digital sensor values without causing diagnostic trouble codes or DTC's. The result is sudden unintended acceleration even though the driver has not stepped on the accelerator pedal. As a result, the increased accelerator pedal sensor values will be stored in the EDR in place of the 0% values, even though the driver has not stepped on the accelerator pedal. This non-zero EDR data makes it appear incorrectly that the driver stepped on the accelerator pedal. Finally, all traces of sudden acceleration disappear when a new calibration is performed using a normal value of the calibration voltage. So EDR accelerator pedal sensor data can be wrong during this sudden unintended acceleration (SUA) caused by an incorrect calibration voltage.

## Introduction

In many cases of sudden acceleration over the past few years the driver has claimed that his/her foot was on the brake pedal or on the floor during the incident instead of on the accelerator pedal. However, a subsequent look at the EDR data showed that the accelerator pedal was pressed to a maximum of 100% in less than a few seconds during the incident, apparently showing that pedal error was the true cause of the incident. Many times drivers have disagreed with this EDR pedal data. But they were unable to refute it because all vehicle manufacturers as well as NHTSA say that it is impossible for the EDR accelerator pedal data to be wrong. Therefore, the drivers were forced to concede that their perception of their foot location during the incident was incorrect, and to acknowledge that they must have caused the incident instead of the vehicle. This has ended to their attempts to seek redress via an NHTSA recall or a court case.

This paper will show that it is indeed possible for the EDR accelerator pedal data to be incorrect during an incident of sudden unintended acceleration. It will do this by showing that a vehicle defect can cause the digitized outputs of the accelerator pedal sensors to increase up to 100% without the driver stepping on the accelerator pedal even though the analog outputs of the accelerator pedal sensors remain at their un-pressed values of 0%. The vehicle defect in this case is that the control software allows ADC calibration with an incorrect value of the calibration voltage. To understand how this is possible requires an understanding of the accelerator pedal sensor digitization process. We will now review this digitization process.

## I. Review of the Digitization Process

At first glance, the digitization process may appear to be the simple process shown in Figure 1. Two accelerator pedal position sensors having separate +5V power supplies are digitized by two separate analog-to-digital converters (ADC's) included on a single DSP. This redundancy adds robustness when operating in the presence of single point faults. The ADC's convert the two analog sensor outputs into a digital format for use by the digital signal processing algorithms within the DSP. The accelerator sensor outputs change with pedal position as shown in Figure 2. Having the output of sensor A equal to two times the output of sensor B is preferred by many auto manufacturers because it provides a sensitive way of detecting faults in the sensor outputs while simplifing the fault detection algorithms.

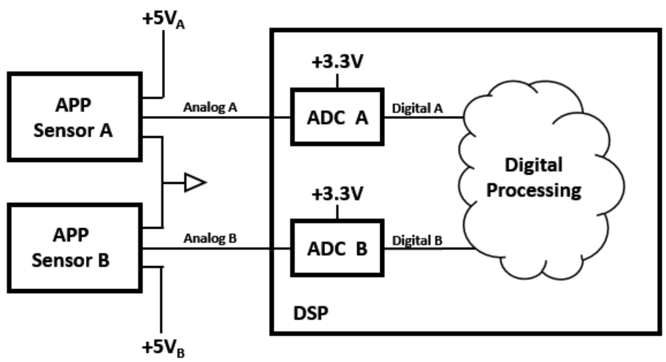



Figure 1. Initial concept of the digitization process

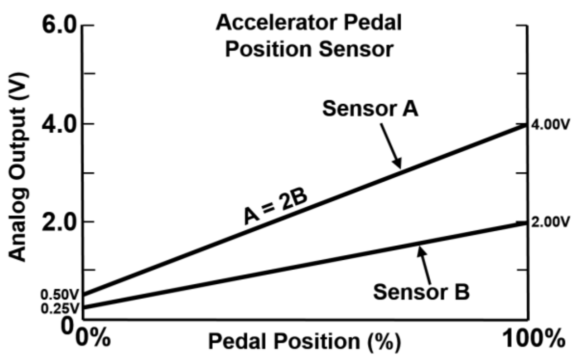



Figure 2a. Generalized accelerator pedal position sensor with outputs A = 2B.

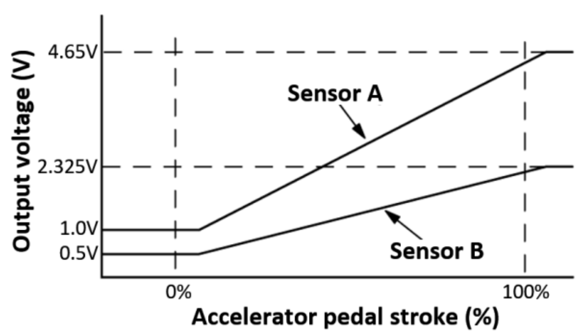



Figure 2b. Actual accelerator pedal position sensors with different transfer functions.

**Sensor Interface Circuitry**

In a real vehicle, digitization is more complicated. First, interface circuitry must be included between the sensors and the ADC's as shown in Figure 3. The 0V to 5V sensor signals must be reduced in amplitude by a resistive voltage divider to stay within the 0V to 3.3V input range of ADC's. And the ADC's require a unity gain buffer between the voltage divider and the ADC inputs to prevent errors due to high source impedance when sampling the ADC channels[1]. Also, an optional EMI filter may be used to eliminate high frequency EMI interference, or else shielded cabling may be used for the same purpose.

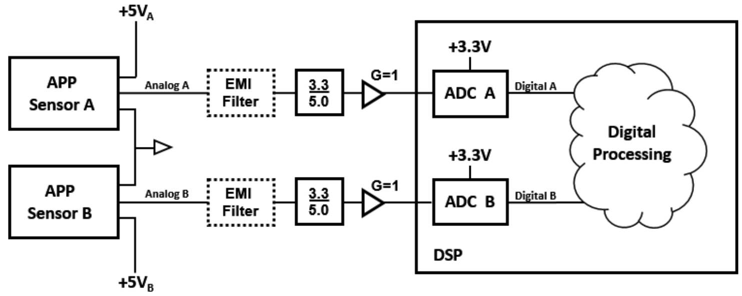
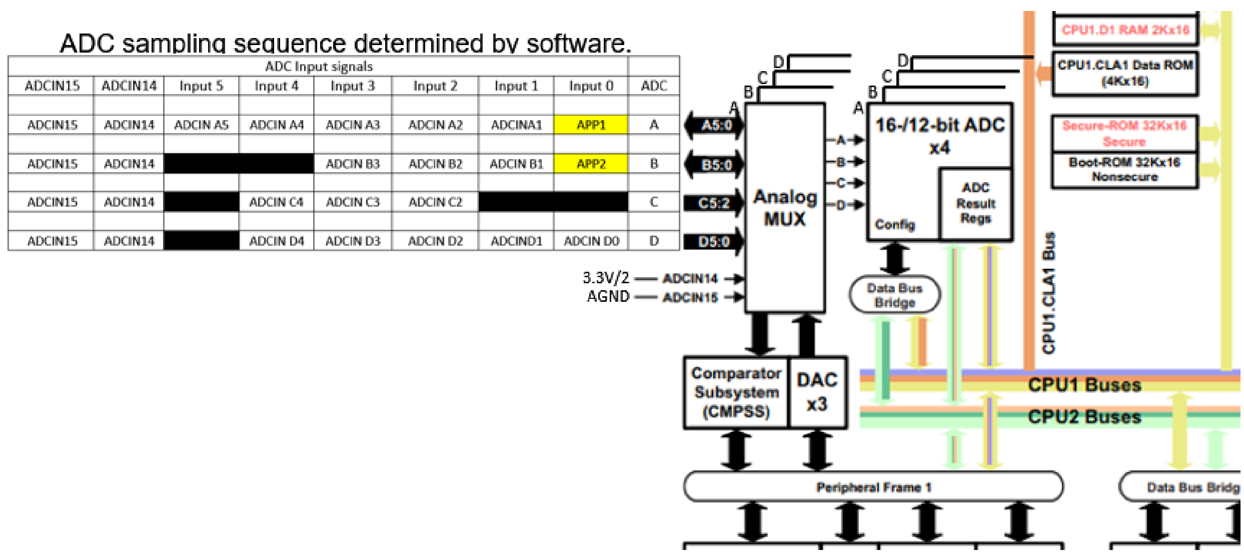



Figure 3. Interface circuitry must be included between the sensors and the ADC's. A voltage divider must be used to get within the 0 to 3.3V range of the ADC's and a unity gain amplifier must be added to increase the output current to the ADC's. An optional EMI filter may also be used to eliminate high frequency EMI interference or else shielded cables may be used for the same purpose.

Finally, inside the DSP chip an analog multiplexer is usually present at the input to each ADC to allow selection of the analog signals to be digitized by each ADC, as shown in Figure 4. These analog signals include signals from the two accelerator pedal sensors, along with other sensors as shown in Table 1. These signals are applied to the DSP pins as shown in Figure 5. The presence of all of these interface circuits increases the likelihood that there can be differences in the gain and offset of each ADC channel as shown in Figure 6. These differences can be minimized by calibrating each ADC channel using the same external calibration signal. We will now describe how this is done.



ADC sampling sequence determined by software.

| ADC Input signals | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ADCIN15 | ADCIN14 | Input 5 | Input 4 | Input 3 | Input 2 | Input 1 | Input 0 | ADC |
| ADCIN15 | ADCIN14 | ADCIN A5 | ADCIN A4 | ADCIN A3 | ADCIN A2 | ADCINA1 | APP1 | A |
| ADCIN15 | ADCIN14 | | | ADCIN B3 | ADCIN B2 | ADCIN B1 | APP2 | B |
| ADCIN15 | ADCIN14 | | ADCIN C4 | ADCIN C3 | ADCIN C2 | | | C |
| ADCIN15 | ADCIN14 | | ADCIN D4 | ADCIN D3 | ADCIN D2 | ADCIND1 | ADCIN D0 | D |



Figure 4. Interface circuitry inside the DSP chip includes an analog multiplexer for each ADC input to allow selection of the analog signals to be digitized by each ADC. In this example, the TI TMS320F28379 DSP has four ADC's with an analog multiplexer on each ADC input. The assignment of analog signals to a given ADC input can be determined by probing the DSP pins as shown in Figure 5. Note that the signals on two of the DSP pins are common to all four ADC channels. This allows one or two signals to be used for ADC calibration.[2]

Table 1. Analog signals multiplexed into the ADC's

| Analog sensor inputs for ICE engine controllers | Analog sensor inputs for eV motor controllers |
|---|---|
| Accelerator pedal sensors (A, B) | Accelerator pedal sensors (A, B) |
| Throttle position sensor | Rotor position sensor (sin, cos) |
| Camshaft position sensor | Motor current sensors ($\varphi$A, $\varphi$B) |
| Crankshaft position sensor | DC link high voltage sensor |
| Mass air flow sensor | 12V battery supply sensor |
| Manifold absolute pressure sensor | Assorted temperature sensors |
| Oxygen or air/fuel ratio sensor | Motor temperature |
| Vapor pressure sensor | Battery coolant temperature |
| Anti-knock sensor | Vehicle speed sensor |
| Intake air temperature sensor | Wheel speed sensors |
| Engine coolant temperature sensor | Tire pressure sensors |
| Vehicle speed sensor | HV interconnect safety sensor |
| Wheel speed sensors | ADC calibration voltage |
| Tire pressure sensors | |
| ADC calibration voltage | |

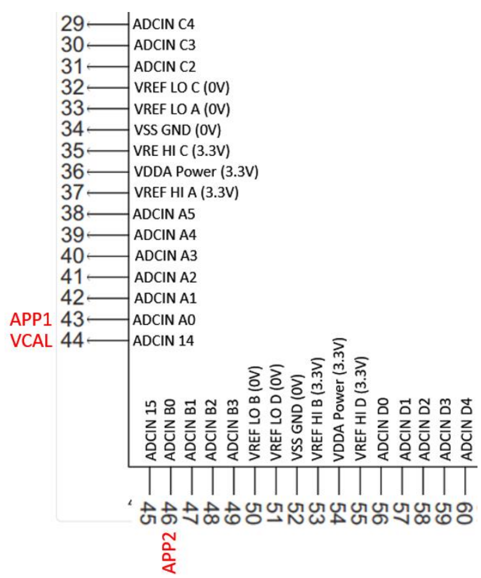



Figure 5. Analog portion of a DSP pin diagram showing the assignment of ADC inputs to DSP pins. By probing these pins one can determine which analog signals go to each ADC. In this case the two APP sensor signals go to different ADC's while the $V_{CAL}$ signal goes to all four ADC's.

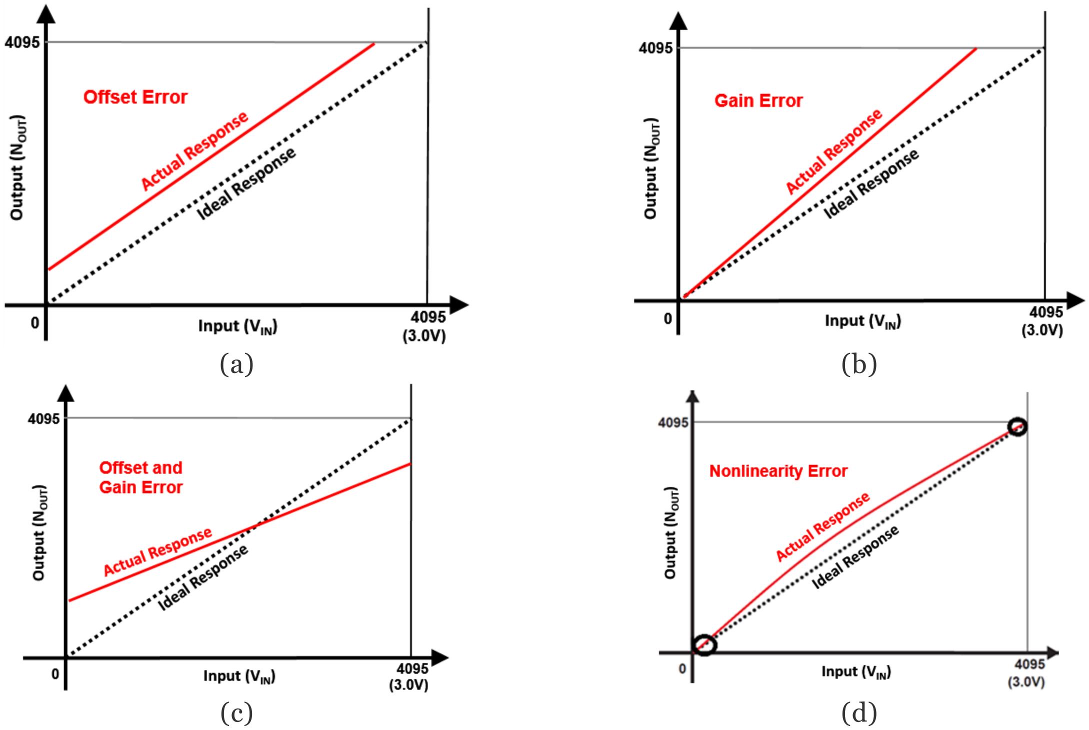



Figure 6. ADC channels can have offset, gain, and nonlinearity errors as shown in red above. The errors shown here are exaggerated for clarity. Calibration minimizes these errors by digitizing two known points on the actual response curve to determine the slope and offset of a linear approximation to the response curve, and then using the inverse slope of this linear approximation to calculate an unknown ADC input value from its measured ADC output value.

## <u>ADC Calibration</u>

The most common approach used to calibrate an ADC is the so-called two-point calibration process. This process is preferred by many because it uses a small number of calculations to minimize the computation time involved. This process has been described by Texas Instruments in their Application Report SPRAAD8A - March 2007 entitled "TMS320280x and TMS3202801x ADC Calibration", which they recommend for all the ADC's on their DSP devices.[3] This process will now be described by using the same figure and equations as found in the TI report. However, to aid the reader in following the somewhat abstract mathematical symbology used by TI, a second set of symbols and equations has been included which may be more intuitive and easier to understand.

First, TI uses Figure 7 to show the relationship between an ideal ADC response curve and a linearized version of an actual ADC response curve. It then shows how the slope *ma* of this linearized response curve is calculated by using two calibration inputs *xH* and *xL*, which give two ADC outputs *yH* and *yL*. These inputs and outputs are defined further by:

$$\begin{aligned} xL &= \text{known reference low input} = V_{IN}(CAL)_L \\ xH &= \text{known reference high input} = V_{IN}(CAL)_H \\ yL &= \text{reference low ADC output} = N_{OUT}(CAL)_L \\ yH &= \text{reference high ADC output} = N_{OUT}(CAL)_H \,. \end{aligned}$$

Then, by using the inverse of this slope, one can calculate the value of an arbitrary unknown input signal $x$ = $V_{IN}$(SIG) that produces the digitized ADC output value $y$ = $N_{OUT}$(SIG). How this is done is described further in Table 2.

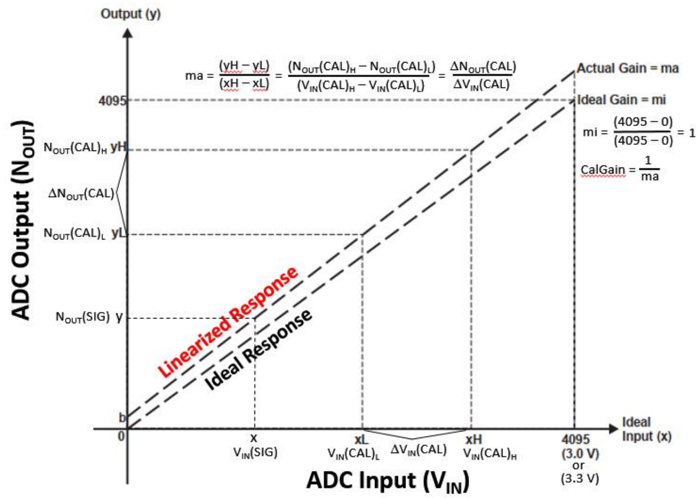



Figure 7.

Table 2.

| The two-point calibration process involves the following five basic steps: | |
|---|---|
| 1. Read the reference connected to ADCLO, set the offset to +10 LSB's (only once from boot) | |
| 2. Input the known reference values xL and xH and read their digitized ADC outputs yL and yH. | $V_{IN}(CAL)_L$ and $V_{IN}(CAL)_H$. $N_{OUT}(CAL)_L$ and $N_{OUT}(CAL)_H$ |
| 3. Calculate the calibrated ADC gain (CalGain) using equation 6.[a] | $\text{CalGain} = \frac{(xH - xL)}{(yH - yL)} = \frac{\Delta V_{IN}(CAL)}{\Delta N_{OUT}(CAL)}$ (6) |
| 4. Calculate the calibrated ADC offset (CalOffset) using equation 7. | $\text{CalOffset} = (yL \times \text{CalGain}) - xL$ (7) $\text{CalOffset} = (N_{OUT}(CAL)_L \times \frac{\Delta V_{IN}(CAL)}{\Delta N_{OUT}(CAL)}) - V_{IN}(CAL)_L)$ |
| 5. Cycle through all the signals to be digitized by applying the calibration Equation 5. | $x = (y \times \text{CalGain}) - \text{CalOffset})$ (5) $V_{IN}(SIG) = (N_{OUT}(SIG) \times \frac{\Delta V_{IN}(CAL)}{\Delta N_{OUT}(CAL)}) - \text{CalOffset}$ |

a. CalGain is the inverse of the actual gain *ma*. CalGain multiplies an output to get its input while *ma* multiplies an input to get its output.

This two-point calibration process can be simplified further by choosing the lower calibration point xL = $V_{IN}(CAL)_L$ to be zero. In this case $\Delta V_{IN}$(CAL) becomes just $V_{IN}$(CAL) and $\Delta N_{OUT}$(CAL) becomes just $N_{OUT}$(CAL) because the two offsets cancel in the difference. Therefore,

$$V_{IN}(SIG) = (N_{OUT}(SIG) \times \frac{V_{IN}(CAL)}{N_{OUT}(CAL)}) - \text{CalOffset} .$$

From this equation one can see that if $N_{OUT}$(CAL) decreases, then $V_{IN}$(SIG) increases even though $N_{OUT}$(SIG) does not change. This behavior can cause serious problems if one does not exercise careful control over the value of the calibration voltage $V_{IN}$(CAL), because $N_{OUT}$(CAL) can decrease if $V_{IN}$(CAL) decreases while it is assumed to remain constant.

**Ratiometric Pedal Sensors**

Auto manufacturers have found that accelerator pedal sensor outputs can vary with time and temperature as a result of the supply voltage changing with time and temperature even when a regulated +5V is used for the supply voltage[4]. In order to minimize these sources of error, manufacturers have used ratiometric sensors for the accelerator pedal sensors. Ratiometric sensors have the behavior that if the supply voltage increases or decreases by a given ratio, then the sensor outputs increase or decrease by the same ratio. This alone does not eliminate the errors caused by changes in the supply voltage with time and temperature. It is also necessary to calibrate an ADC using the sensor supply voltage, and then to digitize the sensor outputs using the ADC calibrated by this supply voltage, as shown in Figure 8.[5] When this is done, it is found that a decrease in the sensor supply voltage will increase the digitized ADC sensor output voltage by exactly the same ratio as the analog sensor output decreases, resulting in a sensor output that is free of time and temperature errors. An increase in the sensor supply voltage is also removed in the same manner.

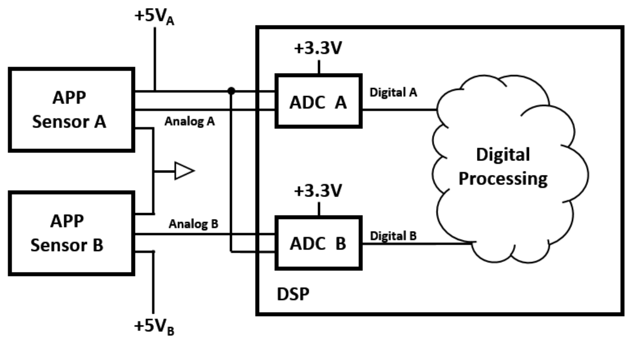



Figure 8. Ratiometric sensors correct for time and temperature errors in the sensor supply voltage that increase or decrease the supply voltage by a given ratio, causing the sensor outputs to increase or decrease by the same ratio.

All accelerator pedal sensors is use today have this ratiometric property, whether they utilize Hall effect sensors, induction type sensors, or potentiometer type resistive sensors.[6] This implies that all auto manufacturers who use these ratiometric sensors must also calibrate their ADC's with the sensor supply voltage. Since all accelerator pedal sensors use a +5V supply voltage, this means that all auto manufacturers calibrate their ADC's with a regulated +5V supply voltage, suitably attenuated to match the 3.3V or 3.0V input range of the ADC's. This same design approach is used by all auto manufacturers, whether their vehicles use internal combustion engines (ICE vehicles) or electric drive motors (eV's). Therefore, all auto manufacturers have a similar susceptibility to defects in the accelerator pedal digitization process. However, some auto manufacturers may use additional design techniques to mitigate these potential defects, like testing the digitized values of the +5V supply voltage and rejecting any values that are not normal.

## Summary of operations performed on the APP sensor signals

Based on the information discussed thus far, which relies on the ADC interface circuitry, the ADC calibration technique, and the information on ratiometric sensors, we can now create a flow diagram showing all the operations performed on the two APP sensor signals by both the hardware and the software. This flow diagram is shown in Figure 9. It assumes that the two APP sensor signals have amplitudes that vary as shown in Figure 10, which applies to many vehicles on the market today.

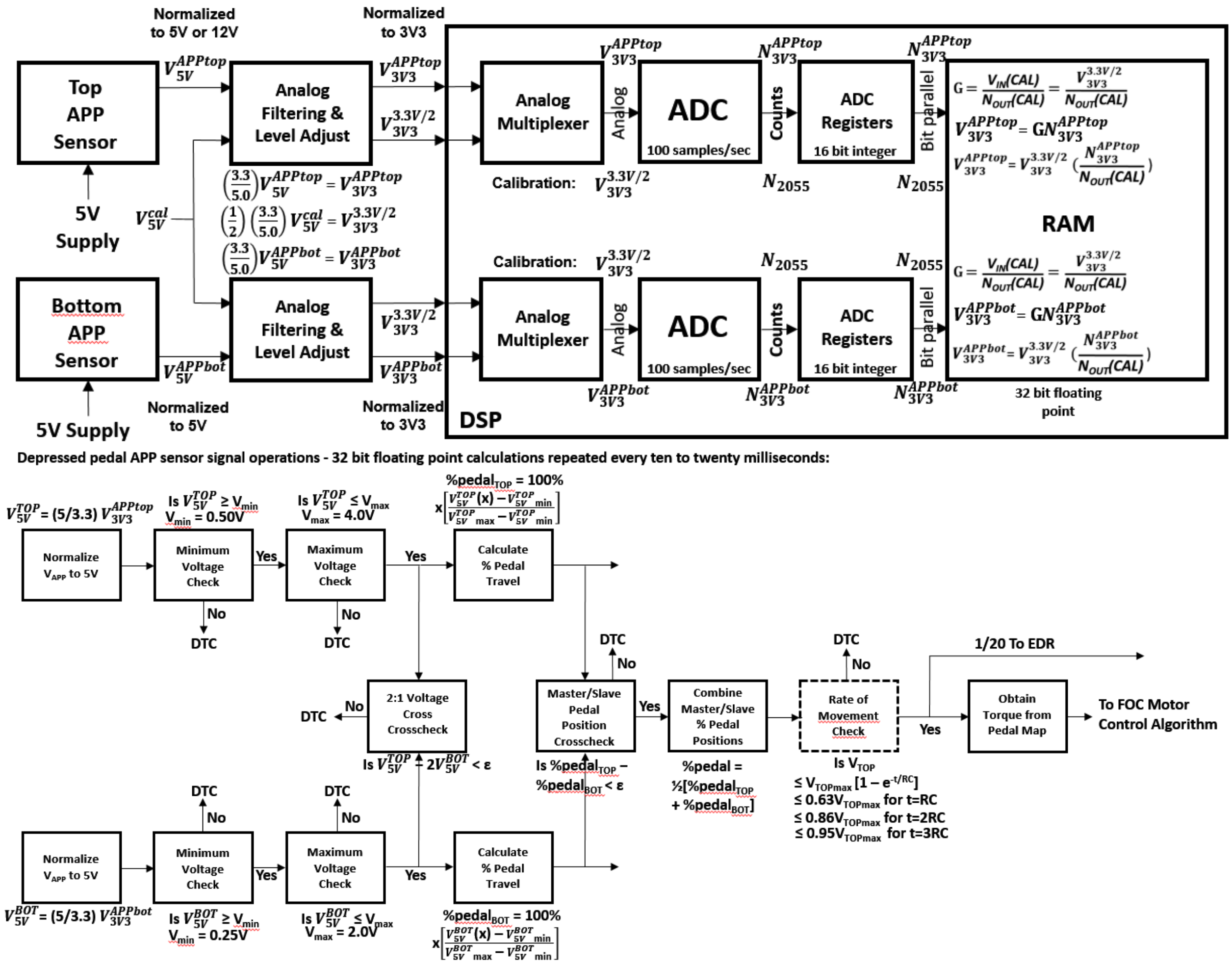



Figure 9. Summary of operations performed on the APP sensor signals. The top figure shows the digitization process while the bottom figure shows the tests done on the digitized APP sensor signals. If a test fails, then vehicle propulsion is inhibited and a diagnostic test code (DTC) is supplied. These DTC's are not specified at this time. The rate of movement check may be used by some, but not all, vehicles.[7]

Figure 10 shows that the two APP sensor signals, which may be created using separate 5V voltage regulators on a separate power management integrated circuit (PMIC) chip, can vary between 0.50 and 4.0V for the top APP sensor and between 0.25V and 2.0V for the bottom APP sensor. Before applying these two APP sensor signals to the inputs of two different ADC's as shown in Figure 10, these voltages must be converted from a 5V basis $V_{5V}$ to a 3.3V basis $V_{3V3}$ by dividing them down using voltage dividers, which multiplies them by the ratio 3.3V/5V. The $V_{3V3}$ signals are then digitized by the ADC's, which give the results as a number of counts $N_{3V3}$ based on the maximum ADC signal $V_{REF}$ being 3.3V. The voltage corresponding to this number of counts is the voltage $V_{3V3}$ equal to $N_{3V3}$ times the gain G of the ADC where the gain $G = 3.3V/N_{MAX}$, with $N_{MAX}$ being the maximum number of counts the ADC can produce. For a 10-bit ADC, $N_{MAX} = 1023$ and for a 12-bit ADC, $N_{MAX} = 4095$. The voltages $V_{3V3}$ are then transferred into CPU RAM as 32-bit floating point values. Before any checks can be performed on the two APP sensor signals, these $V_{3V3}$ values must first be converted back into a $V_{5V}$ values by multiplying by 5V/3.3V. Then, the two signals are checked to see if they lie within the limits of the maximum and minimum signals based on 5V. If either signal falls outside the operating

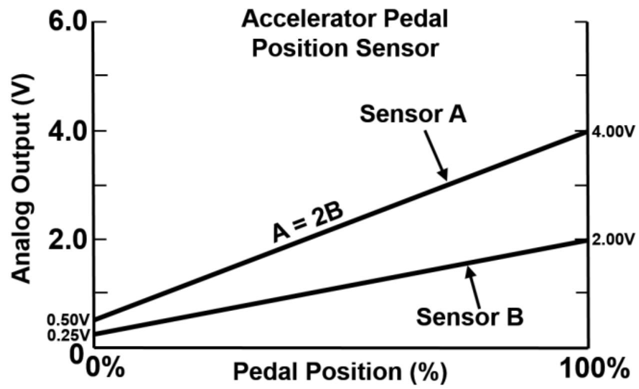



Figure 10. Transfer functions of the APP sensor signals from a typical accelerator pedal.[8] The top sensor is always twice the voltage of the bottom sensor, with the top sensor increasing from 0.50V to 4.0V as the pedal is pressed from 0% to 100% while the bottom sensor increases from 0.25V to 2.0V as the pedal is pressed from 0% to 100%.

limits, then the vehicle torque is limited to a small limp home value and a DTC is posted. A cross check is then performed to determine whether the top APP signal is equal to twice the bottom APP signal within some error limit. If this test fails, then the drive motor torque is set to zero and a DTC is posted. If this test is passed, the % pedal travel for each sensor is then calculated as

$$\%\ \text{pedal} = 100\% \left[\frac{V_{5V}^{TOP}(\text{x}) - V_{5V}^{TOP}{}_{\text{min}}}{V_{5V}^{TOP}{}_{\text{max}} - V_{5V}^{TOP}{}_{\text{min}}}\right],$$

and a cross-check is performed to determine if the pedal % values are equal to within 10%. If this test fails, then the vehicle torque is set to zero and a DTC is posted. If this test is passed, then the two pedal % values are combined to form a single % pedal value that is used for two purposes: 1) every twentieth value is sent to the EDR via a message on the CAN bus, and 2) the % pedal is then tested to determine if the rate of movement is within the limits for a normal driver-induced signal. If this test fails, then the vehicle torque is limited to zero and a DCT is posted. If the test is passed, then the % pedal signal is used to access the pedal map to obtain a % torque command that is given to the engine or drive motor. Finally, Figure 10 shows that the $V_{3V3}^{3.3V/2} = \left(\frac{1}{2}\right)\left(\frac{3.3}{5.0}\right) V_{5V}^{cal}$ calibration signal is common to all four ADC's. We will now discuss this calibration signal in greater detail.

**<u>The ADC calibration signal is key to proper digitization of the APP signals</u>**

Table 3 shows three cases of how $N_{CAL}$ and $V_{APP}$ can vary. In case 1, an accelerator pedal sensor is used whose outputs are ratiometric to the supply voltage. This allows one to correct the sensor outputs for temperature and noise if one knows how the supply voltage changes. But if calibration is done with a fixed calibration voltage instead of the sensor supply voltage, then there is no way to determine how the sensor supply voltage changes. Therefore, one can't correct for the temperature and noise errors in the sensor outputs even though one uses a ratiometric sensor. So, using a fixed calibration voltage does not remove errors in the digitized sensor voltages.

In case 2, an accelerator pedal sensor is used whose outputs are ratiometric to the supply voltage. But this time, ADC calibration is done using a ratio of the APP sensor's 5V supply voltage, $kV_{APP\_SUPPLY}$ = k x 5V. This yields the desired APP sensor outputs even in the presence of time and temperature variations as high as 50% because the ADC calibration changes to remove these variations by exactly the same amount. This is the situation desired by all vehicle manufacturers.

Table 3. Three cases of how $N_{CAL}$ and $V_{APP}$ can vary.

| | Case 1.<br>$V_{CAL}$ independent of $V_{5V}$<br>$N_{APP}$'s are ratiometric | | | Case 2.<br>$V_{CAL} = k\ V_{APP\_SUPPLY}$<br>$N_{APP}$'s are ratiometric | | | Case 3.<br>$V_{CAL}$ can change while<br>$V_{APP\_SUPPLY}$ does not change | | |
|---|---|---|---|---|---|---|---|---|---|
| | *N* | *V* | *V* | *N* | *V* | *V* | *N* | *V* | *V* |
| Set $V_{FULLSCALE}$= 3.3V with $N_{FULLSCALE}$= 4095 | 4095 | 3.3V | 5.0V | 4095 | 3.3V | 5.0V | 4095 | 3.3V | 5.0V |
| Digitize 3.3V/2 = 1.65V, get $N_{CAL}$. Calibrate gain G with Eq 1. | 2055 | 1.65V | 2.5V | 1027[a] | 1.65V | 2.5V | 1027[b] | 1.65V | 2.5V |
| Digitize $APP_{TOP}$(max), get $N_{APP}$, calculate $VAPP_{TOP}$(max) by Eq 2. | 1638[a] | 1.31V | 2.0V | 1638[a] | 2.63V | 4.0V | 3276 | 5.26V | 8.0V SNA |
| Digitize $APP_{TOP}$(min), get $N_{APP}$, calculate $VAPP_{TOP}$(min) by Eq 2. | 278[a] | 0.225V | 0.34V | 278[a] | 0.45V | 0.68V | 557 | 0.90V | 1.36V |
| Digitize $APP_{BOT}$(max), get $N_{APP}$, calculate $VAPP_{BOT}$(max) by Eq 2. | 819[a] | 0.66V | 1.0V | 819[a] | 1.32V | 2.0V | 1638 | 2.64V | 4.0V SNA |
| Digitize $APP_{BOT}$(min), get $N_{APP}$, calculate $VAPP_{BOT}$(min) by Eq 2. | 140[a] | 0.112V | 0.17V | 140[a] | 0.225V | 0.34V | 279 | 0.45V | 0.68V |
| Result | If $V_{APP\_SUPPLY}$ decreases by 50%, but calibration does not change because $V_{CAL}$ is constant, then ratiometric APP signals are decreased by 50% | | | If $V_{CAL} = k\ V_{APP\_SUPPLY}$, and APP signals are ratio-metric, then the desired APP signals are obtained when $V_{APP\_SUPPLY}$ decreases by 50%. | | | If $N_{CAL}$ decreases by 50% while $V_{APP\_SUPPLY}$ does not change, then APP signals are increased by 50% with foot off pedal to cause SUA. | | |
| Eq 1 | $G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{2055}\right)$ | | | $G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{1027}\right)$ | | | $G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{1027}\right)$ | | |
| Eq 2 | $V_{APP} = N_{APP}\,G$ | | | $V_{APP} = N_{APP}\,G$ | | | $V_{APP} = N_{APP}\,G$ | | |
| Example | $V_{APP} = 1368\ G$<br>$V_{APP} = 1638\left(\frac{1.65V}{2055}\right)$ | | | $V_{APP} = 1368\ G$<br>$V_{APP} = 1638\left(\frac{1.65V}{1027}\right)$ | | | $V_{APP} = 3276\ G$<br>$V_{APP} = 3276\left(\frac{1.65V}{1027}\right)$ | | |

a) A factor of two change in $N_{APP}$ has been used to make the changes more noticeable. Normal changes are only a few percent.
b) While a factor of two change in $N_{CAL}$ has been use for clarity, changes caused by a voltage dip in the 5V supply during digitization can reduce $N_{CAL}$ by a factor of 6 or more, causing $V_{APP}$ to increase by 6X or more.

In case 3, an interesting situation is considered in which the APP sensor is assumed to have no changes due the driver pressing on the accelerator pedal. But the ADC calibration voltage can decrease momentarily because of a voltage dip condition caused by a negative-going voltage spike occurring while the calibration voltage is being digitized. In this case, the APP sensor outputs are <u>increased</u> by the inverse ratio that the ADC calibration voltage decreases. Therefore, if the ADC calibration voltage decreases by a factor of 2 as a result of the APP supply voltage decreasing from 5V to 2.5V, then the APP sensor outputs can increase by a factor of 2, causing both APP sensors to read 2 times higher even though the accelerator pedal is not pressed. This can happen because the two APP sensors have non-zero output values even when the accelerator pedal is not pressed. And because both APP sensor outputs are multiplied by the same calibration value, these two non-zero sensor outputs continue to have same 2:1 ratio to each other when the calibration value increases as aa result of an under-voltage in the calibration signal. This means that sudden unintended acceleration can occur even though the driver does not step on the accelerator pedal.

So, how can a negative-going voltage spike occur on the attenuated 5V calibration voltage while it is being digitized by the ADC? First, the negative-going voltage spike can occur on the "12V" supply line because it is used by the electric power steering booster motor, which draws a whopping 100A or greater DC current in some heavy vehicles. Then, when the power assist motor in this system is suddenly turned on by turning the vehicle's steering wheel while making a sharp low-speed turn in a parking lot, the assist motor suddenly draws an inrush current three to five times higher than the DC current for several hundred microseconds. This higher inrush current can't be supported by the "12V" battery, which can supply a maximum current of only 100A or less, or a DC/DC converter, which can only supply about 200A or less. Therefore, the "12V" supply line is pulled down to near zero volts for several hundred microseconds. See Figures 12 and 13 which provide evidence on the existence these voltage dips.

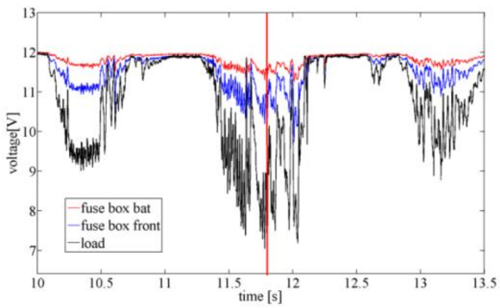



Fig. 11. Voltage spikes on the "12V" supply line of an ICE vehicle as caused by an electronic power steering (EPS) system during a slalom maneuver.[9]

NHTSA Recall 18V-586 for temporary loss of electric power steering (EPS) in GM vehicles (Sep 2018):

- "These vehicles may experience a temporary loss of EPS assist followed by a sudden return of EPS assist, particularly during low-speed turning maneuvers"
- "Events that demand high current, such as low speed turns, can cause temporary low voltage conditions. When the system voltage drops below 8.8 volts for more than 1 second—e.g., during low-speed turns—EPS assist is disabled until voltage returns to 9 volts for a minimum of 40 milliseconds, at which point EPS assist returns"
- "The loss and sudden return of EPS assist typically happens within a 1 second period
- Affects more than 1M pickups & SUVs

Fig. 12. NHTSA recall 18-586 mentions EPS causes voltage drops below 8.8V for more than one second during low speed turns causing loss of EPS.[10]

If we now look at the spec sheet for a typical PMIC chip, we find that the ADC, APP1, APP2, and CAN power supplies continue to operate during an under-voltage condition.[11] This means that the attenuated 5V calibration voltage used to create the ADC calibration voltage continues to operate, but with a short negative-going voltage spike superimposed on it that lasts several hundred microseconds. If this voltage spike occurs while the ADC calibration voltage is being digitized, then an incorrect ADC calibration voltage will be produced that is very close to zero volts. It will last until another ADC calibration is performed, which may be minutes later.

One may ask why a dip in the APP sensor analog outputs caused by a dip in the APP supply voltage is not removed by an ADC calibrated with the APP supply voltage if ratiometric sensors allow time and temperature errors in the APP sensor analog outputs to be removed by an ADC calibrated with this same sensor voltage. To ask this question in another way, if ratiometric sensors that are digitized by an ADC calibrated with the sensor supply voltage are able to have time and temperature variations removed from their digitized sensor outputs, then why can't a voltage dip be removed from the sensor outputs in the same manner? The answer is that for a voltage dip to be removed in this manner requires that the same voltage dip be present when both the calibration voltage and the two analog sensor outputs are digitized. But this voltage dip is extremely short, being only about 100 microseconds long. Therefore, if the voltage dip is present when the ADC calibration voltage is digitized, then it is practically impossible for this same voltage dip to be present later when the sensor output is digitized by the same ADC. This is because an ADC can't switch rapidly enough between two different signals. And even if it could, then only one sample of the sensor output would have the voltage dip removed in this manner. All succeeding samples of the analog sensor output would not have this voltage dip present to be removed because succeeding samples arrive every 10 milliseconds later, by which time the short voltage dip is long gone. However, the ADC calibration that is used to correct all succeeding samples of the analog sensor output still has the effects of the calibration voltage that contains the voltage dip because this calibration is stored in digital memory until a new value of the sensor supply voltage is digitized. Therefore, all succeeding samples of the analog sensor output will be increased in value because the ADC calibration is affected by the voltage dip while the analog sensor outputs are not.

## II. Vehicle Operation During Sudden Acceleration

During sudden acceleration the ADC calibration process used during normal vehicle operation does not work as expected. This is because the APP sensor supply voltage can also have very short-duration negative-going voltage spikes superimposed on it as a result of in-rush currents from electric motors and electric solenoids turning on that are powered by the "12V" supply voltage from which the APP sensor supply voltage used for calibration is derived. These in-rush currents on the “12V” supply voltage can be very high (>300 amps) due to the low resistance of the motors involved (<10 ohms) causing the 12V supply voltage to drop down to 7v or less for a short time period on the order of a hundred microseconds or less. In some cases, the “12V” supply voltage can go as low as 2V or less, causing the ADC calibration voltage to drop to 0.275V or less. If the attenuated sensor supply voltage is being sampled while one of these negative-going voltage spikes occurs, then the ADC calibration voltage will read 0.275V or less, causing the voltage correction to both APP sensor signals to be (1.65/1.275V), or nearly a factor of six higher. And since both APP sensor signals are increased by the same ratio, both corrected APP sensor signals will pass all the signal checks done on the two APP sensor signals, producing an immediate increase in the vehicle’s drive motor torque without the driver stepping on the accelerator pedal. The result is a sudden increase in the drive motor torque leading to a sudden unintended acceleration.

One can see more clearly how a decrease in the ADC calibration voltage $V_{CAL}$ can cause the APP sensor signals to increase in a way that mimics the driver stepping on the accelerator pedal by using a table containing different calibration voltages. Table 4 shows how the APP sensor signals change with different calibration voltages when the accelerator pedal is released. These changes produce non-zero digitized APP sensor signals similar to when the driver has his foot on the accelerator pedal even though the driver’s foot is off the accelerator pedal.

Table 4. Decreases in the ADC calibration voltage cause increases in the digitized APP sensor output voltage in a way that mimics stepping on the accelerator pedal

| Released pedal APP analog voltage[a] | % pedal from analog | 12V Supply Voltage[b] | $V_{CAL}$ Calibration Voltage[b] | Correction factor X for $V_{CAL}$ Voltage | Digitized APP signal after Calibration | % pedal after Calibration |
|---|---|---|---|---|---|---|
| 0.50V | 0% | 12.6V | 1.650V | 1 | 0.50V | 0% |
| 0.50V | 0% | 6.3V | 0.825V | 2 | 1.00V | 14% |
| 0.50V | 0% | 4.2V | 0.550V | 3 | 1.50V | 29% |
| 0.50V | 0% | 3.2V | 0.412V | 4 | 2.00V | 43% |
| 0.50V | 0% | 2.5V | 0.330V | 5 | 2.50V | 57% |
| 0.50V | 0% | 2.0V | 0.275V | 6 | 3.00V | 71% |
| 0.50V | 0% | 1.7V | 0.236V | 7 | 3.50V | 86% |
| 0.50V | 0% | 1.5V | 0.206V | 8 | 4.00V | 100%[c] |

a. The table shows only the upper APP sensor. The lower APP sensor is affected in exactly the same way, allowing both APP sensors to pass all tests performed on the two APP sensor signals after the signals have been corrected for ADC calibration while the driver’s foot is off the accelerator pedal.
b. These voltages are the voltages digitized during a temporary voltage dip caused by an inrush current from a high current power steering motor. The DC values of these supply voltages remain unchanged.
c. A value >100% produces a SNA signal (Signal Not Available), which has been seen in some EDR readouts.

Figure 13 shows the values X in Table 4 that multiply the released APP sensor signals after they have been calibrated superimposed on the transfer function (APP sensor voltage vs pedal depression) of the normal APP sensor signals. One can see that the released APP sensor signals, when corrected for a decrease in the ADC calibration voltage, lie on the same transfer function as the original APP sensor signals, making it clear that they will pass all tests performed on the original APP sensor signals.

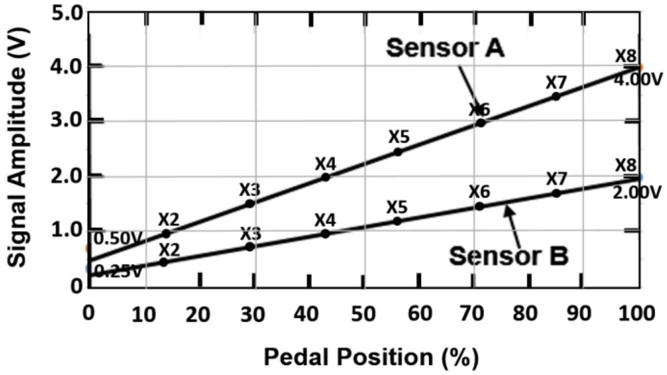


Figure 13. APP signal transfer functions showing that multiplying the released pedal values by the factors xN produces values that lie on the same curves as the original transfer functions, allowing the corrected signals to pass all tests performed on the original APP signals.

Even worse, both incorrectly increased APP sensor signals will be sent via the CAN bus to the the EDR, causing the vehicle manufacturer and NHTSA to conclude that the driver caused the sudden increase in torque by stepping on the accelerator pedal. But in this case the sudden acceleration was caused not by the driver stepping on the accelerator pedal, but by a random superposition of a negative-going voltage spike (which is about 100 microseconds long), and the sampling time of the ADC (which is about 10 microseconds long). This random superposition explains the low rate of occurrence of sudden acceleration in some vehicles of about $20x10^{-4}$ events per vehicle-year. And the chances of an event happening are increased when high current loads like electronic power steering are turned on more often while in low-speed driving situations like parking lots and traffic intersections, where turns are made at low speed causing power steering motors to turn on under high counterforces.

So, to summarize what is happening, the vehicle's ECU calibrates all four ADC's using the same ADC calibration signal. If the ADC calibration signal decreases, then the APP sensor signals increase by the inverse ratio that the ADC signal decreases. This normally does not happen because the ADC calibration signal and the APP sensor bias voltages are created by regulated 5V supply voltages that mask the slow DC changes in the 12V supply voltage from which they are obtained. These changes in the 12V supply voltage are usually very small, being less than 10% due to changes in the state of charge (SOC) of the 12V battery. Therefore, the APP sensor output voltages see no changes in the ADC calibration signal, and are changed only by the driver stepping on the accelerator pedal.

But once in a while a negative-going voltage spike can occur on the "12V" supply line. In this case, the PMIC chip that provides the ADC VREF, APP1, APP2, and CAN power supplies continues to operate during an under-voltage condition.[12] This means that the attenuated 5V calibration voltage used to create the ADC calibration voltage continues to operate, but with a short negative-going voltage spike superimposed on it that lasts several hundred microseconds. If this voltage spike occurs while the ADC calibration voltage is being digitized, then an incorrect ADC calibration voltage will be produced that is 0.275V or less, which is 1/6 the original calibration voltage. When this lower ADC calibration voltage is used to multiply the two APP sensor signals by the usual factor $V_{CAL}/N_{CAL}$, the two APP sensor outputs get increased by a factor much larger than the usual 10%, but more like a factor of 2 to 6. Yet, the increased APP sensor signals still pass all checks performed on the two APP signal amplitudes because the larger changes are still indistinguishable from changes normally made by the driver as he presses the accelerator pedal to the floor. These large 12V supply voltage corrections occur even though the driver does not press on the accelerator pedal. They depend on the fact that the APP sensor readings are not zero when the accelerator pedal is released, but are some small nonzero value like a half a volt. So when the APP sensor readings are multiplied by the factor $V_{CAL}/N_{CAL}$, it is not like multiplying the number zero to get zero, but the resulting non-zero released APP sensor outputs get multiplied by a factor of 2 to 6 times to become a much larger number. Yet, since the larger APP sensor outputs are indistinguishable from the values produced when the driver presses the accelerator pedal, they are treated as normal by the subsequent pedal monitor checks and are sent on to the pedal map to generate a motor torque and to be recorded by the EDR. The result is sudden unintended acceleration, with the driver being accused of stepping on the accelerator pedal to cause the acceleration because the EDR data show that the APP sensor signals have been increased. But although the driver did not step on the accelerator pedal, he cannot convince the vehicle manufacturer or NHTSA that he did not step on the accelerator pedal because everyone says that the only way the APP sensors can increase is by stepping on the accelerator pedal. As a result of this belief, some drivers may even concede that they unknowingly stepped on the accelerator pedal instead of the brake pedal when they possibly did not.

## III. Verification of This Cause of Sudden Acceleration

One can verify that the proposed cause of sudden acceleration is correct by opening the ECU to access the motor controller PWB as shown in Figure 14A. Then, one can lift the DSP pin for the ADC calibration voltage from its PWB pad and attach a wire to the lifted pin as shown in Figure 14B below. This wire can then be passed through the ECU connector on one of its three unused pins. If this wire is then accessed on the other side of the ECU connector when the ECU is closed back up, one can then impose a variable voltage on the wire. If one keeps this voltage

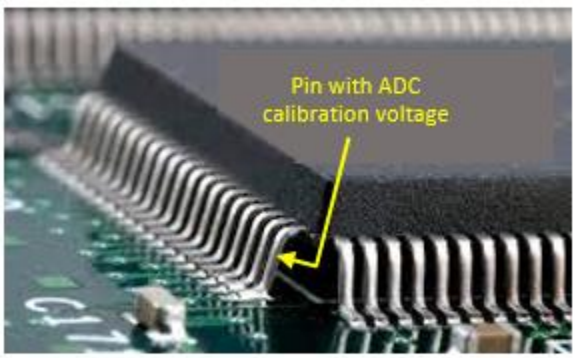



Figure 14A. DSP pin for the ADC calibration voltage which uses a ratio of the APP sensor supply voltage

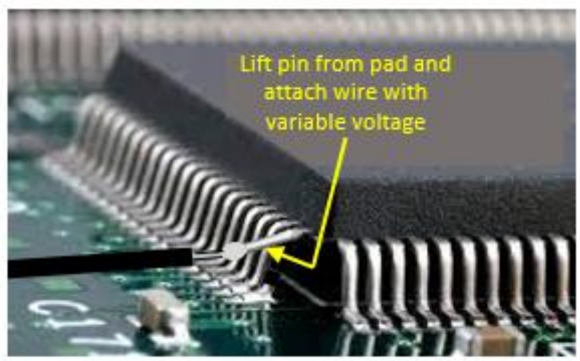



Figure 14B. Lift the DSP pin with the ADC calibration voltage and attach a wire with a variable voltage.

constant at 5V scaled down to 1.65V, then the vehicle will run normally with torque being varied by pressing on the accelerator pedal. But if one changes this voltage to 0.206V or less, which can happen when the 12V supply dips temporarily to 1.5V, then the APP sensor outputs will read 4V and 2V, which is equivalent to flooring the accelerator pedal. This causes sudden unintended acceleration without the driver pressing on the accelerator pedal.

## IV. Elimination of Sudden Acceleration

Knowing the potential cause of sudden acceleration allows one to come up with possible mitigation measures for eliminating the sudden acceleration. Adding more capacitance to the 12V supply line to eliminate the large negative-going voltage spikes is futile because the inrush currents are so high. But the following techniques for dealing with the spikes may be considered:

1) Add a second 12V supply line with its own battery and use it only for powering the APP sensors and the ADC's to provide clean power to these functions free of negative-going

voltage spikes from electric motors and solenoids. Use the existing 12V supply with its battery for all other 12V applications (dirty power).

    a. The battery for the APP sensors and the ADC's may tolerate a smaller capacity because its drain current will be lower as a result of other loads being removed.
    b. A battery for the APP sensors and the ADC's having the same capacity or larger may be used because it retains charge longer. In this case, a study may reveal that charging the battery once a day is sufficient.

2) Modify the calibration routine software for sampling the ADC calibration voltage by testing the calibration voltage before using it and then doing one of the following:
    a. If the sampled calibration voltage is found to be less than the normal calibration voltage, then don't change the calibration voltage from the previous value.
    b. If the sampled calibration voltage is found to be less than the normal calibration voltage, then use some default calibration voltage instead.
    c. If the sampled calibration voltage is found to be less than the normal calibration voltage, then set the two APP signal amplitudes to zero in order to cause the APP sensor checks to reject both amplitudes. This will then generate a DTC that can be used to take appropriate action.

## V. Summary and Conclusion

A hypothetical model has been constructed of all hardware and software operations performed on the two accelerator position sensor (APP) sensor signals inside the ECU as they pass from the APP sensor to the vehicle motor controller. Even though redundancy is used to eliminate the effects of single-point errors on the two APP sensor signals, and even though different ADC's are used to digitize the two signals, there are still some operations performed on the two signals that allow a single-point error to affect both APP sensor signals.

One of these operations is ADC calibration. ADC calibration leads to a susceptibility for unintended acceleration when a negative-going voltage spike can occur on the "12V" supply line that causes a temporary dip in the ADC calibration voltage while it is being digitized by the ADC's. When this lower calibration voltage is used to multiply the two APP sensor signals by the usual factor $V_{CAL}/N_{CAL}$, the two APP sensor outputs get increased by a factor of 1 to 6. Yet, the increased APP sensor signals still pass all checks performed on the two APP signal amplitudes because the larger changes are still indistinguishable from changes normally made by the driver as he presses the accelerator pedal to the floor. These large calibration corrections to the APP outputs occur even though the driver does not press on the accelerator pedal. They depend on the fact that the APP sensor outputs are not zero when the accelerator pedal is released, but are some small nonzero value like a half a volt. So when the APP sensor readings are multiplied by the factor $V_{CAL}/N_{CAL}$, it is not like multiplying the number zero to get zero, but more like multiplying the non-zero APP sensor outputs by a factor of 1 to 6 times to become a much larger number. Yet, since the larger APP sensor outputs are indistinguishable from the values produced when the driver presses the accelerator pedal, they are treated as normal by the subsequent pedal monitor checks and are sent on to the pedal map to generate a motor torque and to be recorded by the EDR. The result is sudden unintended acceleration, with the driver being accused of stepping on the accelerator pedal to cause the acceleration because the EDR data show that the APP sensor signals have been increased.

This mechanism for unintended acceleration does not require any defects in the accelerator pedal sensors or their analog outputs. This is why no DTC's are produced. Instead, it is caused by a change in the ADC calibration voltage used when the sensor outputs are digitized, which can make the digitized accelerator pedal sensor outputs increase to a maximum of 100% even though the analog accelerator pedal outputs remain unchanged because the accelerator pedal is not being pressed by the driver. These increased digital outputs mimic in every way the changes made when the driver steps on the accelerator pedal, but they are produced without the driver stepping on the accelerator pedal. This mechanism explains how sudden unintended acceleration can occur in many ICE and eV vehicles with the EDR accelerator pedal sensor data showing that the accelerator pedal was pressed during the incident even though the driver maintains that he/she did not press the accelerator pedal. A test for verifying this SUA mechanism is described, and solutions for this susceptibility to SUA are presented.

## VI. References

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[1] Texas Instruments, Application Report "*An Overview of Designing Analog Interface with MS320F28xx/28xxx DSC's*", SPRAAD6A, May 2008, p.6.

[2] If one purchases a used ECU, then the ECU can be opened to access the PWB. By reading the DSP part number on the PWB, one can obtain the spec sheet for that part and learn a lot about how the DSP is designed. One can then probe the DSP pins while varying the voltage of the APP sensor signals to determine which DSP pins are used for the APP signals and which ADC inputs are associated with them.

[3] Texas Instruments, Application Report "*TMS320280x and TMS3202801x ADC Calibration*", SPRAAD8A, March 2007. See also:

a) Christy She, Texas Instruments, "*Why Your Embedded ADC Does Not Perform to the Data Sheet and How to Improve its Performance, Part 2: Clock and Reference Selection*", https://embeddedcomputing.com/technology/analog-and-power/why-your-embedded-adc-does-not-perform-to-the-data-sheet-and-how-to-improve-its-performance-part-2-clock-and-reference-selection

b) Freescale Semiconductor, Application Note, "*Design, Accuracy, and Calibration of Analog to Digital Converters on the MPC5500 Family*", AN2989, Rev. 2, 02/2010.

[4] T. Isobe and N. Kobayashi, "*Method and Device for Internal Combustion Engine Condition Sensing and Fuel Injection Control*", US Patent 4580221, April 1, 1986. See also:

a) K Hashimoto et al, "*On-Vehicle Electronic Control*", US patent 7031822B1, April 18, 2006.

[5] Christy She, Texas Instruments, "*Why Your Embedded ADC Does Not Perform to the Data Sheet and How to Improve its Performance, Part 2: Clock and Reference Selection*", https://embeddedcomputing.com/technology/analog-and-power/why-your-embedded-adc-does-not-perform-to-the-data-sheet-and-how-to-improve-its-performance-part-2-clock-and-reference-selection

[6] Hella, "*Accelerator Pedal Sensors*", December 2008, contains specs for accelerator pedal sensors which state they are ratiomertic, p18. https://docplayer.net/43872926-Hella-accelerator-pedal-sensors-december-2008.html or https://www.allhella.ru/upload/msent.pdf2html/31d/Accelerator%20Pedals%20Truck.pdf See also:

a) Hella, "*Accelerator Pedal Sensor Brief Information*", containing spec sheet on 6PV_009_591-011 accelerator pedal which shows it is ratiometric and has A = 2B. https://www.hella.com/truck/assets/media_global/1571_Brief_info_Pedal_HELLA_EN.pdf

b) Renesas, "*Inductive Position Sensor IC*", dated 21 July 2020, showing that the sensor is ratiometric. https://www.renesas.com/us/en/document/dst/zmid520x-datasheet?r=249156

[7] Several automobile manufacturers use a pedal rate-of-motion test on the APP sensor signals, including Nissan, BMW, Land Rover. See:

1) Nissan http://muraniste-50.e-monsite.com/medias/files/z50muranolintroduction.pdf,
2) BMW, https://ia801005.us.archive.org/11/items/BMWTechnicalTrainingDocuments-/ST055%20Engine%20Electronics%20%28Archive%201%29/1%20M1-7-2.pdf
3) Land Rover, https://docplayer.net/102710214-Electronic-engine-controls.html

[8] http://www.nissantechnicianinfo.mobi/htmlversions/2013_Q50_Special/Mechanical.html and https://www.nisentra.com/component_parts-470.html

[9] T. Kohler, et.al., "*Experimental Investigation on Voltage Stability in Vehicle Power Nets for Power Distribution Management*", 2010 IEEE Vehicle Power and Propulsion Conference, Lille, France, 2010, pp. 1-6. http://www.iri.upc.edu/people/riera/VPPC10/vppc2010.univ-lille1.fr/uploads/PDF/papers/RT4/95-68107-final.pdf

[10] Phil Koopman, "*Automotive software defects*", https://betterembsw.blogspot.com/p/potentially-deadly-automotive-software.html

[11] Infineon data sheet, "*TLF35584 Multi Voltage Safety Micro Processor Supply*", Rev. 2.0, 2017-03-16, p. 86. https://www.farnell.com/datasheets/2820312.pdf

[12] Infineon data sheet, "*TLF35584 Multi Voltage Safety Micro Processor Supply*", Rev. 2.0, 2017-03-16, p. 86. https://www.farnell.com/datasheets/2820312.pdf