Tesla Model 3 Susceptibility to Sudden Unintended Acceleration

by

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Abstract: Tesla's Model 3 inverter design has been revealed recently by electric vehicle enthusiasts who desire to use salvaged Tesla drive motors to convert gasoline engine vehicles into electric-powered vehicles. Design details include high resolution photographs of printed wire boards, electronic component part numbers, connections between various components, oscilloscope traces of various signals, and schematics of some of the key circuits involved. An analysis of this data has found a cause for sudden unintended acceleration (SUA) in Tesla Model 3's that increases the accelerator pedal percent readings in both the vehicle log and in the EDR report without the driver stepping on the accelerator pedal. This cause of SUA also explains why Tesla's pedal monitor cannot prevent unintended acceleration when it should prevent torque from being generated while the accelerator pedal is not pressed. It may also explain how one case of sudden acceleration occurred while the driver was outside the vehicle.[1]

Introduction

On January 8, 2021, NHTSA denied a defect petition alleging 232 complaints of sudden unintended acceleration (SUA) in Tesla vehicles, citing that they were caused by pedal misapplication. NHTSA's analysis of the EDR data and/or log data from 118 of the crashes showed that the accelerator pedal was applied to 85 percent or greater in 97 percent of the 118 SUA crashes reviewed. NHTSA's response to the defect petition went on to state:

> "The APPS system used in the subject Tesla vehicles has numerous design features to detect, and respond to, single point electrical faults, including: redundant position sensors, contactless inductive sensing technology, independent power and ground connections to the sensors, and sensor voltage curves that differ by a fixed 2:1 ratio. All subject vehicles are equipped with accelerator pedal assemblies with two independent inductive sensors that convert the angular position of the pedal to voltage signals. The pedal position can only be changed in response to an external force being applied, such as the driver's foot. [In addition,] The Drive Inverter main processor controls motor torque based on accelerator pedal voltage. A separate processor (Pedal Monitor) acts as a safety monitor, continually checking both APPS signals for faults and independently calculating motor torque. Any malfunction or deviation in the APPS system results in a fault mode, cutting torque to zero for driver pedal applications or regenerative braking. In addition, the Pedal Monitor can shut off the Drive Inverter if driver's commanded motor torque and actual motor torque do not match."[2]

Finding a cause of sudden unintended acceleration consistent with these numerous design features has been a daunting task because of the lack of design information on Tesla's electric vehicles as opposed to decades of information on vehicles with internal combustion engines. However, the details of Tesla's inverter design for the Model 3 drive motor have been revealed recently, enabling a more thorough examination of this design for a cause of sudden unintended acceleration. The following sections describe these newly revealed details of Tesla's Model 3 inverter design, followed by a potential cause of sudden unintended acceleration extracted from these details that defeats the numerous design features mentioned by NHTSA.

I. Model 3 Inverter Design Details

Details of Tesla's Model 3 inverter design have been revealed by an Irish electronics engineer named Damien Maguire, who publishes under the pseudonym of Jack Bauer. His results are documented in the forum entitled "Tesla Model 3 Rear Drive Unit Hacking"[3] on the website Openinverter.org[4] and in the following three YouTube videos:

1) Tesla Model 3 Rear Drive Unit Inverter Reverse Engineering Part 1 (43:05), March 14, 2020[5],
2) Tesla Model 3 Drive Unit Hacking Update (33:01), July 28, 2020[6], and
3) Tesla Model 3 Drive Unit Inverter Reverse Engineering Marathon (1:39:14), Nov 28, 2020[7].

His results are detailed enough to identify all the components on the printed wire inverter board and all the signals on its connectors as well as on all pins of the DSP-based motor control unit that lies at the heart of the inverter unit. This has allowed him to substitute a new STM32F103 DSP for the existing TMS320F28377 DSP on the board, thereby freeing the inverter from Tesla's over-the-air (OTA) software control. Firmware for the new STM32F103 DSP capable of digitizing all sensor signals and running the FOC-based motor algorithms is provided by a German researcher named Johannes Hübner aka Johannes Huebner (johu). This same approach has been followed by Damien in developing new printed wire boards (PWB's) for other vehicles that successfully substitute for the manufacturer's original inverter boards, thereby freeing their inverter hardware from the manufacturer's firmware controls.

The details of Tesla's Model 3 inverter board design to be discussed are extracted from Damien's results cited above. Only details relevant to the acquisition and logging of the APP sensor signals by the EDR are discussed in this paper and examined for possible relevance to sudden acceleration. Other details such as control of the high voltage DC/AC inverter drive circuitry by the DSP and operation of the FOC motor control algorithms inside the DSP will not be discussed.

Figure 1 shows the Tesla Model 3 inverter board located inside the rear drive motor assembly. The bottom half of the PWB contains six GAP1AS low voltage isolated drivers for the SiC power transistors that control the three-phase high voltage power signals to the drive motor. These high voltage signals are placed on the three large pins labeled A, B, and C at the bottom of the figure that pass through the PWB but do not contact the PWB. In fact, no high voltage signals are present on the PWB, as the SiC transistors that modulate these high voltage signals are located off the PWB underneath it and are fed by a line from the high voltage DC battery that runs in parallel to the PWB from a point near the top of the figure.

The top half of the PWB in Figure 1 is divided functionally into three separate sections. The top left section between the connector and the large DSP contains the circuitry for sending power to the sensors outside the inverter and for translating the voltage of the returning sensor signals to the lower voltage used by the DSP's analog and digital voltage inputs. The center section between the DSP and the left edge of the pink thermal conductor contains a voltage regulator IC that supplies all the regulated 5V, 3.3V, and 1.8V voltages to the DSP and to the APP and resolver sensors along with JTAG circuitry and an EEPROM that contains start-up code for the DSP.

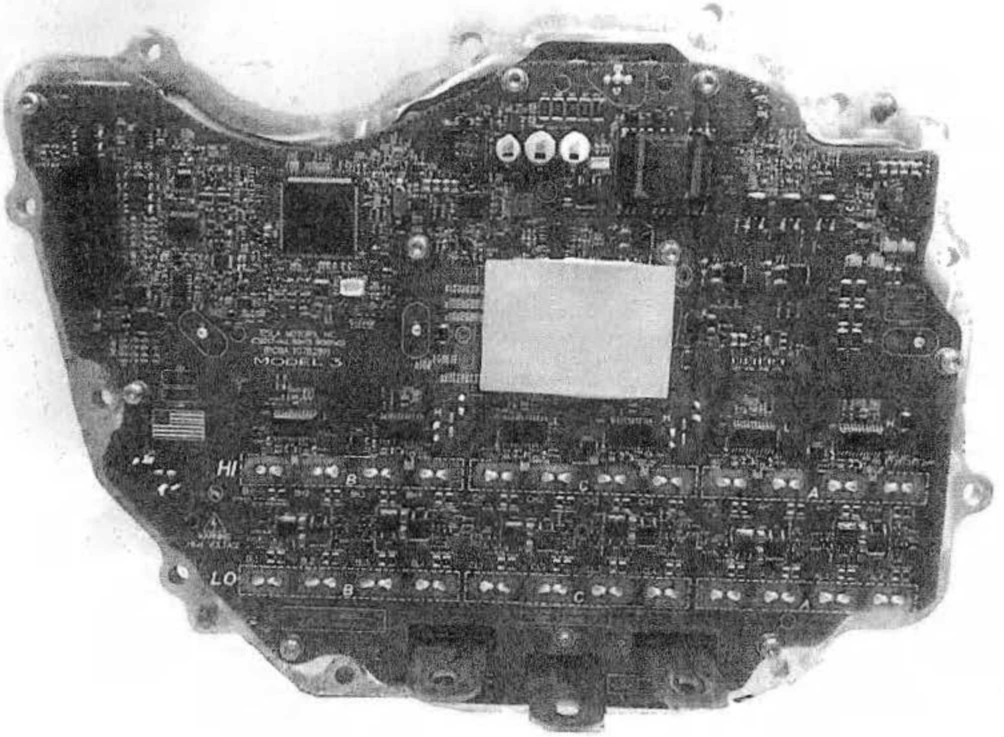


Figure 1. Tesla Model 3 inverter board also used on the new Model Y.

The top right section contains two power supplies that each power the +15V and -8V DC rails to the isolated drivers used to turn on and off the SiC power transistors under DSP control. One supply is powered by the 12V battery and the other is powered by the high voltage battery. The latter supply is believed to be a backup to keep the isolated drivers operating in the event that 12V battery power is lost, preventing the energy stored in the motor windings from damaging the closed drivers if 12V battery power is suddenly lost while the vehicle is moving at high speeds. The +15V and -8V DC rails supplied by the 12V battery are regulated by regulating the 12V input to the primary side of the isolation transformer that generates the +15V and -8V DC rails. The +15V and -8V DC rails remain regulated when the backup power supply is used either by having the backup supply provide an unregulated 12V input to the original main supply, in which case the same primary side regulator is used, or by having the backup supply provide regulated +15V and -8V DC rails directly to the isolated drivers. The first option is more likely because a backup 12V must also be provided to keep the DSP operational.

Figures 2 and 3 show the top three sections of the inverter board in greater detail. The functions of all integrated circuits are shown along with their reference designators Ux. In Figure 2, notation on the DSP shows that the analog ADC inputs are all grouped into the lower left-hand corner of the DSP. The SPI I/O's are on the lower right-hand corner of the DSP with the EEPROM inputs nearby, the CAN and LIN I/O's are at the top of the DSP, and the digital I/O's fill in the remaining sides of the package. In Figure 3 the pink thermal conductor over the bleed resistors has been removed to show a bank of fifty 2KΩ resistors used as a 4K ohm resistor to discharge the high voltage capacitor. Part numbers for the integrated circuits in both figures can be read under higher magnification with the right lighting conditions and are listed in Table 1.

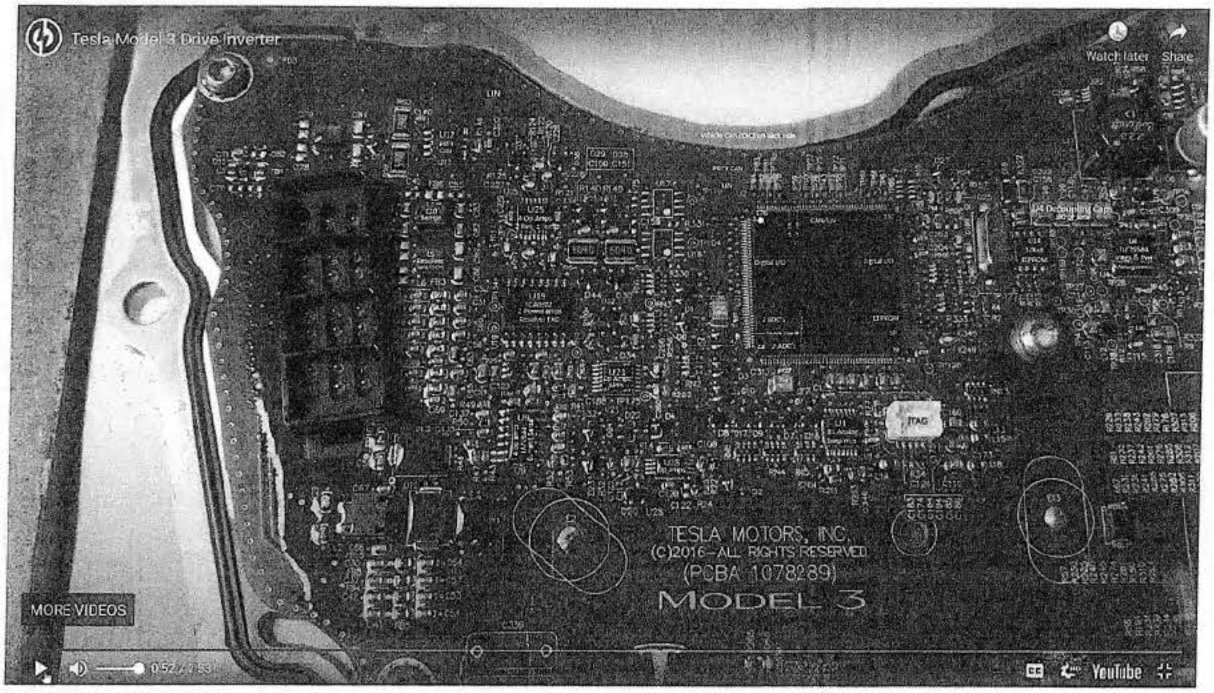


Figure 2. Top left section of the Model 3 inverter board

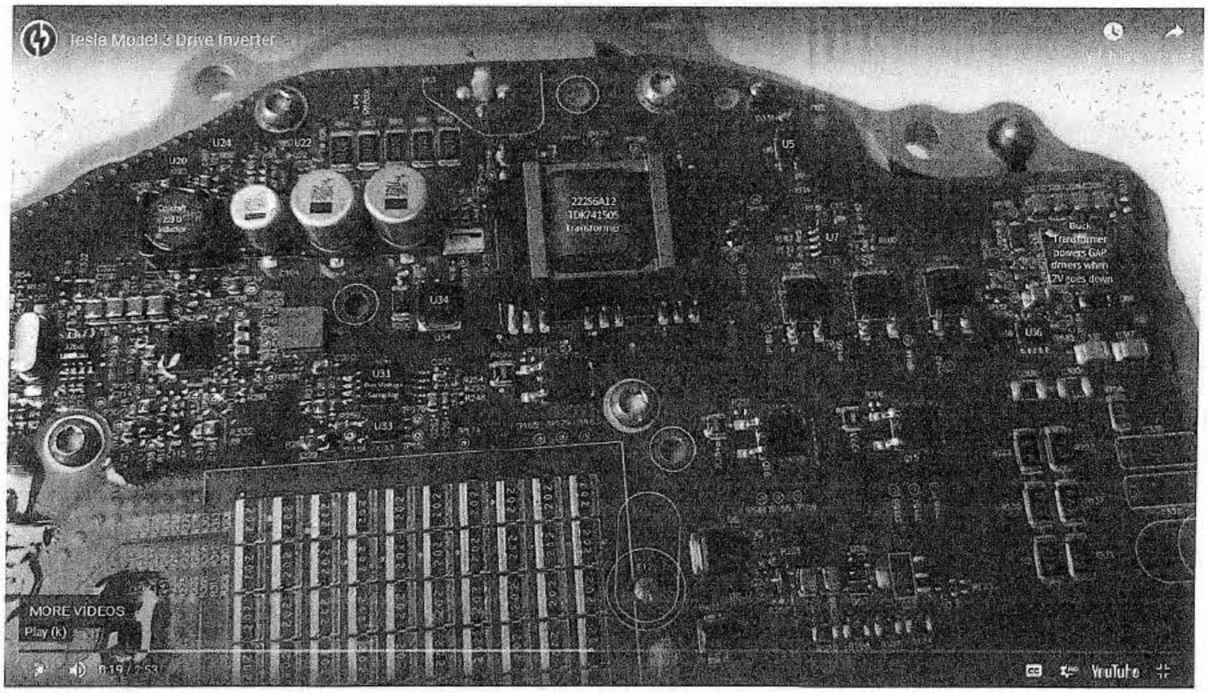


Figure 3. Top right section of the Model 3 inverter board

Table 1. Part numbers for the Model 3 inverter board.

Component	Device P/N	Mfgr	# pins	Function	Comments
U2	TMS320F28377DPTPQ	TI	176	Sensor input & motor controller	
U14	25LC256E	uChip	8	32Kx8 EEPROM with SPI I/O	
U4	TLF35584QVVS2	Infineon	48	PMIC/voltage regulators	
U9	LMV844	TI	14	Translates temp signals 5V to 3V	Temp or resolver
U1	SN74HCT4051		16	8:1 analog multiplexer for temperature signals	Temperature
U19	TCA0372BDW	On Semi	16	Resolver excitation amplifier	Susceptible to phase reversal within 1.3V of VDD
U12	SN65HVD1040	TI	8	CAN bus XCVR	
U13 (back)	SN65HVD1040	TI	8	CAN bus XCVR	
U15 (back)	TJA1021	NXP	8	LIN XCVR	
U31	ACPL-C87BT-000E	Broadcom	8	HV sense	
U8 (back)	TPS40210	TI	10	Driver power supply	Regulated output
	VGT22EPC-222S6A12	TDK		DC-DC transformer	
U302, U303	STGAP1AS (6)	ST		Isolated gate drivers	
	GK026 (24)	ST		SIC FET's	
U3 (back)	74LVC8T245		24	Bi-directional buffer	Buffers DSP to drivers
U21	Op amps		14	Translates APP signals 5V to 3V	
U25	Op amps		14	Translates resolver signals 5V to 3V	
U22	LT1494H	Linear Tec	8	Op amps, to 125C	
U28	Op amps		8	Translates U1 signals 5V to 3V	
U36	SPS1087 47125-C	SPS	10	Transformer	
U36	Power supply	Viper	10	Provides emergency power from HV battery when 12V down	
U5	Op amp		6	Adds drive to U3	
U42	Op amp		5	Adds drive to U3	
U44	Op amp		5	Adds drive to U3	
U28			8	Op amps	
U6			8	Op amps?	
U20			8	Op amps?	
U7			8	Op amps?	
U34			3	VReg?	
U23 (back)			8		
U24			5		
U33	A10CLA4019T	Broadcom	5	Optocoupler	

Figure 4 shows an even higher magnification of the top left section of the board containing the sensor interface circuitry. Connector pin assignments on the PWB have been confirmed by probing and agree with the connector pin assignments on the left provided by Tesla for the X090 rear inverter connector in its Model 3 wiring diagrams. Op amps are used to interface the 0 to 5V analog signals returned from sensors like the accelerometer pedal position (APP) sensors, temperature sensors, motor voltage sensors, and motor current sensors, all of which are powered by regulated 5V power supplies, to the ADC's which require signals with an amplitude between 0V and 3.3V. The op amp circuits used to carry out this voltage translation are shown in Figure 5. They consist of a voltage divider in series with the op amp configured as a unity gain amplifier for higher driving power. The op amps are powered by a regulated 3.3V supply that can be switched on after the DSP and ADC's have been fully powered up, thereby providing the proper power sequencing required for DSP operation.

Model 3 X090 Rear inverter Connector OEM

Pin	Signal
1	Proximity Digital in (charge port)
2	Vehicle CAN L (on back side)
3	Switched +12V in
4	HVIL OUT
5	Accel 2 GND
6	Accel 1 GND
7	Resolver SIN–
8	Resolver COS+
9	Unused
10	LIN Oil Pump status
11	Brake NO Digital in
12	Vehicle CAN H (on back side)
13	Chassis (+12V) GND
14	Accel 2 +5V
15	Accel 1 +5V
16	Resolver EXC- (on back side)
17	Resolver SIN+
18	Stator temp–
19	Unused
20	PRTY CAN L (CAN3)
21	Brake NC Digital in
22	Unswitched +12V in
23	HVIL IN
24	Accel 2 signal
25	Accel 1 signal
26	Resolver EXC+ (on back side)
27	Resolver COS–
28	Stator temp+
29	Unused 10 kHz Resolver?
30	PRTY CAN H

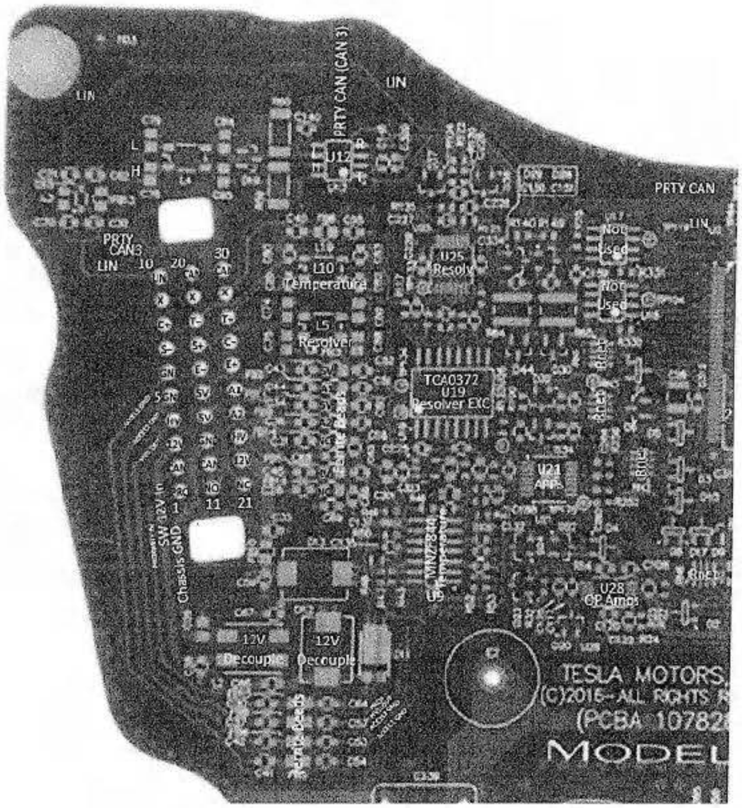
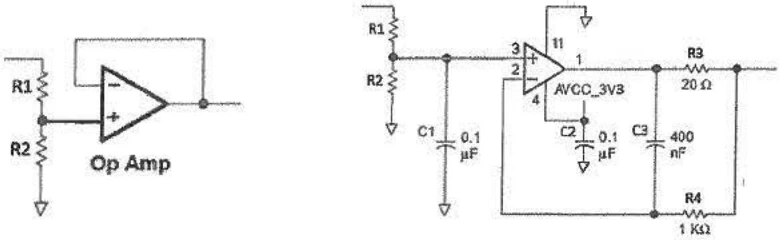


Figure 4. Detailed view of the connector and interface circuitry.



(a) Conceptual circuit (b) Physical implementation

Figure 5. Typical circuit used for analog signal 5V to 3.3V level conversion

Figure 6 shows a functional block diagram of the TMS320F28377 DSP used on the PWB. The DSP consists of two 32-bit floating point CPU's each with their own ROM and RAM that can transfer data from one to the other asynchronously using a dual-port RAM. Each CPU is connected to a peripheral bus that can access a host of on-chip peripherals including four ADC's, DAC's, serial data message buses like CAN, LIN, and SPI buses, general-purpose digital I/O ports, and off-chip memory like RAM (via DMA) and a boot EEPROM. When used on the inverter board, CPU1 is used to take in all analog sensor data from the ADC's and all digital control inputs from the CAN and LIN buses and general-purpose digital I/O ports and use them along with a pedal map and an inverse torque map to generate motor current and stator field commands for the drive motor. These commands are then transferred via the dual-port memory to CPU2, which uses them as input to a field-oriented control (FOC) algorithm to generate the required three-phase high voltage drive waveforms used to run the motor at the desired torque level. CPU2 then outputs the required three-phase drive waveforms to the high voltage current drivers via an SPI bus. As this happens, CPU1 continues to monitor the motor current, motor voltage, and motor temperature, as well as the temperatures of other important driver electronics like the SiC MOSFET drivers, to verify that they are operating properly within the design limits.

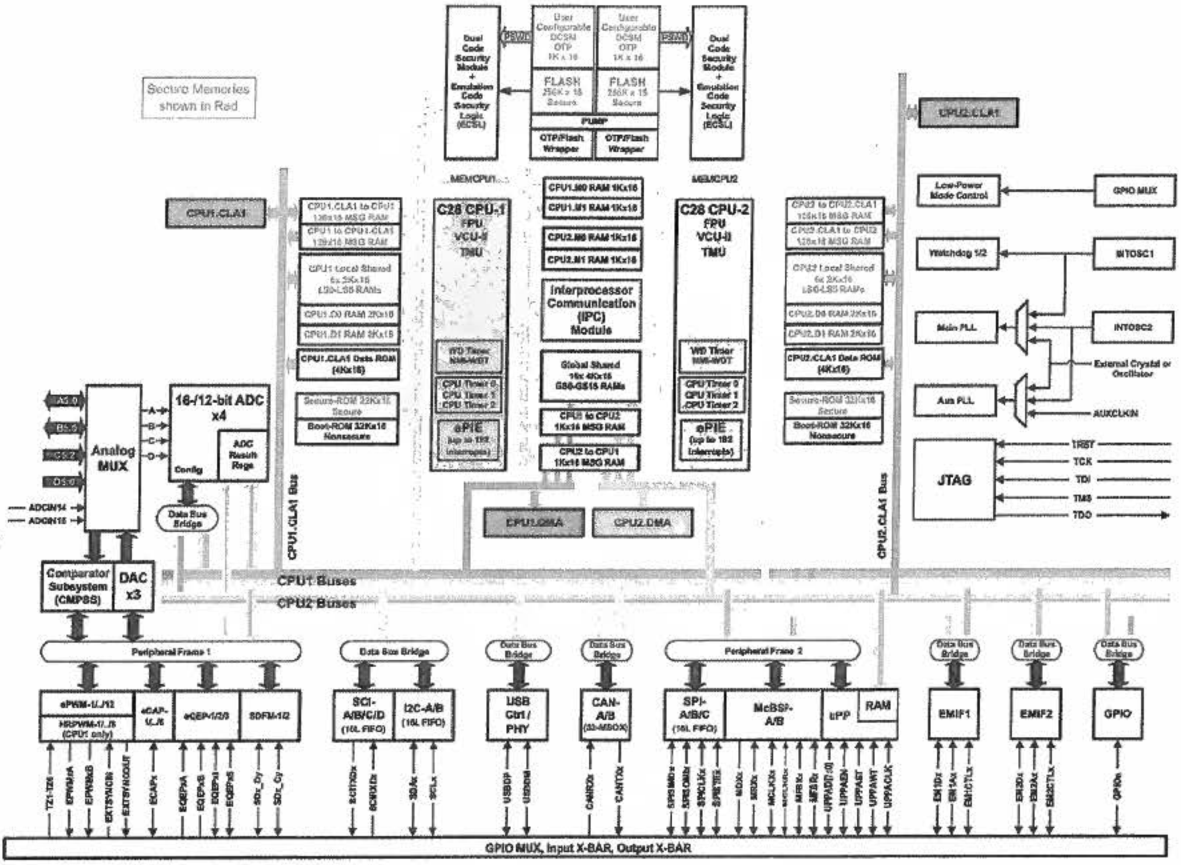


Figure 6. TMS320F28377 functional block diagram[8]

One of the key pieces of design information needed to understand the operation of the DSP and how it controls the inverter is the mapping of the DSP inputs to their originating sensor and control functions and the mapping of DSP outputs to their subsequent high voltage drive amplifier functions. This information was carefully collected by Damien Maguire by probing the signals on each of the 176 DSP pins and then searching for the origin of each input signal and the destination of each output signal. This information has been summarized in the pin map shown in Figure 7 and in a pin assignment table. A portion of this pin assignment table containing only the ADC-related pins is shown in Table 2.

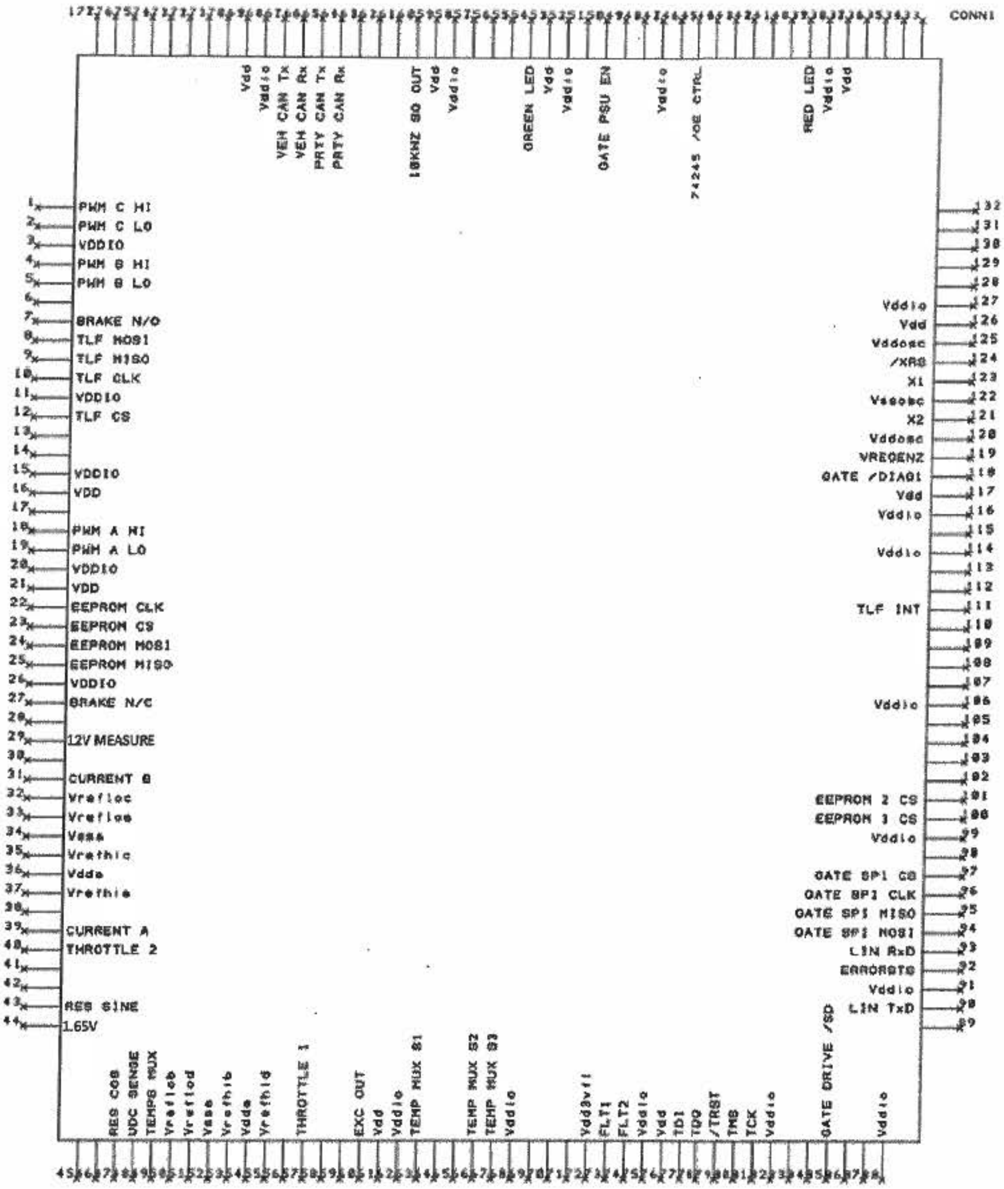
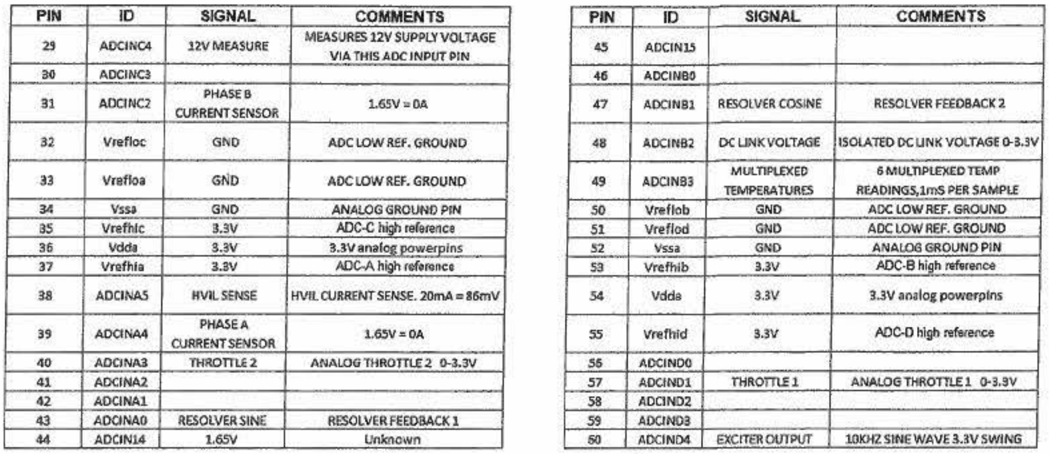


Figure 7. Pin map for the DSP pins in the Model 3 inverter found by probing [9].

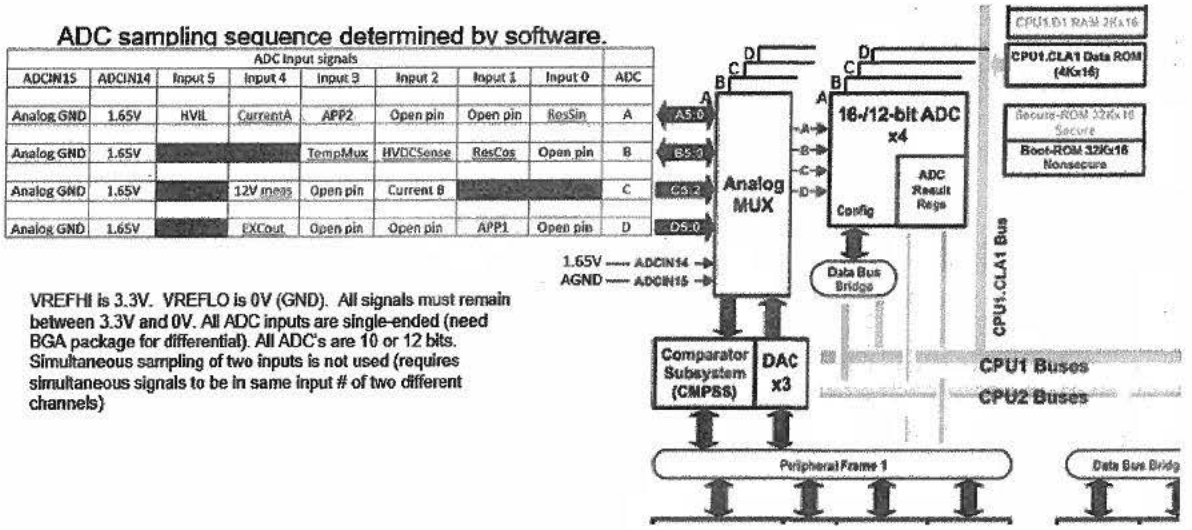
The data in Table 2 allow one to determine how the two APP sensor signals get to the ADC's, the magnitudes of these signals at the ADC's, and the presence of other sensor signals on the same analog multiplexer that can possibly interfere with the two APP sensor signals. This information is summarized in Figure 8, which includes a small table showing the assignment of all analog signals to the four ADC's. One thing to note in this figure is that one of the signals, the "1.65V" signal that is applied to pin ADCIN14, is common to all four input multiplexers. This makes it possible for each of the four ADC's to digitize any of the signals applied to its input multiplexer. But whether any of the four ADC's actually exercise this possibility is determined by a software program.

Table 2. ADC-related pin assignments for the DSP in the Model 3 inverter found by probing [10]



PIN	ID	SIGNAL	COMMENTS
29	ADCINC4	12V MEASURE	MEASURES 12V SUPPLY VOLTAGE VIA THIS ADC INPUT PIN
30	ADCINC3		
31	ADCINC2	PHASE B CURRENT SENSOR	1.65V = 0A
32	Vrefloc	GND	ADC LOW REF. GROUND
33	Vrefloa	GND	ADC LOW REF. GROUND
34	Vssa	GND	ANALOG GROUND PIN
35	Vrefhic	3.3V	ADC-C high reference
36	Vdda	3.3V	3.3V analog powerpins
37	Vrefhia	3.3V	ADC-A high reference
38	ADCINA5	HVIL SENSE	HVIL CURRENT SENSE. 20mA = 86mV
39	ADCINA4	PHASE A CURRENT SENSOR	1.65V = 0A
40	ADCINA3	THROTTLE 2	ANALOG THROTTLE 2 0-3.3V
41	ADCINA2		
42	ADCINA1		
43	ADCINA0	RESOLVER SINE	RESOLVER FEEDBACK 1
44	ADCIN14	1.65V	Unknown
45	ADCIN15		
46	ADCINB0		
47	ADCINB1	RESOLVER COSINE	RESOLVER FEEDBACK 2
48	ADCINB2	DC LINK VOLTAGE	ISOLATED DC LINK VOLTAGE 0-3.3V
49	ADCINB3	MULTIPLEXED TEMPERATURES	6 MULTIPLEXED TEMP READINGS,1mS PER SAMPLE
50	Vreflob	GND	ADC LOW REF. GROUND
51	Vreflod	GND	ADC LOW REF. GROUND
52	Vssa	GND	ANALOG GROUND PIN
53	Vrefhib	3.3V	ADC-B high reference
54	Vdda	3.3V	3.3V analog powerpins
55	Vrefhid	3.3V	ADC-D high reference
56	ADCIND0		
57	ADCIND1	THROTTLE 1	ANALOG THROTTLE 1 0-3.3V
58	ADCIND2		
59	ADCIND3		
60	ADCIND4	EXCITER OUTPUT	10KHZ SINE WAVE 3.3V SWING

The order of sampling these signals for ADC conversion is determined by software, and not necessarily by the increasing value of the pin number. This freedom in sampling order is clarified in Figure 9, which shows a functional block diagram of each of the four ADC's. Figure 9 shows that the order of digitizing each ADC signal is determined by a sequencer containing software-programmable pointers that select samples from the analog multiplexer in any desired order. The same sequencer determines the order of entering the results of each ADC conversion into 16 ADC result registers. The results consist of N-bit counts in integer format where N can be anywhere from 10 to 16 bits. Transfers from the ADC's to the result registers are done serially as the successive approximation ADC's develop the results. The data in the result registers are then transferred in parallel to the 32-bit registers of the CPU while converting them into a floating point representation. The sequencer contains up to 16 samples, which means that the ADC operations are done on a group of signals at one time, and not just one signal at a time, with a start of conversion (SOC) signaling the beginning of converting the group and an end of conversion (EOC) signaling the end of converting the group, causing the group of 16 ADC registers to transfer their results to CPU memory.



ADC sampling sequence determined by software.

ADC Input signals								
ADCIN15	ADCIN14	Input 5	Input 4	Input 3	Input 2	Input 1	Input 0	ADC
Analog GND	1.65V	HVIL	CurrentA	APP2	Open pin	Open pin	ResSin	A
Analog GND	1.65V	▨	▨	TempMux	HVDCSense	ResCos	Open pin	B
Analog GND	1.65V	▨	12V meas	Open pin	Current B	▨	▨	C
Analog GND	1.65V	▨	EXCout	Open pin	Open pin	APP1	Open pin	D

VREFHI is 3.3V. VREFLO is 0V (GND). All signals must remain between 3.3V and 0V. All ADC inputs are single-ended (need BGA package for differential). All ADC's are 10 or 12 bits. Simultaneous sampling of two inputs is not used (requires simultaneous signals to be in same input # of two different channels)

Figure 8. Assignment of signals to the four TMS320F28377 ADC's as determined by Table 2. Notice that the "1.65V" signal is common to all four ADC's.

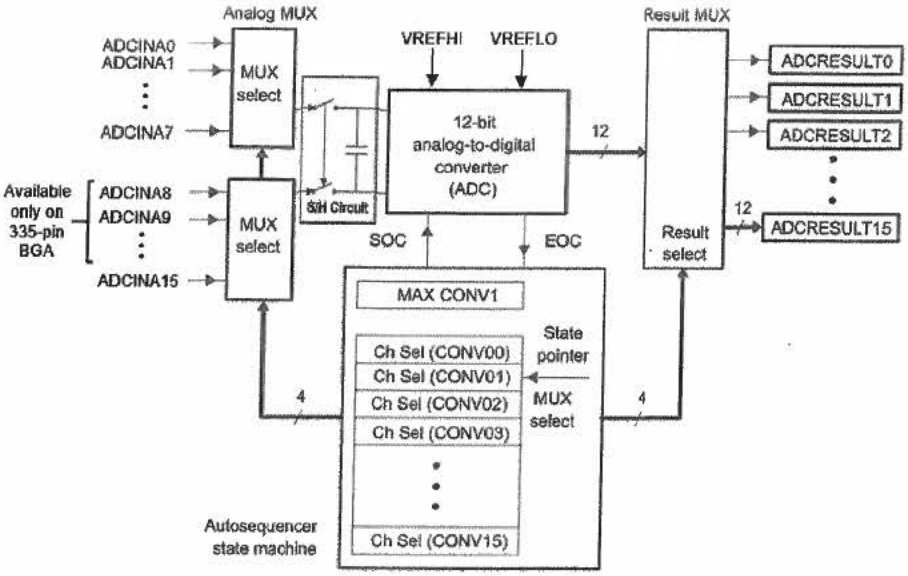


Figure 9. Functional block diagram of the TMS320F28377 ADC circuit showing how the order of signal sampling is determined by software manipulating a pointer in a sequencer

Figure 9 shows two other interesting features. The first feature is that input pins numbered ADCINx9 and higher, which are used for differential inputs to the ADC's, are not available on the 176-pin version of the DSP chip used in the Model 3, but only on the 343-pin BGA version of the DSP chip. This means that all ADC inputs in the Model 3 inverter must be single-ended signals between 0V and VREFHIx > 0V, which requires translating signals with plus and minus values, like the sin and cos signals from the resolver, into single-ended signals between 0V and VREFHIx before applying them to the ADC inputs. It also means that all ADC converters in the Model 3 inverter can only be configured as 10-bit or 12-bit ADC's and not as 14-bit or 16-bit ADC's because the latter two require the use of differential inputs. The second feature is that the maximum and minimum signal amplitudes to be converted can be configured separately for each ADC. The maximum signal amplitude can be anywhere between 0V and 3.3V if VREFHIx is equal to the ADC bias voltage of VDDA = 3.3V. The minimum signal amplitude can be any voltage below the maximum signal voltage for differential signals, which is not allowed by the 176-pin version of the DSP used in the Model 3, or only 0V for single-ended signals. Therefore, the Model 3 single-ended signals must lie between 0V and 3.3V maximum. TI, the manufacturer of the DSP chip, recommends that VREFHIx be set at 3.0V. However, Damien Maguire has measured that VREFHIx is actually set at 3.3V by Tesla. This may have done to avoid the need for a special 3.0V regulator device on the PWB. If any ADC signals exceed 3.3V by 300mV or more, then the ADC will give an incorrect result and may be permanently damaged.

Based on the information discussed thus far, which relies heavily on the oscilloscope probing results of Damien Maguire in Table 2 and on the explanations of ADC operation given in the TMS320F28377 spec sheet, 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 10. It assumes that the two APP sensor signals have amplitudes that vary as shown in Figure 11, which was obtained by wk057 from a working Tesla Model 3.

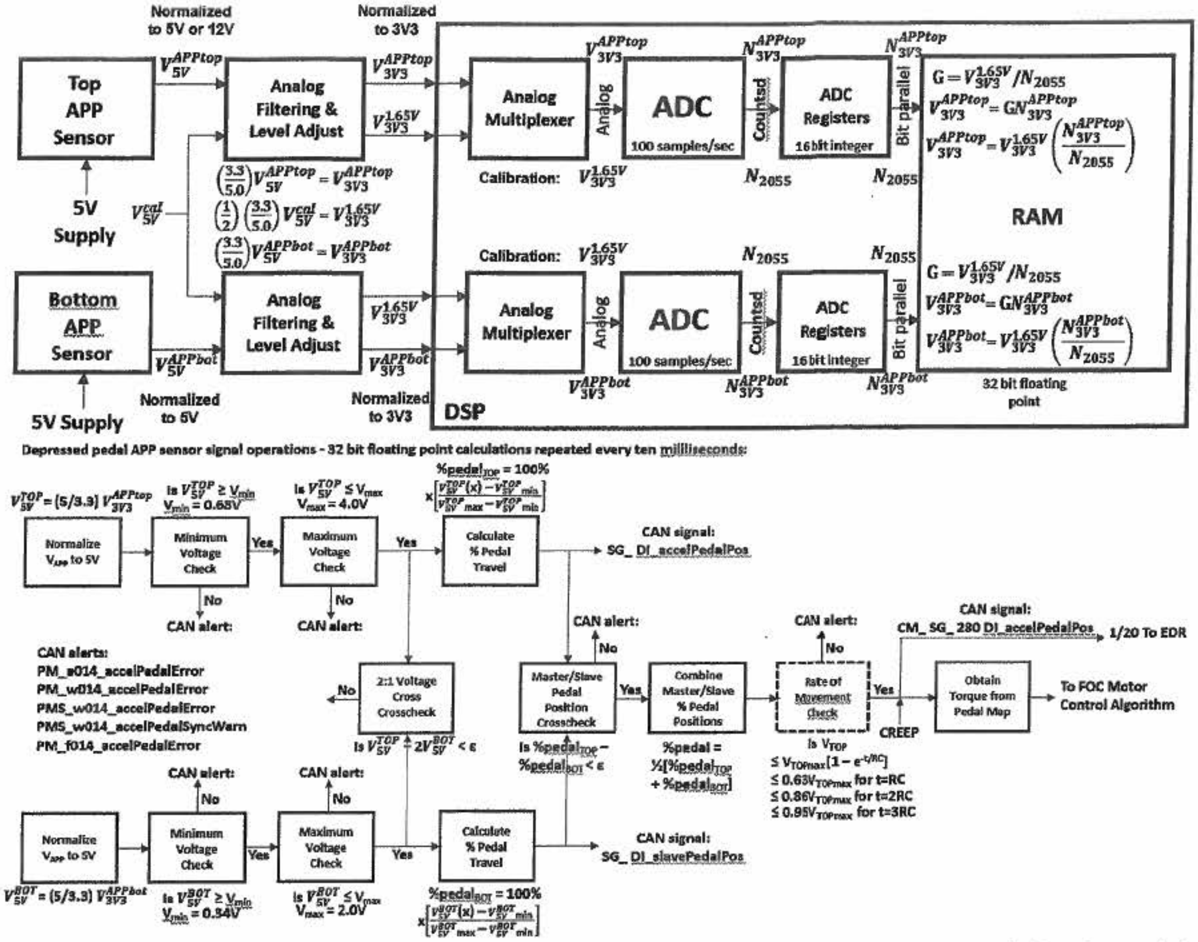


Figure 10. Summary of operations performed on the Model 3 APP sensor signals by the pedal monitor in the TMS320F28377 DSP. CAN alerts and CAN signals replace the OBD-II DTC's and OBD-II connector CAN signals found in most non-Tesla vehicles. There are three kinds of CAN alerts: aXXX (Alert), wXXX (Warning), and fXXX (Fault). The assignment of alerts to specific functions is tentative pending further information from Tesla. The rate of movement check is also tentative at this time.[11]

Figure 11 shows that the two APP sensor signals, which are created using separate 5V voltage regulators on the TLF35584QVVS2 PMIC chip, can vary between 0.68 and 4.0V for the top APP sensor and between 0.34V 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

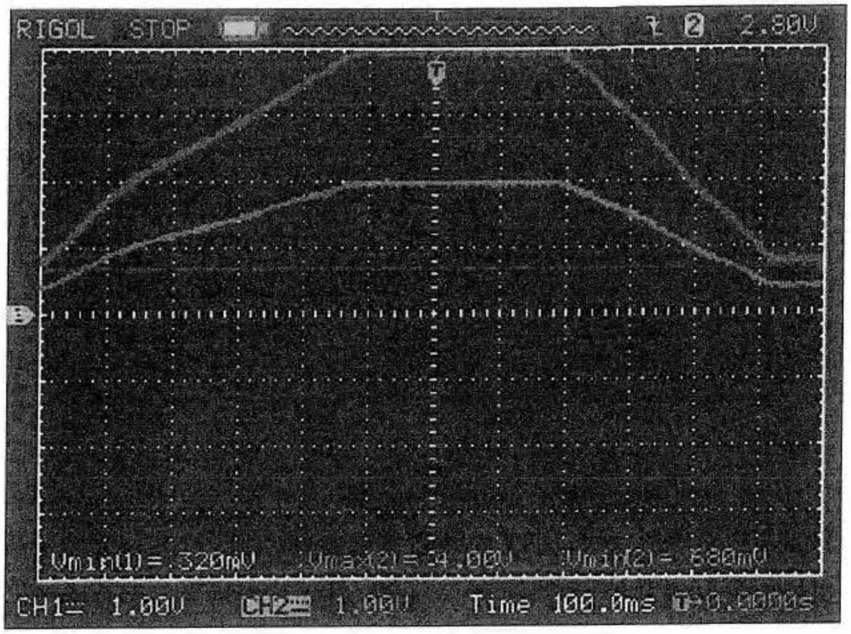


Figure 11. Oscilloscope traces of the APP sensor signals from a Tesla accelerator pedal.[12] The top sensor is always twice the voltage of the bottom sensor, with the top sensor increasing from 0.68V to 4.0V as the pedal is pressed from 0% to 100% while the bottom sensor increases from 0.32V to 2.0V as the pedal is pressed from 0% to 100%.

signal falls outside the operating limits, then a CAN alert is posted and the drive motor torque is limited to a small limp home value. 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 a CAN alert is posted and the drive motor torque is set to zero. If this test is passed, the % pedal travel for each sensor is then calculated as

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

and a cross-check is performed to determine if the pedal % values are equal to within 10%. If this test fails, then a CAN alert is posted and the torque is set to zero. If this test is passed, then the two pedal % values are combined to form a single % pedal value that is used for four purposes: 1) a % CREEP value is added if CREEP is selected, 2) every value is stored in the vehicle log, 3) every twentieth value is sent to the EDR via a message on the CAN bus, and 3) the % pedal with CREEP added 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 a CAN alert is posted, and the torque is limited to zero. 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 drive motor. In the pedal map, if the % pedal value is below about 20% and the vehicle speed is above 10 MPH, then regen is applied. If the % pedal is below about 20%, and the vehicle speed is below 10 MPH, then the % torque command is set to 0%. If the % pedal is above about 20%, then the % torque command is obtained from the pedal map. This % torque command from the pedal map is then sent to the inverse motor map to obtain the required motor current commands for the drive motor. Finally, Figure 10 shows that the "1.65V" signal is common to all four ADC's. But its use is still to be determined. We will now discuss this "1.65V" signal in greater detail.

II. Discussion of the "1.65V" signal and its role in sudden acceleration

The first thing to discuss about the "1.65V" signal is why it is being used as an input common to all four ADC's on the DSP. After all, if Tesla had wanted to use the voltage of the "1.65V" signal in a calculation, they could have selected an input pin associated with a single ADC channel, several of which are still available. This would allow the "1.65V" signal to be digitized by a single ADC, just all the other signals are digitized by a single ADC in a similar manner. So, why is the "1.65V" signal different in being connected to an input pin that is common to all four ADC's?

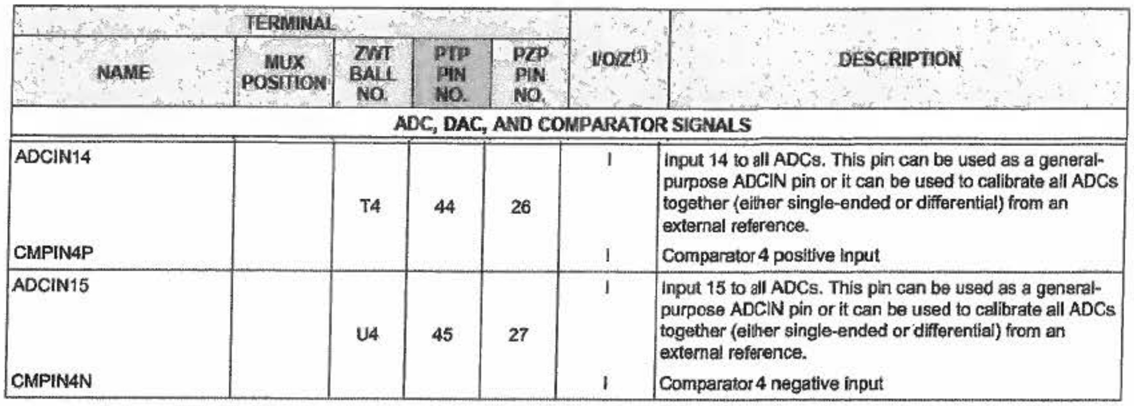
The only reason why one would input the same signal into two or more ADC's is to calibrate two or more converter ADC's; i.e., to ensure that they give the same output in the event that the circuitry used to connect their inputs to the two or more ADC's produce different gains and offsets. Having the same calibration insures that pairs of similar signals are better-matched to provide a more accurate output from their combined values. Looking at the table of ADC input signals in Figure 10, we see that there are three possible pairs of similar signals:

a) ResSin on ADC A and ResCos on ADC B
b) CurrentA on ADC A and CurrentB on ADC C, and
c) Throttle2 on ADC A and Throttle1 on ADC D (ie, APP sensor 1 and APP sensor 2)

So, which pair of similar signals requires the same calibration? After all, it is possible that only one pair of ADC's requires the same calibration, while the other two ADC's have a different calibration. But if we look at the table in Figure 8, we see that all three pairs of signals use ADC A. Therefore, if the "1.65V" signal is used to calibrate ADC channels A and B, but not ADC channels C and D, then ADC channels A and B carrying ResSin and ResCos would both be calibrated along with CurrentA and Throttle2. But signals CurrentB and Throttle 1 in ADC channels C and D would have different calibrations, which would increase the error for these two pairs of signals. Since this can't be tolerated, ADC's C and D must also be calibrated with the same "1.65V" signal as ADC A. Therefore, one must conclude that the "1.65V" signal is used to calibrate all four of the ADC channels with the same calibration. There is no other reason to digitize the same "12V measure" signal using four different ADC channels other than to calibrate all four ADC channels with the same calibration.

TI documents describing the ADC functions on the TMS320F28377 show that each ADC channel has a maximum offset error of ±15 LSB and maximum gain error of ±30 LSB.[13] These errors are largely associated with temperature variations and signal noise. Therefore, these errors might be large enough to cause the checks done on the two APP sensor signals to produce a false error if the check parameter is tight enough. The solution is to calibrate the gains and offsets of all four ADC's using a common external calibration voltage, which can reduce the channel-to-channel errors to below 0.5%.[14] The external calibration voltage is accessed by all four ADC's as shown in Figure 11 below.

The calibration itself can be done by a calling a built-in calibration function cal( ). It can be called each time the ADC is booted up, or at any other times as the programmer desires. From then on all other signals are corrected automatically.



TERMINAL						
NAME	MUX POSITION	ZWT BALL NO.	PTP PIN NO.	PZP PIN NO.	I/O/Z[1]	DESCRIPTION
ADC, DAC, AND COMPARATOR SIGNALS						
ADCIN14		T4	44	26	I	Input 14 to all ADCs. This pin can be used as a general-purpose ADCIN pin or it can be used to calibrate all ADCs together (either single-ended or differential) from an external reference.
CMPIN4P					I	Comparator 4 positive input
ADCIN15		U4	45	27	I	Input 15 to all ADCs. This pin can be used as a general-purpose ADCIN pin or it can be used to calibrate all ADCs together (either single-ended or differential) from an external reference.
CMPIN4N					I	Comparator 4 negative input

Figure 11. TMS320F28377 spec sheet notes that ADCIN14 on pin 44 can be used to calibrate all four ADC channels using the same external reference signal.

Now the built-in cal( ) function on the TMS320F28377 DSP only calibrates the DC offsets of the ADC channels, and not the gains of the ADC channels. This built-in calibration function operates either with or without an external D/A reference signal and brings the ADC's up to specification. But the programmer can include code to calibrate the gains of the four ADC channels by using an external calibration signal for each channel. The code uses the conversion results N_{CAL} obtained from digitizing an external calibration signal V_{CAL} after the N_{CAL} values have been changed to floating point values in memory. He can then calculate the calibrated gain for each ADC channel using the equation[15]

$$G = \left(\frac{Ideal\ span}{Actual\ span}\right) = \left(\frac{xH-xL}{yH-yL}\right),$$

where two calibration points H and L (high and low) are used to determine a straight line:

xL = known reference low input = $V_{CAL}(L)$ on ADCIN15 (pin 45)
xH = known reference high input = $V_{CAL}(H)$ on ADCIN14 (pin 44)
yL = reference low ADC output = $N_{CAL}(L)$
yH = reference high ADC output = $N_{CAL}(H)$.

If the low calibration point L on ADCIN14 (pin 45) is assumed to be zero, then only one calibration point is needed[16], giving

$$G = \left(\frac{V_{CAL}}{N_{CAL}}\right).$$

One can then correct all other signals V_{signal} using the same ADC channel after their conversion by calculating

$$V_{signal} = N_{signal}\mathrm{G} = N_{signal}\left(\frac{V_{CAL}}{N_{CAL}}\right) = V_{cal}\left(\frac{N_{signal}}{N_{CAL}}\right),$$

where V_{CAL} is the external voltage "1.65V" and N_{CAL} is the number of counts obtained when the external calibration voltage "1.65V" signal is digitized. So, it is possible to calibrate all four ADC channel gains and offsets using a common enhanced cal( ) function that will reduce all channel-to-channel gain and offset errors. It is likely that Tesla uses this type of external gain calibration because it makes no sense to use a "1.65V" signal on pin 44 for offset calibration only, since this can be done by using the internal cal( ) function without an external calibration signal.

Now that we know the "1.65V" signal is being used for calibration, we can ask why the value of 1.65V is used and how is it being generated. It is likely that the value 1.65V has been selected to allow for errors that can increase the value of N_{CAL} as well as decrease the value of N_{CAL}. Errors that increase the value cannot be accommodated if a maximum voltage of 3.3V is used causing N_{CAL} = 4095. Any lower voltage calibration voltage that can accommodate such high-side errors would be acceptable. But it is interesting that Texas Instruments in their application report on ADC calibration using the TMS320F28377 DSP recommends a calibration voltage that is half scale for this purpose.[17] In this case, with full scale being 3.3V, a half-scale voltage would be 1.65V. Therefore, it is likely that Tesla has followed TI's example in selecting this half-scale voltage.

The question of how the "1.65V" signal is generated is a little more complicated. It is likely not because it is just half of 3.3V, which would be easy to produce. To understand this better, let's take a look at Table 2, which shows four cases of how N_{CAL} and V_{APP} can vary.

Table 2. Four cases of how N_{CAL} and V_{APP} can vary.

	Case 1. N_{CAL} doesn't change N_{APP}'s don't change			Case 2. V_{CAL} independent of V_{5V} N_{APP}'s are ratiometric			Case 3. $V_{CAL} \propto V_{APP\_SUPPLY}$ N_{APP}'s are ratiometric			Case 4. V_{CAL} can change while V_{APP_SUPPLY} does not change		
	N	*V*	*V*	*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	4095	3.3V	5.0V
Digitize 1.65V and AGND, get N_{CAL}. Calibrate gain G with Eq 1.	2055	1.65V	2.5V	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.	3276	2.63V	4.0V	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.	557	0.45V	0.68V	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.	1638	1.32V	2.0V	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.	279	0.225V	0.34V	140[a]	0.112V	0.17V	140[a]	0.225V	0.34V	279	0.45V	0.68V
Result	Desired APP signals are obtained. But changes in N_{CAL} and V_{APP_SUPPLY} are not allowed.			If V_{APP_SUPPLY} changes, but calibration does not change because V_{CAL} is constant, then incorrect APP signals are obtained.			If $V_{CAL} \propto V_{APP\_SUPPLY}$, APP signals track calibration, giving desired APP signals even when V_{APP_SUPPLY} changes.			If V_{CAL} decreases while V_{APP_SUPPLY} does not change, then APP signals are increased with foot off pedal and SUA can result.		
Eq 1	$G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{2055}\right)$			$G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{2055}\right)$			$G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{1027}\right)$			$G=\left(\frac{1.65V}{N_{cal}}\right)=\left(\frac{1.65V}{1027}\right)$		
Eq 2	$V_{APP}=N_{APP}\mathrm{G}$			$V_{APP}=N_{APP}\mathrm{G}$			$V_{APP}=N_{APP}\mathrm{G}$			$V_{APP}=N_{APP}\mathrm{G}$		
Example	$V_{APP}=3276\,\mathrm{G}$ $V_{APP}=3276\left(\frac{1.65V}{2055}\right)$			$V_{APP}=1368\,\mathrm{G}$ $V_{APP}=1638\left(\frac{1.65V}{2055}\right)$			$V_{APP}=1368\,\mathrm{G}$ $V_{APP}=1638\left(\frac{1.65V}{1027}\right)$			$V_{APP}=3276\,\mathrm{G}$ $V_{APP}=3276\left(\frac{1.65V}{1027}\right)$		

a) Changes due to temperature and noise will normally be less than a few percent. A factor of two change has been used to make changes more noticeable.

b) Changes to V_{CAL} 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 1, a fixed V_{CAL} of 1.65V is used with an N_{CAL} of 2055, but changes in the V_{APP} outputs with temperature and noise are not considered. In this case, equations Eq1 and Eq2 produce the desired transfer function of the accelerator pedal as shown in the oscilloscope traces of Figure 11. But changes in the accelerator pedal output created by temperature and noise can cause changes in the sensor outputs that are indistinguishable from changes due to pedal pressure.

In case 2, 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 we calibrate with a fixed calibration voltage of 1.65V, there is no way to determine how the sensor supply voltage changes. Therefore, we can't correct for the temperature and noise errors in the sensor outputs even though we use a ratiometric sensor. So, using a fixed calibration voltage still allows errors in the sensor voltages.

In case 3, 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} = k5V. The ratio k can be set to (3.3/5)/2, giving V_{CAL}= 1.65V. This allows one to correct the APP sensor outputs for temperature and noise because one now knows how the APP supply voltage changes. This explains why the 1.65V calibration signal is obtained from 5V power supply of the APP sensors[18]. This same option of using a ratiometric APP sensor along with an ADC calibration voltage that tracks the sensor supply voltage is used by Toyota in all its vehicles since 2005[19]. It is likely a standard design feature in the vehicles of all manufacturers on the road today. This makes it likely that Tesla would be using this feature in all its vehicles.

In case 4, 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 an under-voltage condition caused by a negative-going voltage spike occurring while the calibration voltage is being digitized. In this case, the APP sensor outputs are increased by the inverse ratio that the ADC calibration voltage decreases. Therefore, if the ADC calibration voltage decreases from 1.65V to 0.33V or less as a result of the APP supply voltage decreasing from 5V to 1V, then the APP sensor outputs can increase by a factor of 5 or more, causing both APP sensors to read 100% 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 Tesla vehicles. This current load is so high because the weight of Tesla's high voltage battery makes Tesla vehicles some of the heaviest passenger vehicles on the road, requiring a power steering system with the greatest torque and the highest current available. 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, and the 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.

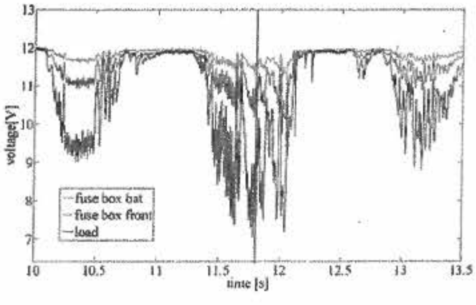
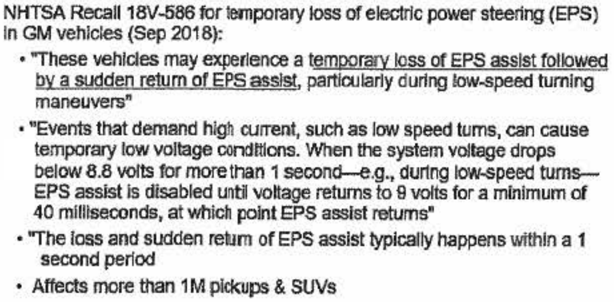


Fig. 12. Voltage spikes on the "12V" supply line of an ICE vehicle as caused by an electronic power steering (EPS) system during a slalom maneuver.[20]



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. 13. 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.[21]

If we now look at the spec sheet for the Infineon TLF35584QVVS2 PMIC chip, we find that the ADC VREF, APP1, APP2, and CAN power supplies continue to operate during an under-voltage condition.[22] This means that the attenuated 5V calibration voltage used to create the 1.65V 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.

If the digitized APP sensor outputs are to be multiplied by some number to cause sudden acceleration, it is also required that the analog APP sensor outputs prior to digitization remain unchanged from their values without being pressed. For ratiometric sensors, this means that the 5V supply voltage powering the sensors does not change. So, how can the 5V reference voltages used for the APP sensor supplies not change while the same 5V reference voltage is used for ADC calibration and does change temporarily because it has a voltage spike on it? The answer may be either: 1) the APP sensor outputs do not contain very short negative-going voltage spikes because the sensors essentially filter the 5V supply voltage to end up using only the DC value of the 5V supply voltage, or 2) the APP sensor outputs do contain very short negative-going voltage spikes, but the dip in the two APP sensor output voltages does not occur while they are being digitized at a different time, so the APP sensor output voltages essentially remain unchanged. Either explanation would cause the probability for sudden acceleration to depend only on the probability that a negative-going voltage spike occurs during digitization of the calibration signal by the ADC, and not during the digitization of the APP sensor signals. And either explanation would make the duration of the sudden acceleration equal to the time between successive calibrations.

Vehicle Operation During Sudden Acceleration

During sudden acceleration the "1.65V" calibration process used on the APP sensor signals during normal vehicle operation does not work as expected. This is because the "1.65V" 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 "1.65V" calibration voltage 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 "1.65V" calibration voltage to drop to 0.275V or less. If the "1.65V" signal is being sampled while one of these negative-going voltage spikes occurs, then the "1.65V" 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 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 3 shows how the APP sensor signals change with different calibration voltages when the accelerator pedal is released. These changes produce non-zero APP sensor signals similar to when the driver has his foot on the accelerator pedal even though his foot is off the accelerator pedal.

Table 3. Decreases in the "1.65V" calibration voltage cause increases in the released APP sensor output voltage in a way that mimics stepping on the accelerator pedal

Released pedal APP signal voltage[a]	% pedal	12V Supply Voltage[b]	V_{CAL} Calibration Voltage[b]	Correction factor X for V_{CAL} Voltage	Released APP signal after Calibration	% pedal after Calibration
0.68V	0%	12.6V	1.65V	1	0.68V	0%
0.68V	0%	6.3V	0.825V	2	1.36V	20%
0.68V	0%	4.2V	0.550V	3	2.04V	40%
0.68V	0%	3.2V	0.412V	4	2.72V	60%
0.68V	0%	2.5V	0.330V	5	3.40V	80%
0.68V	0%	2.14V	0.281V	5.88	4.00V	100%
0.68V	0%	2.1V	0.275V	6	4.08V	>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 voltages remain unchanged.

c. A value >100% produces a SNA signal (Signal Not Available), which has been seen in EDR readouts.

Figure 13 shows the values X in Table 3 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 "1.65V" 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.

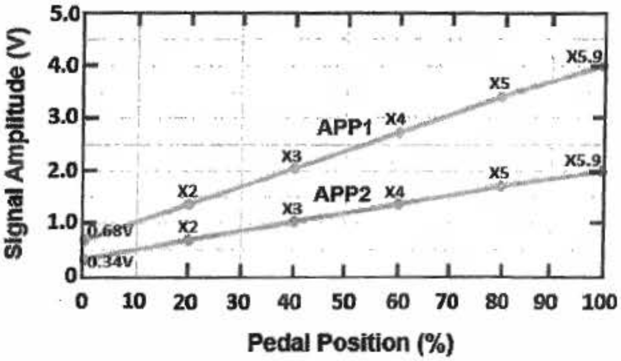


Figure 13. APP signal transfer functions showing that multiplying the released pedal values by the factors xN produces values that lie on the same curves as the original transfer functions, allowing the corrected signals to pass all tests performed on the original APP signals.

Even worse, both incorrectly increased APP sensor signals will be sent via the CAN bus to the vehicle log and to the EDR, causing Tesla 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 Tesla vehicles of about 20×10^{-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 Model 3 inverter calibrates all four ADC's using the same "1.65V" calibration signal. If the "1.65V" calibration signal decreases, then the APP sensor signals increase by the inverse ratio that the "1.65V" signal decreases. This normally does not happen because the "1.65V" 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 "1.65V" 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 Infineon TLF35584QVVS2 PMIC chip that provides the ADC VREF, APP1, APP2, and CAN power supplies continues to operate during an under-voltage condition.[23] This means that the attenuated 5V calibration voltage used to create the 1.65V 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 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 vehicle log and 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 log data and 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 Tesla 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 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 Model 3 inverter housing to access the inverter PWB as shown in Figure 1. Then, one can lift DSP pin 44 from its PWB pad and attach a wire to the lifted pin as shown in Figure 13 below. This wire can then be passed through the 30-pin connector on one of its three unused pins (pin 9, 19, or 29). If this wire is then accessed on the other side of the 30-pin connector when the inverter housing is closed back up, one can then impose a variable voltage on the wire. If one keeps this voltage

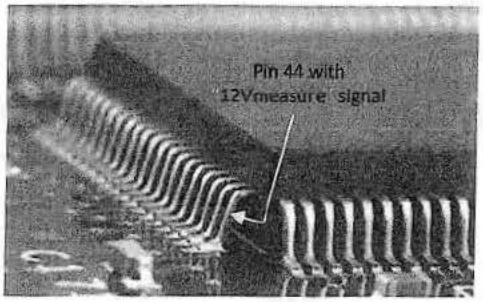


Figure 14A. DSP pin 44 with the "12V measure" signal is the last pin on the left.

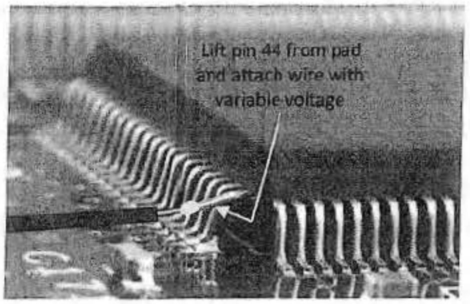


Figure 14b. Lift DSP pin 44 and attach a wire with a variable voltage.

constant at 5V scaled down to 1.65V, then the inverter will run normally with torque being varied by pressing the accelerator pedal. But if one changes this voltage to 0.281V or less, which can happen when the 12V supply dips temporarily to 2.14V, 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. Susceptibility of Other Tesla Vehicles to Sudden Acceleration

The potential cause of sudden acceleration discussed in Section III exists in all inverters made by Tesla and used in all models of Tesla vehicles. This is because all Tesla inverters use a "1.65V" signal to calibrate the multiple ADC's in the inverter. This "1.65V" calibration voltage can have large negative-going voltage spikes or dips on it as a result of the electronic power steering drawing more current during low speed turning maneuvers (which can draw over 300 amps at times). If such negative-going voltage spikes or dips happen while the ADC is digitizing the calibration voltage, then the ADC calibration can change, causing an increase in the APP sensor signals without the driver pressing on the accelerator pedal.

In Model S and Model X vehicles the ADC function is slightly different than in the Model 3 as a result of a different DSP controller chip being used. In the inverters of these vehicles, there is only one ADC fed by two different analog multiplexers. The two APP sensor signals are then run through different analog multiplexers. This requires connecting the same "1.65V" calibration voltage to both analog multiplexers in order to implement the same voltage correction. If an inspection of the inverter design on these vehicles shows that the same "1.65V" calibration voltage is brought into both analog multiplexers, then this would be good evidence that Model S and Model X vehicles are subject to the same cause of sudden acceleration as the Model 3.

V. Susceptibility of Tesla Vehicles to SUA while in Cruise Control and Autopilot Mode

While in cruise control or autopilot mode, calibration of the ADC's might take place during which voltage dips on the "1.65V" calibration voltage can cause the APP sensors outputs to increase from the values found at their normal released pedal position. The increase in the APP sensor outputs would mimic the driver pressing on the accelerator pedal to temporarily override the cruise control or autopilot mode. Further investigation of this possibility is warranted to determine whether it can explain the cause of the many Tesla crashes encountered in these modes.

VI. Elimination of Sudden Acceleration

Knowing the potential cause of Tesla 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 DC/DC converter 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 and DC/DC converter 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 APP sensors and the ADC's having the same capacity or larger may be used for the inverters because it retains charge longer. In this case, a study may reveal that charging once a day is sufficient. This may allow the use of only one DC/DC converter if battery charging is done only at night while the vehicle is not being driven.
2) Modify the calibration routine software for sampling the "1.65V" 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.

VII. Summary and Conclusion

The details of Tesla's Model 3 inverter design as revealed by Irish engineer Damien Maguire have been presented. These details were used to construct a hypothetical model of all hardware and software operations performed on the two accelerator position sensor (APP) sensor signals inside the inverter as they pass from the APP sensor to the electric 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 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 "1.65V" calibration voltage while it is being sampled 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 vehicle log and 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 log data and the EDR data show that the APP sensor signals have been increased.

This mechanism for unintended acceleration can exist in all models of Tesla vehicles. It does not require any changes in the accelerator pedal sensors or their analog outputs. Instead, it is caused by a change in the ADC calibration 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. This mechanism explains how sudden unintended acceleration can occur in all Tesla vehicles with the accelerator pedal sensor data in both the EDR and the vehicle log showing up to 100% pedal even though the driver never stepped on the accelerator pedal. It also explains why the drive torque is not limited by the torque monitor during sudden acceleration when it should be limited to zero if the accelerator pedal is not pressed. This is because the digitized pedal sensor outputs are increased 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. Finally, it may also explain the many crashes that Tesla's have encountered while in cruise control and autopilot modes. A test for verifying this SUA mechanism is described, and solutions for this susceptibility to SUA are presented.

Acknowledgments

The author would like to thank Damien Maguire for his detailed hacking results that revealed the internal design of the Model 3 inverter. These results provided an unprecedented understanding of Tesla's inverter design that supported an analysis of the design for sudden unintended acceleration.

Appendix A. Examination of EDR Data from Alleged Sudden Acceleration Incidents

Accelerator pedal position (APP) sensor signals have been recovered from the EDR's of two vehicles involved in alleged sudden unintended acceleration (SUA) incidents. These EDR signals are shown in Figs A1 and A2. Can we explain how these signals are produced by the cause of sudden acceleration proposed in this paper?

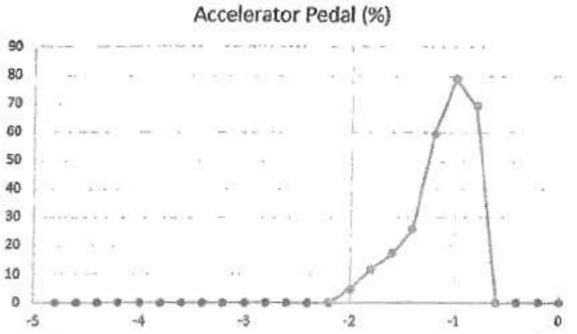


Fig A1. EDR data for a female driver approaching a garage on a level driveway[24]

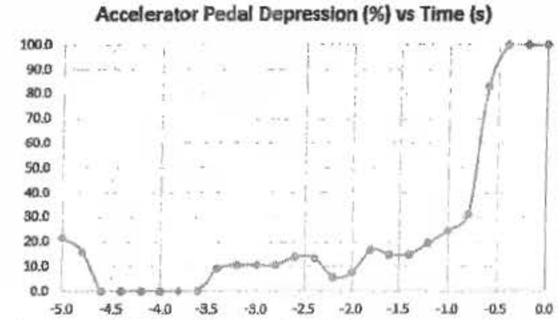


Fig A2. EDR data for a male driver going down-hill in a parking ramp[25]

At first it would seem that both these signals were made by drivers pressing on the accelerator pedal instead of the brake pedal. This is a common conclusion when it is believed that the signals can be non-zero only when the driver is pressing on the accelerator pedal. Whoever believes these EDR APP sensor signals were made by drivers pressing on the accelerator pedal instead of the brake pedal must also explain the similarity between the two signals even though they were produced by two different drivers in vastly different situations. This similarity lies not only in the large amplitudes of the two signals, but also in the similarity of the two rise times; namely, a slow one lasting for about 0.8 seconds followed by a faster one that rises to a maximum in less than a half a second. Are we to believe that two drivers of different sexes and in two entirely different driving situations could press the accelerator pedal inadvertently at almost exactly the same rates of movement with a slow depression first followed by a faster occurring at almost the same time later? This author believes not.

Can we then explain how the two APP sensor signals are caused electronically while the driver's feet are off the accelerator pedal? If we assume that the explanation proposed in the paper is correct that the APP sensor signals are increased electronically by the inverter electronics when an ADC calibration is performed while the "12V" supply line and the "1.65V" calibration voltage are pulled low by a negative-going voltage spike or voltage dip, then we would expect to see a sudden jump in the two APP sensor signals instead of a slow rise time. If so, then why do the excursions in the EDR APP sensor signals last much longer (approximately 1.5 seconds) than the negative-going inrush current voltage spikes (approximately 100 microseconds) and the ADC sample times (approximately 10 microseconds) whose overlap is supposed to cause the increases in the APP sensor signals? And wouldn't the sudden jump in the APP sensor signals last for only one sample of the APP sensor signals, or 10 milliseconds, if the 1.65V calibration voltage is sampled continuously like the APP sensor signals? We will now provide an answer to these two questions and explain how the APP sensor signals arise.

The answer for the long excursions in the APP sensor signals is that the 1.65V calibration voltage is not sampled at the same rate as the APP sensor signals (every 10 milliseconds) because the normal variations in the high voltage battery voltage occur so slowly that it is not necessary to sample the derived 1.65V calibration voltage as often. Once every second or longer is sufficient. This can save valuable ADC time that can be used for operations on other signals. In between these longer 1.65V calibration samples the stored value of the 1.65V calibration can be used to make corrections to the APP sensor signals. In this case, instead of a APP signal spike lasting only one sample time of 100 milliseconds, the excursions in the APP sensor signals become step functions whose durations are determined either by a new 1.65V calibration sample that does not include a negative voltage spike, or by the amplitude of the corrected APP sensor signal exceeding some implausible value, like greater than 100% pedal. These step functions are shown in Figures A3 and A4. These step functions show that the 12V battery voltage decreases in discrete steps: e.g., from 12.6V to 9.5V to 2.0V in Figure A3 and from 12.6V to 11.3V to 8.8V to 2.0V in Figure A4. The step function for 11.3V is actually three step functions for three successive samples of the 12V supply voltage having the same voltage. These steps are plausible because step functions for 12V supply voltages above about ten volts corresponds to a battery still retaining charge, so its voltage changes little as a voltage spike occurs. However, step functions for 12V supply voltages less than about ten volts correspond to a battery fully depleted of charge, which makes the battery incapable of supplying charge to offset a later voltage spike, thereby increasing the amplitude of the later voltage spikes. The minimum time between changes in the step functions appears to be approximately 0.8 seconds and 2.4 seconds, which implies that the 1.65V calibration voltage is sampled once every 0.8 seconds.

While this may explain the longer durations of the excursions in the EDR APP sensor signals, it does not explain their rise times. The explanation for the longer rise times is that the APP sensor signals must be filtered in order to slow their rise times before being sent to the EDR, the vehicle log, and the pedal map to obtain a commanded torque value. This is because the calibrated APP sensor signals are later tested for their plausible movement by a driver by assuming that the movements have been made more slowly than a signal that has been filtered by a first order exponential filter with a time constant of about 300 milliseconds. The possibility of such a test has been mentioned by Jason Hughes.[8] This plausibility test can be done either just before or just after the APP sensor signals are converted to % pedal values. Although there are two slopes in the signals of Figs 3 and 4, the two slopes have the same RC time constant. The slower slopes arise from the smaller amplitudes of the two signals.

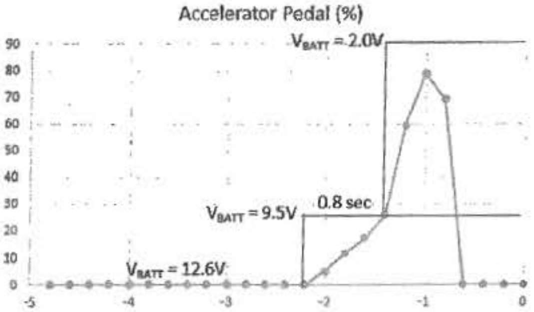


Fig A3. EDR data shows two step functions with V_{BATT}'s equal to 9.5V and 2.0V separated by 0.8 sec

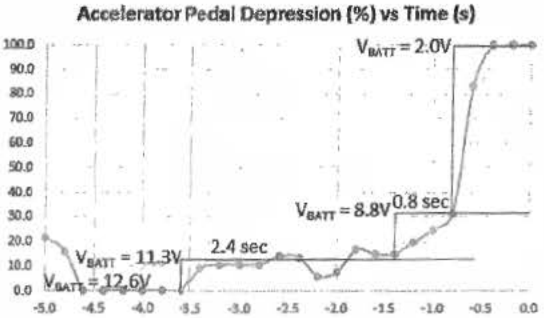


Fig A4. EDR data shows three step functions with V_{BATT}'s equal to 11.3V, 8.5V, and 2.0V separated by 2.4 sec and 0.8 sec

Filtering of the APP sensor signals is easily done by using an exponentially weighted moving average algorithm implemented by

$$y_i = \alpha x_i + (1 - \alpha) y_{i-1}$$

where the original APP sensor voltage samples are given by $(x_1, x_2, \ldots, x_n)$ and the filtered APP sensor voltage samples are given by $(y_1, y_2, \ldots, y_n)$, where Δ_T is the sampling time, RC is the exponential time constant, and α is the smoothing factor defined by

$$\alpha = \frac{\Delta_T}{RC + \Delta_T}$$

with $0 \le \alpha \le 1$. The *RC* time constant is then given in terms of terms the smoothing factor α and the sampling period Δ_T by

$$RC = \Delta_T \left(\frac{1-\alpha}{\alpha} \right)$$

If we apply this RC filter to the step functions in the % pedal EDR data while recognizing that the EDR samples are down-sampled by selecting every 20th sample from original APP sensor data rate of $\Delta_T = 100$ milliseconds, then we get the rise times shown in Figures 3 and 4 assuming an RC time constant of 300 milliseconds. This provides a good match to the rise times of the EDR % pedal signals.

VIII. References

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[1] NHTSA complaint #11291423 from Palmdale, California, in which the owner of a 2015 Tesla Model S claims their vehicle suddenly accelerated while the owner was outside the vehicle. Cited in ODI memo DP20-001 Second Addendum Attachment of letter to James Owens, dated 12-30-2020. https://static.nhtsa.gov/odi/inv/2020/INME-DP20001-81994.pdf

[2] NHTSA ODI Resume DP20-001 denying defect petition, dated 1/8/2021, https://static.nhtsa.gov/odi/inv/2020/INCLA-DP20001-6158.PDF

[3] Damien Maguire at https://openinverter.org/forum/viewtopic.php?f=10&t=575

[4] Damien Maguire at https://openinverter.org/wiki/Main_Page

[5] Damien Maguire at https://www.youtube.com/watch?v=qvEuErZWr8c

[6] Damien Maguire at https://www.youtube.com/watch?v=hBhNcad7zTA

[7] Damien Maguire at https://www.youtube.com/watch?v=vDH-EKbXmrA

[8] Texas Instruments, "TMS320f28377d data sheet", https://www.ti.com/product/TMS320F28377D

[9] Damien Maguire at https://github.com/damienmaguire/Tesla-Model-3-Drive-Unit/blob/master/M3_TMS_PINOUTDIAG1.pdf. This pinout diagram was first published on November 24, 2020, and has never been revised. It should have been revised on March 24, 2023, to make it agree with the pin map in reference 10 below.

[10] Damien Maguire at https://github.com/damienmaguire/Tesla-Model-3-Drive-Unit/blob/master/TMS320F28377D_M3_PinMap.ods. The first version of this table was released on November 24, 2020, and showed a 12V_measure signal on pin 44. The most recent version of this table is dated March 25, 2023, and shows the 12V_measure signal on pin 29 instead of pin 44. Pin 44 is now undefined, although a private communication reveals that more recent probing shows that pin 44 has a 1.655V signal on it that provides an ADC value of 2005 out of 4095.

[11] Several automobile manufacturers use a pedal rate-of-motion test on the APP sensor signals, including Nissan, BMW, Land Rover, and Tesla. 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
4) Tesla, Jason Hughes, at https://teslamotorsclub.com/tmc/threads/sudden-unintended-acceleration.107134/page-22

[12] Jason Hughes (wk057) at https://teslamotorsclub.com/tmc/threads/sudden-unintended-acceleration.107134/page-22

[13] An Overview of Designing Analog Interface with TMS320F28xx/28xxx DSCs, TI Application Report SPRAAP6a – May 2008, p18.

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[14] TMS320280x and TMS3202801x ADC Calibration, TI Application Report SPRAAD8a – March2007, p1. https://www.ti.com/lit/an/spraad8a/spraad8a.pdf

[15] TMS320280x and TMS3202801x ADC Calibration, TI Application Report SPRAAD8a – March2007, p1. https://www.ti.com/lit/an/spraad8a/spraad8a.pdf This reference derives the equations used for calibration with an external signal, which assume that two calibration points determine the slope of a line. However, one calibration point can be the origin (0,0), which allows only one external signal to be used.

[16] In this case ADC input 15 on pin 45 is not used, and should be set to analog GND. However, Tesla may have merely left this pin open, which has no effect on calibration because it is not accessed during calibration. But it is safer to set the pin to analog GND.

[17] TMS320280x and TMS3202801x ADC Calibration, TI Application Report SPRAAD8a – March2007, p9. https://www.ti.com/lit/an/spraad8a/spraad8a.pdf

[18] Note that there are two APP sensors with separate 5V supply voltages while only one ADC calibration voltage is used. Therefore, while the attenuated 5V calibration voltage from one APP sensor works perfectly to remove errors from its ratiometric APP sensor, errors in the other ratiometric APP sensor are not removed completely unless they are identical in both APP sensors. This flaw could be eliminated by using two different ADC calibration voltages; i.e., a different one for each APP sensor channel. Why this is not done by Tesla is unknown at this time.

[19] Exponent, "Analysis of Toyota ETCS-I System Hardware and Software", September 2012, p. 84-86, p. 175, and p. 216. https://archive.org/details/AnalysisOfToyotaETCS-iSystemHardwareandSoftware

[20] 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

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

[22] 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

[23] 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

[24] R. Belt, "*Tesla Regen, Brakes, and Sudden Acceleration*", https://www.autosafety.org/dr-ronald-a-belts-sudden-acceleration-papers/, 1 June 2020.

[25] Michael Cantu, "Valet Driver Crashes Tesla Model 3 Into Car, Blames Autopilot", https://insideevs.com/news/496305/valet-crashes-tesla-data-recorder-legal-case/, 24 March 2021.

Motor Vehicle Defect Petition to Recall All Tesla Vehicles Due to Sudden Unintended Acceleration

Mr. Jack Danielson
Executive Director
National Highway Traffic Safety Administration
1200 New Jersey Avenue SE, West Building
Washington, DC 20590

12 May 2023

Dear Executive Director Carlson,

On December 19, 2019, NHTSA received a petition from Mr. Brian Sparks requesting that the Agency "recall all Tesla Model S, Model X, and Model 3 vehicles produced from 2013 to the present" due to sudden unintended acceleration (SUA), citing 232 driver complaints to NHTSA, including 203 reported crashes. On January 13, 2020, NHTSA opened investigation DP 20-001 in response to this petition. The investigation was closed on January 8, 2021, stating:

> "After reviewing the available data, ODI has not identified evidence that would support opening a defect investigation into SUA in the subject vehicles. In every instance in which event data was available for review by ODI, the evidence shows that SUA crashes in the complaints cited by the petitioner have been caused by pedal misapplication. There is no evidence of any fault in the accelerator pedal assemblies, motor control systems, or brake systems that has contributed to any of the cited incidents. There is no evidence of a design factor contributing to increased likelihood of pedal misapplication."

The purpose of this letter is to request that investigation DP 20-001 be re-opened because of new information, enclosed with this letter, that NHTSA investigators erred in ascribing the cause of these incidents to pedal misapplication. The enclosed paper shows that nearly all of these incidents may have been caused instead by a change in the analog-to-digital converter (ADC) calibration used when the accelerator pedal sensor outputs were digitized, which can make the digitized accelerator pedal sensor outputs increase to a maximum of 100% even though the analog accelerator pedal outputs are never changed because the accelerator pedal is not being pressed by the driver. This mechanism explains how sudden unintended acceleration can occur in all Tesla vehicles, with the accelerator pedal sensor data in both the EDR and the vehicle log increasing up to 100% pedal, even though the driver has never stepped on the accelerator pedal. It also explains why the drive motor torque is not limited by the torque monitor during sudden acceleration when it should be limited to zero if the accelerator pedal is not pressed. This is because the digitized pedal sensor outputs are increased up 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.

The change in ADC calibration in this case is caused by a voltage dip on the "12V" power supply bus caused by an inrush current in the booster motor of the electronic power steering system while suddenly turning on as a result of the electronic power steering system requiring greater boosting force during low-speed turning maneuvers (which can draw over 300 amperes temporarily). This voltage dip can cause a dip in the ADC calibration voltage that lasts for several hundred microseconds. If this voltage dip happens while the ADC is digitizing the calibration voltage, then the digitized ADC calibration voltage can decrease and remain at a lower voltage until another calibration is performed, which can be minutes later. A lower digital ADC calibration voltage results in higher digitized values for the two APP sensor outputs even though the analog values of the two APP sensor outputs do not change. The result is that the two APP sensor analog outputs, which remain unchanged at their unpressed values, are multiplied by a value of 1 to 6 while being digitized, which mimics in every way the changes produced in the two APP sensors by the driver stepping on the accelerator pedal. Therefore, the two APP sensor digital outputs pass every test performed subsequently on the two digitized APP sensor signals, creating no diagnostic test codes (i.e., alerts in Tesla's nomenclature) and creating non-zero pedal data that is stored in the EDR and the vehicle's data log, even though the accelerator pedal has not been pressed by the driver.

The enclosed paper proposes a simple test that can be done to prove or disprove the explanation provided. This test has not been done by the author because of the cost involved with acquiring the needed Tesla Model 3 inverter PWB. But this test can be performed easily by NHTSA investigators, which generates a strong motivation for re-opening investigation DP 20-001 on this topic. It must be remembered that NHTSA investigations are meant to gather further information about an alleged defect that can aid a decision about a defect, and not merely to decide that there is insufficient information to justify an investigation, in which case the request for an investigation is denied.

The time for NHTSA to respond to this request to re-open a previous investigation should be the same as for a request to open a new investigation. If you desire to contact me for any reason relevant to this letter, please use the email address given below.

Sincerely yours,

[redacted]

Ronald A. Belt
[redacted]
Plymouth, MN [redacted]
Email: [redacted]

Encl: Paper entitled "Tesla Model 3 Susceptibility to Sudden Unintended Acceleration" by Ronald A. Belt, 26 pages, dated 1 May 2023.

Motor Vehicle Defect Petition to Recall All Tesla Vehicles Due to Sudden Unintended Acceleration

Ann Carlson, Acting Administrator
National Highway Traffic Safety Administration
400 Seventh Street, S.W.
Washington, DC 20590

19 May 2023

Dear Acting Administrator Carlson,

NHTSA has several options to consider as a response to a petition to re-open investigation DP 20-001 on Tesla sudden unintended acceleration as requested by my letter dated 12 May 2023.

Research shows that sudden unintended acceleration is caused by a faulty digital value of the ADC calibration voltage. Therefore, NHTSA should require Tesla to revise its vehicle control software to check the value of this calibration voltage after digitization, and if it is too low, replace it with a new value of the reference voltage obtained by repeating the reference voltage digitization process. NHTSA should also specify how to test whether the digitized calibration voltage is too low, rather than leaving it up to Tesla to determine how this should be done. But if NHTSA requires only that a faulty digital value of the ADC calibration voltage should be replaced, then although this would eliminate sudden unintended acceleration in Tesla vehicles, there will be little feedback to prove that the problem has been solved. The only feedback that will result is a drop in the number of sudden unintended acceleration incidents in the press and a drop in the number of vehicle owner questionnaires (VOQ's) to NHTSA describing sudden unintended acceleration incidents.

NHTSA can improve the feedback it receives on its solution to unintended acceleration by also requiring Tesla to keep a vehicle log of each time it replaces a faulty digital value of the ADC calibration voltage with a new digitized value. This log would require setting aside only one word of non-volatile memory that could store one integer value that could be incremented whenever a faulty digitized value of the ADC calibration voltage is replaced by a new value. Then, NHTSA could require that Tesla interrogate this vehicle log periodically (e.g., yearly) from all the vehicles in its fleet, which would yield statistics on how often sudden unintended acceleration could have occurred in the fleet, but did not, because a fix for sudden acceleration had been installed. This would provide rigorous statistical proof that sudden unintended acceleration was caused by a faulty digital value of the ADC calibration reference voltage and was effectively cured by NHTSA's required solution.

NHTSA can go even further and require that each time a faulty digital value of the ADC calibration voltage is replaced with a new digitized value, then the faulty digital value must be stored in non-volatile memory. Since vehicles rarely have more than three or four incidents of sudden unintended acceleration, this would require setting aside no more than four or five words of non-volatile memory with each word storing one 32-bit value of a faulty calibration voltage. By interrogating these faulty values of the ADC calibration voltage, one can then determine how much the accelerator pedal outputs would have increased and the depths of the voltage dips on the 5V and 12V supply voltages required to cause each faulty calibration voltage. The voltage dips on the 12V supply bus may point to the origin of the dips, e.g., possibly the electronic power steering system. This information would help engineers to come up with design techniques to avoid these voltage dips in the future, e.g., possibly using supercapacitors for the power steering system.

Finally, NHTSA could go still further and require that the log containing the number of times that a faulty digital value of the ADC calibration voltage is replaced with a new digitized value, the faulty digital values of the ADC calibration voltage that have been stored, and the current ADC calibration voltage, be made available to vehicle owners by transferring them via the CAN bus to the EDR module, where they can be accessed by suitably modified EDR reading software for use by the vehicle owner. This would give vehicle owners the data they need to challenge Tesla in court in cases of sudden unintended acceleration instead of forcing vehicle owners to rely on Tesla to supply this information. This reliance has put vehicle owners at a serious disadvantage, allowing Tesla to claim in the press that sudden unintended acceleration in Tesla vehicles is impossible while denying vehicle owners access to EDR and vehicle log information for use in court cases or during mandatory arbitration imposed by Tesla's sales agreements.

Sincerely yours,

[redacted]

Ronald A. Belt
[redacted]
Plymouth, MN [redacted]
Email: [redacted]

Motor Vehicle Defect Petition to Recall All Tesla Vehicles Due to Sudden Unintended Acceleration

Sophie Shulman, Acting Administrator
National Highway Traffic Safety Administration
400 Seventh Street, S.W.
Washington, DC 20590

5 June 2023

Dear Acting Administrator Shulman,

The purpose of this letter is to provide additional evidence in support of my petition to NHTSA dated 12 May 2023 to re-open NHTSA's Office of Defects Investigation number DP 20-001, entitled "Tesla Sudden Unintended Acceleration". This letter is a follow-up to two previous petition letters to NHTSA dated 12 May 2023 and 19 May 2023.

The first item of new evidence is a second paper entitled "EDR Accelerator Pedal Data Can Be Wrong With This Cause of Sudden Acceleration", dated 1 June 2023. This new paper goes into more detail on how ADC calibration is performed and how ratiometric sensors require using the APP supply voltage for ADC calibration. It also explains why voltage dips in the APP supply voltage are not removed by ADC calibration like slower voltage changes caused by temperature changes are removed. You can obtain a copy of this new paper by going to the Center for Auto Safety web site: https://www.autosafety.org/dr-ronald-a-belts-sudden-acceleration-papers/ and clicking on the paper EDR Accelerator Pedal Data Can Be Wrong With This Cause of Sudden Acceleration. Note that this new paper does not mention Tesla or any other auto manufacturer, but deals only with the technical issues involved to avoid disparaging any auto manufacturer.

The second item of new evidence is a list of design factors that contribute to sudden acceleration as compiled from this author's two recent papers.

In the January 8, 2021 Denial of Petition to NHTSA's Office of Defects Investigation (investigation number DP 20-001), it is clearly stated by NHTSA that *"There is also no evidence of a design factor contributing to increased likelihood of pedal misapplication."* This assertion was used by NHTSA as a reason for denying the petition. In response to this assertion, here is a list of design factors that provide new evidence of an increased likelihood of the pedal sensors increasing during sudden acceleration [aka "pedal misapplication" in NHTSA's terminology] to support reopening investigation number DP 20-001:

1) [New evidence] Both ADC's that digitize the APP sensor outputs in Tesla's inverters are being calibrated by a single ADC calibration voltage or reference voltage.
2) [New evidence] If the ADC calibration voltage decreases by some ratio, then both digitized APP signals will increase by the same ratio even though the two analog APP signals do not change.
3) If the two digital APP output signals increase because of a decrease in the calibration voltage, then:

   a. [New evidence] The increased digital APP output signals will produce a point that lies on the original transfer function of each sensor that normally is produced by stepping on the accelerator pedal.
   b. [New evidence] The increased digital APP signals will mimic in every way the driver stepping on the accelerator pedal even though the driver has not stepped on the accelerator pedal.
   c. [New evidence] The increased digital APP signals will pass all tests performed on the digital APP signals, causing no alerts or DTC's.
   d. [New evidence] The increased digital APP signals will produce non-zero log data and no-zero EDR data even though the driver did not step on the accelerator pedal.
4) [New evidence] If the decrease in the ADC calibration voltage is large enough, then both digital APP signals can be increased up to 100% without the driver stepping on the accelerator pedal.
5) All of the operations 1) through 4) above are true regardless of the cause for a decrease in the ADC calibration voltage.
   a. [New evidence] One reason for a decrease in the ADC calibration voltage is a change in the ADC calibration voltage due to temperature changes in the reference voltage. This produces only a small increase or decrease in the ADC calibration voltage.
   b. [New evidence] Another reason for a decrease in the ADC calibration voltage is a voltage dip in the reference voltage. This can produce a large decrease in the ADC calibration voltage that can produce a large increase in the digitized APP sensor signal.
6) [New evidence] Specifically, there is evidence that a decrease in the ADC calibration voltage can occur during its digitization if a voltage dip occurs while the analog ADC calibration voltage is being sampled.
   a. [New evidence] It is known that voltage dips occur on the 12V supply line that are caused by inrush currents created when electric motors turn on.
   b. [New evidence] In Tesla vehicles the electric motor having the largest inrush current is the booster motor for the electronic power steering, which produces an inrush current of over 300 amps. This is because Tesla vehicles are very heavy and create very large forces during turns at low speeds, which require very large currents.
   c. [New evidence] This EPS inrush current can cause a voltage dip in the 12V supply line that reaches below 2V and that lasts for about 100 microseconds.
   d. Evidence a) through c) above has been verified by several academic papers.
   e. [New evidence] There is evidence from PMIC device operation used in the Tesla inverter that a voltage dip in the 12V supply line can cause a voltage dip in the ADC calibration voltage.

    f. [New evidence] The probability of a coincidence of a 100 microsecond dip in the 12V supply line with a 10 microsecond sample time of the ADC calibration voltage can explain the probability for SUA occurring in the sudden acceleration statistics for Tesla vehicles.

7) [New evidence] It is known that ADC calibration is performed continuously during vehicle operation. This can explain:
    a. [New evidence] Why some SUA events can have long durations, like the incidents in China and Paris, if the time between ADC calibrations is on the order of a minute or so.
    b. [New evidence] Why some drivers have reported that re-starting the vehicle after an SUA incident causes the vehicle to return to normal operation. This can be explained by a new ADC calibration voltage being digitized immediately after starting that yields a normal value of the ADC calibration voltage. The probability for no voltage dip to occur during digitization of the ADC calibration voltage is much higher than the probability for a voltage dip to occur during digitization.

These design factors provide new evidence that the same design factors that cause sudden intended acceleration also cause an increase in the accelerator pedal sensor values in the EDR and the log data, which is what NHTSA has referred to as "pedal misapplication". However, it is not the driver that is causing the sudden unintended acceleration because of pedal misapplication. It is the vehicle's control system that is causing the sudden acceleration because it allows an incorrect lower ADC calibration voltage to be used that creates an increase in the digitized accelerator pedal outputs even though the analog values of the accelerator pedal outputs remain the same because the driver has not pressed on the accelerator pedal. As a result of this new evidence, it is essential for NHTSA to re-open ODI investigation DP 20-001, entitled "Tesla Sudden Unintended Acceleration" in order to determine whether Tesla sudden unintended acceleration incidents are caused by an ADC calibration error or by pedal misapplication.

Sincerely yours,

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PROTECT ENDANGERED SPECIES

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