A Cause of Sudden Unintended Acceleration Common to All Vehicles with Electric Throttles

by

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Abstract: All vehicles with electronic throttles use accelerator pedal position sensors whose analog outputs are ratiometric. The advantage of ratiometric sensors is that the sensor outputs can be made independent of changes in the sensor supply voltage by dividing the sensor output voltage by the sensor supply voltage. This can be done either by digitizing the analog sensor output voltage while using the analog sensor supply voltage as a reference, or by digitizing both the analog sensor and supply voltage using a common voltage reference and then taking the ratio of the two digital outputs. However, the latter correction assumes that all changes in the sensor signals and the sensor supply voltage are correlated by sampling the two signals at the same time. If the two signals are sampled at different times, then an error is introduced that depends on how much the sensor supply voltage changes between the two sample times. This creates an error in the correction process whereby the sensor supply voltage can dip temporarily as it is being sampled because the supply voltage gets pulled low by some other load on the same supply bus as a result of a high transient inrush current. Yet, if the sensor signal remains unchanged by this temporary voltage dip because it is sampled at a different time, then the ratio of the sensor signal to the sensor supply voltage becomes larger because the lower supply voltage in the denominator does not cancel the higher supply voltage in the numerator. The result is a larger digitized sensor signal. This larger digitized sensor signal is produced even though the original <u>analog</u> sensor signal never changes. The consequence of this error is that the digitized accelerator pedal position sensor signal can increase up to 100% to cause sudden acceleration of the vehicle even though the <u>analog</u> accelerator pedal sensor signal remains unchanged because the driver never steps on the accelerator pedal. The vehicle's control system recognizes no difference between this larger digitized sensor signal and the driver stepping on the accelerator pedal. And since this error mechanism is a consequence of how the ratiometric analog sensor signals from all accelerator pedal assemblies are digitized, it exists in all vehicles having electronic throttles, including cars with gasoline engines, diesel engines, and electric drive motors, along with trucks, buses, motorcycles, possibly even electric bicycles. This paper discusses this error mechanism in further detail and explains how dips in the sensor supply voltage can occur to cause sudden unintended acceleration in all these vehicles.

I. Introduction

In many cases of sudden acceleration over the past twenty-five years drivers have claimed that the vehicle accelerated while their foot was on the brake pedal or on the floor instead of on the accelerator pedal. However, auto manufacturers and the NHTSA have maintained that the drivers in nearly all cases of sudden acceleration pressed on the accelerator pedal, often citing EDR results to prove their claim. This has led to the common belief, as published in countless news reports, echoed by endless internet forum commenters, and even shared by some police investigators, that all claims of sudden unintended acceleration are caused by the driver stepping on the accelerator pedal instead of the brake pedal. This common belief persists even though cases of sudden acceleration have occurred while both of the driver's feet were outside the vehicle.[1]

This common belief has been accepted because the NHTSA has consistently maintained that no cause for sudden unintended acceleration has ever been found within the vehicle's electronics during any of their previous investigations or by the investigations of many auto manufacturers. However, none of NHTSA's investigations have ever looked into the detailed design of an electronic throttle system and followed the signal all the way from the accelerator pedal sensors to the output of the throttle motor control system or to the output of the electric drive motor control system. Therefore it is easy to miss a cause of sudden unintended acceleration if one does not look for it in sufficient detail. The goal of this paper is to show that if an investigation of the electronic throttle system is carried out in sufficient detail, then an electronic cause of sudden unintended acceleration can be found. Our investigation starts with the accelerator pedal position (APP) sensors.

II. Accelerator Pedal Position (APP) Sensors

Analog pedal position sensors are used in all vehicles having electronic throttles. They are sold to auto manufacturers by suppliers as part of an accelerator pedal assembly that includes the accelerator pedal and a pedal position sensor. In some cases the pedal assembly also includes a brake pedal and a brake light switch or a brake pedal position sensor. The accelerator pedal assemblies are usually just one of a large assortment of sensors provided by the same supplier. These accelerator pedal assemblies have the characteristics shown in Table 1.

Table 1. Common Characteristics of Accelerator Pedal Assemblies

- All accelerator pedal assemblies provide multiple sensor outputs that measure the angle at which the accelerator pedal is depressed.
  - Early accelerator pedal assemblies used resistive sensors (i.e., potentiometers) that required a mechanical slider making physical contact to a resistive path. They deteriorated rapidly with age.
  - Modern accelerator pedal assemblies use Hall effect sensors or inductive (CIPOS) sensors that require no mechanical contact. They remain reliable over time.
- Most modern accelerator pedal assemblies provide two analog outputs.
  - The two analog outputs usually have an A=2B (aka half-scale) characteristic in which the sensor outputs increase at different rates as the pedal is depressed.
  - The outputs usually start at some voltage above 0V (e.g., 0.50V or 0.25V) when the accelerator pedal is not pressed and end at some voltage below 5V (e.g., 4.0V or 2.0V) when the accelerator pedal is fully pressed, with a linear increase in between.
  - Some pedal assemblies may provide a third analog output that has a negative slope as the excitation increases or a digital output using a PWM protocol or the SENT protocol. However, most auto manufacturers prefer just two analog outputs.
- All analog outputs on all accelerator pedal assemblies are ratiometric.
- The accelerator pedal sensors on all accelerator pedal assemblies use a 5V supply voltage.

Further discussion of how auto manufacturers use these accelerator pedal position assemblies is provided Appendix 1.[Footnote 1] However, this investigation uses only the fact shown in Table 1 that all analog outputs on all accelerator pedal assemblies are ratiometric. This fact has been stated by a company named Engine Control and Monitoring (ECM), who supplies a product called an "appsCAN Pedal Simulator Module" that is used to control a vehicle's throttle while it is being tested on a dynamometer. Their spec sheet for this product explicitly states that "all analog outputs from accelerator pedals are ratiometric", and that their product can supply sensor outputs having this property.[2]

This fact has been verified by examining the catalogs of multiple suppliers of accelerator pedal assemblies. They all state that their analog sensor outputs are ratiometric.[3] This includes sensors with outputs having positive as well as negative slopes as the sensor input is increased. Finally, in 2012 Exponent did a study and published a report entitled "*Analysis of Toyota ETCS-*

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[1] This further discussion has been put into Appendix 1 because the material is not used in the present investigation. Placing it here can create a distraction for some readers who may disagree with one or more of the assertions found in the discussion.

i System Hardware and Software".[4] Their report describes tests performed on three types of accelerator pedal position sensors, a potentiometer type sensor, a Hall-based sensor from CTS, and a Hall-based sensor from Denso. All three were stated to be ratiometric sensors and confirmed to be so by testing.[5] Therefore, based on these three sources, this paper assumes the truth of the statement that "all analog outputs from accelerator pedals are ratiometric". We will now examine the consequences of using ratiometric sensors in all vehicles having electronic throttles.

III. Consequences of Ratiometric Sensors

First of all, what does it mean when we say that a sensor is ratiometric? By definition, ratiometric sensors are sensors whose outputs are directly proportional to the supply voltage, as shown in Figure 1. So, for example, if a 5 Volt supply voltage produces an output of 2.5V on a sensor having a positive slope, then a 10% increase in the supply voltage to 5.5V will produce an output of 2.5V + 10% • (2.5V) = 2.75V, or plus 10%. If a 5 Volt supply voltage produces an output of 2.5V on a sensor having a negative slope, then a 10% increase in the supply voltage to 5.5V will produce an output of 2.5V – 10% • (2.5V) = 2.25V, or minus 10%.

In order to use ratiometric sensors in electronic throttle systems, their outputs must first be digitized by an analog-to-digital converter (ADC). All ADCs operate by comparing the variable input voltage with a fixed reference voltage, as shown in Figure 2. The fixed reference voltage determines the maximum signal level in counts N_{max} that the ADC can convert. The ADC divides the variable input voltage V_{ADCin} by the fixed reference voltage V_{Ref} and then multiplies the maximum signal level N_{max} by the ratio of the two voltages. Therefore, all quantized digital outputs N_{out} from an ADC will be some ratio of the fixed ADC reference voltage. This makes the accuracy of the reference voltage a great concern when precision measurements are needed.

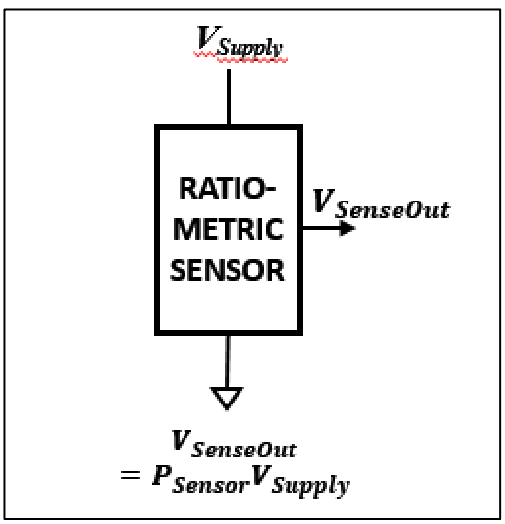

Fig 1. A ratiometric sensor is a sensor whose output voltage is directly proportional to the sensor input P and the sensor supply voltage V_{supply}. In other words, the output voltage of a ratiometric sensor has the same variation in percent as the sensor supply voltage.

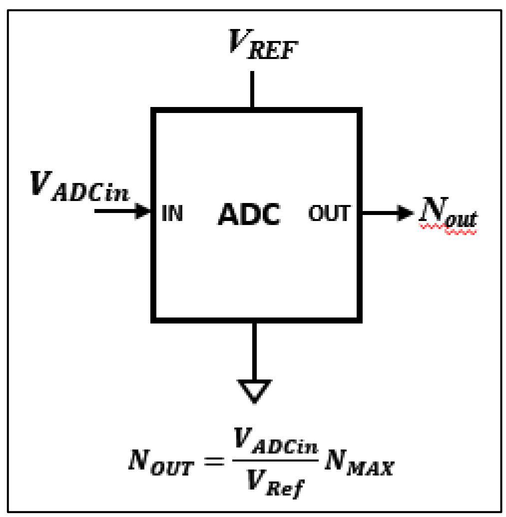

Fig 2. All ADC's operate by comparing the input voltage V_{ADCin} with a fixed reference voltage V_{Ref}. The reference voltage V_{Ref} determines the highest signal level that the ADC can convert, which corresponds to the maximum ADC output count N_{MAX}. The ADC output N_{out} is the number of counts given by the ratio $N_{out} = (V_{ADCin}/V_{Ref})\, N_{max}$.

Now, nearly all ADC's allow one to select either an internal reference voltage or an external reference voltage. The internal reference voltage provides a minimum cost application with smaller board space, while the external reference voltage provides a more accurate and more stable voltage reference. If one uses the internal ADC reference when digitizing a ratiometric sensor as shown in Figure 3, then the ADC output will not be free of changes in the sensor supply voltage. This is because the ADC produces an output that is proportional to the ratio

V_{supply}/V_{INTRef} where the two voltages do not cancel because the sensor supply voltage V_{supply} can vary relative to the fixed V_{INTRef}.

Similarly, if one uses the external ADC reference with a fixed reference voltage when digitizing a ratiometric sensor as shown in Figure 4, then the ADC output will not be free of changes in the sensor supply voltage. This is because the ADC produces an output that is proportional to the ratio V_{supply}/V_{EXTRef} where the two voltages do not cancel because the sensor supply voltage V_{supply} can vary relative to the fixed V_{EXTRef}.

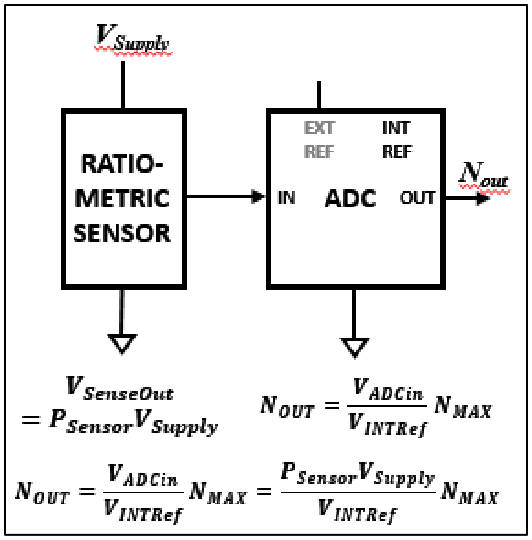

Fig. 3. If an ADC uses the internal reference voltage V_{INTRef} to digitize the output of a ratiometric sensor, the ADC output N_{out} will change with variations in V_{supply} relative to changes in the fixed ADC internal reference voltage V_{INTRef}. This does not take advantage of the ratiometric property of the sensor to obtain a digitized sensor output free of changes in the sensor supply voltage.

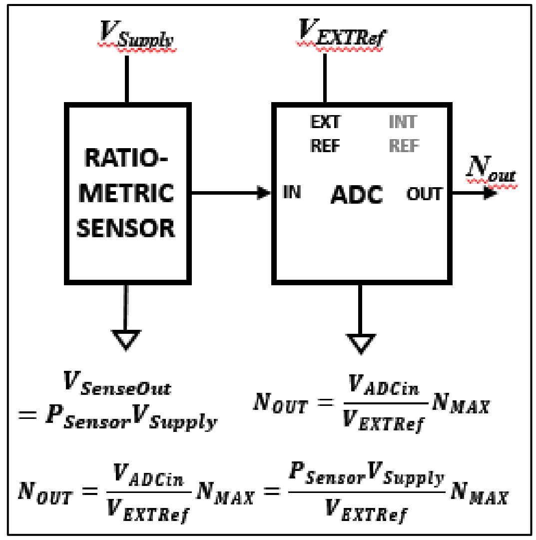

Fig. 4. If an ADC uses an external reference voltage V_{EXTRef} that is not the sensor supply voltage to digitize the output of a ratiometric sensor, the ADC output N_{out} will change with variations in V_{supply} relative to changes in the ADC external reference voltage V_{EXTRef}. This does not take advantage of the ratiometric property of the sensor to obtain a digitized sensor output free of changes in the sensor supply voltage.

Only if one uses the sensor supply voltage V_{supply} as the external ADC reference voltage, as shown in Figure 5, will the digitized sensor output (i,e., ADC output) be free of changes in the sensor supply voltage. This is because the ADC is comparing a sensor output voltage that varies with V_{supply} with an ADC reference voltage that also varies with V_{supply}, so the two V_{supply} voltages cancel exactly.

Now sometimes one may want to digitize the output of a sensor that is not ratiometric. In this case, a fixed V_{INTRef} is preferred for the non-ratiometric sensor signal while a variable V_{supply} voltage is preferred for the remaining ratiometric sensor signals. Both of these options can be accommodated by the configuration shown in Figure 6, which digitizes the V_{supply} voltage using a fixed V_{INTRef} and then calculates outside of the ADC the ratio of the sensor output N_{sensor} to the output N_{supply} to get a digitized sensor output that is free of changes in the supply voltage V_{supply}. This method also has the advantage that one can use an attenuated supply voltage V_{supply} that falls in the middle of the ADC output range to get a better calibration of the ADC. The method in Figure 6 has been patented by Infineon Technologies in US patent 8604961, as shown in Figure 7. This method is the one used in the electronic throttle control (ETC) systems of nearly all automobile manufacturers worldwide. It is also used in the ETC systems of all trucks, buses, and motorcycles worldwide.

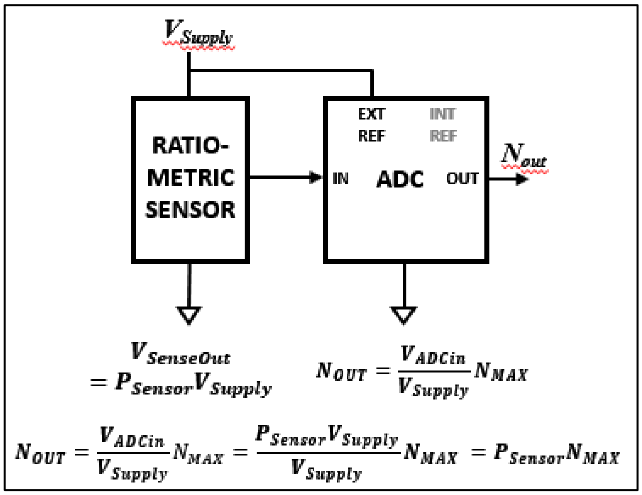

Fig 5. Only when an ADC uses the sensor supply voltage V_{supply} as an external reference, will the digitized sensor output (i.e., ADC output N_{out}) be free of variations in the sensor supply voltage V_{Supply}. This takes full advantage of the ratiometric property of the sensor to obtain a digitized sensor output that is free of changes in the sensor supply voltage. Multiple sensors having the same supply voltage can be digitized in this manner by using an analog multiplexer on the input of the ADC.

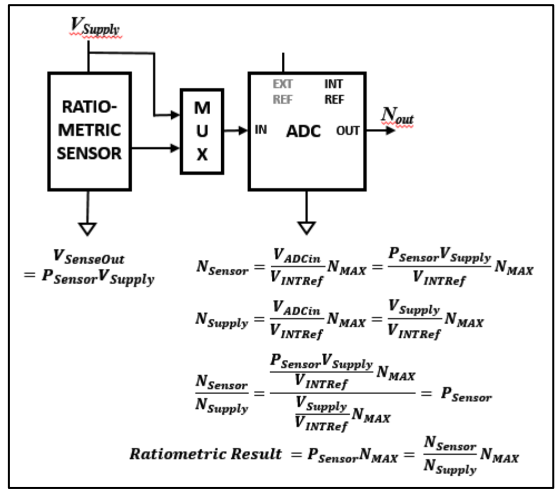

Fig 6. Another way to get an ADC output free of changes in the sensor supply voltage is to digitize both the sensor output and the sensor supply voltage using the internal ADC reference, and then calculate the ratio of the digital sensor output to the digitized supply voltage outside the ADC followed by appending the maximum ADC output count N_{MAX}.[6] This takes full advantage of the ratiometric property of the sensor to obtain a digitized sensor output that is free of changes in the sensor supply voltage.

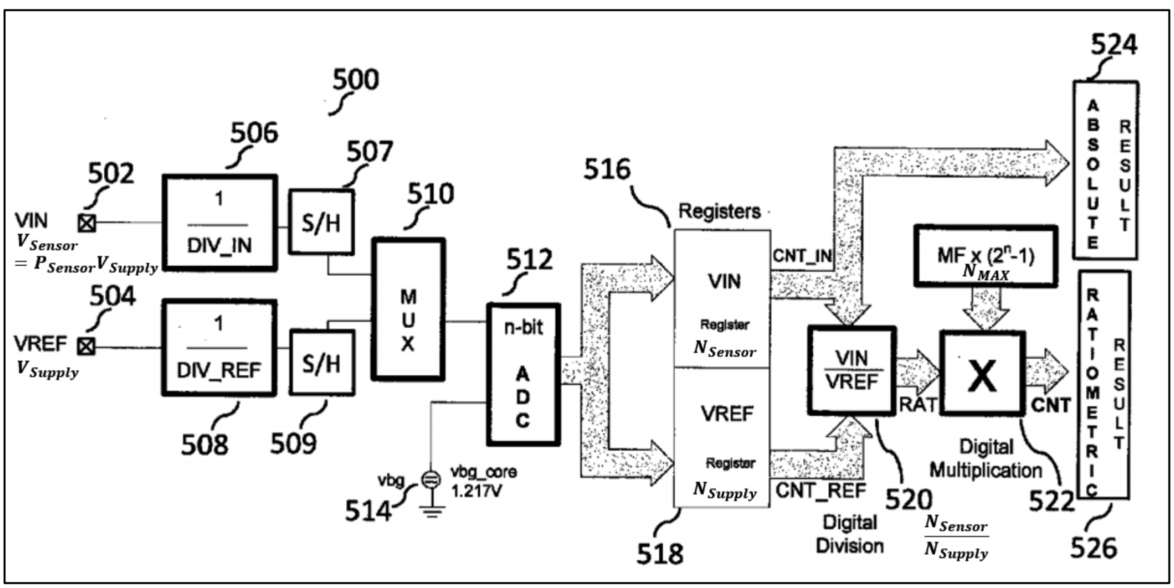

Fig. 7. US patent 8604961 by Infineon Technologies[7], a major supplier to the automotive industry, provides this method of obtaining a digital ratiometric sensor output. The sensor and supply inputs are divided down to keep them below the maximum voltage of the ADC, which in this case is Vbg = 1.217V. The sample and hold functions ensure that the sensor output and the sensor supply voltage are sampled at the same time so that the supply voltage V_{supply} does not change between the two samples, allowing the supply voltage to cancel when the ratio is calculated. The mathematical operations are performed by a control microprocessor after signal digitization and are the same as shown in Fig. 6. A non-ratiometric or absolute output is also provided for sensors that are not ratiometric.

IV. Discussion of An ADC Approach That Provides Sensor Outputs Free of Changes in the Sensor Supply Voltage

Based on the knowledge that the analog outputs of all accelerator pedal sensors are ratiometric, and an understanding of how the analog-to-digital conversion operation must use the sensor supply voltage as the external ADC reference voltage, we have been able to deduce two circuit designs for how the accelerator pedal sensor outputs are processed in all vehicles with electronic throttles. These circuit designs allowed us to obtain the following equations that describe how the analog sensor outputs are digitized by the ADC:

$$\boldsymbol{N_{OUT}} = \frac{\boldsymbol{V_{ADCin}}}{\boldsymbol{V_{Supply}}} N_{MAX} = \frac{\boldsymbol{P_{Sensor}V_{Supply}}}{\boldsymbol{V_{Supply}}} \boldsymbol{N_{MAX}} = \boldsymbol{P_{Sensor}N_{MAX}} \quad \text{(Figure 5)}$$

$$\boldsymbol{Ratiometric\ Result} = \boldsymbol{P_{Sensor}N_{MAX}} = \frac{\boldsymbol{N_{Sensor}}}{\boldsymbol{N_{Supply}}} \boldsymbol{N_{MAX}} \quad \text{(Figures 6 \& 7)}$$

From these equations we can see that if the sensor output $\boldsymbol{V_{SenseOut}} = \boldsymbol{P_{Sensor}V_{Supply}}$ changes with variations in the sensor supply voltage $\boldsymbol{V_{Supply}}$, the ADC will cancel out the variations by dividing the ADC input by the ADC reference voltage that varies in the same way as the ADC input. In other words, if the analog sensor output increases or decreases by K%, the ADC reference voltage will also increase or decrease by K% to provide a digitized sensor output that is free of variations in the sensor supply voltage $\boldsymbol{V_{Supply}}$. These variations in the sensor supply voltage usually result from variations in the temperature of the 5V voltage regulator within the vehicle's ECU. They are usually less than 10%. However, the equations show that the method works for variations of all magnitudes, as long as the sensor supply voltage and the ADC reference voltage are exactly the same.[Footnote 2]

What we learn from Figures 5, 6, and 7 is that in order to obtain a digital sensor output that is free of variations in the sensor supply voltage, one must either compare the analog sensor voltage with the varying sensor supply voltage using an ADC (Figure 5), or else use the ADC to digitize both the analog sensor output and the varying sensor supply voltage, and then outside the ADC divide the digitized sensor voltage by the digitized sensor supply voltage to obtain a digitized sensor voltage free of variations in the sensor supply voltage (Figure 6 and 7).

If the method shown in Figure 5 is used, then an ADC software programmer does not need to manage how the sensor supply voltage is used by the ADC. The ADC will automatically choose the correct value of the sensor supply voltage to be used for comparison with each analog sensor output being digitized. However, this method is rarely used in automobiles to date.

If the method shown in Figures 6 and 7 is used, a decision must be made by an ADC software programmer of how often the supply voltage must be digitized. There are always two or more ratiometric accelerator pedal sensors that use the same supply 5V voltage, as well as several other ratiometric sensors, like two throttle sensors, that also use the same 5V supply voltage. It seems logical that one should not need to re-digitize the 5V supply voltage each time a different

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[2] Before discussing these circuit diagrams and equations further, it is worth mentioning that these circuit diagrams and equations have never been discussed at this level of detail in any previous NHTSA investigation, including NHTSA's investigation of Audi sudden acceleration, NHTSA's NASA-assisted investigation of sudden acceleration, or NHTSA's investigation of any other vehicle with an electronic throttle. Also, no auto manufacturer has ever publicly discussed these circuit diagrams and equations in any previous technical report, service manual, service bulletin, advertising material, or communications with NHTSA. Manufacturers often attribute this silence to the fact that the circuit diagrams and equations are considered proprietary. But it is more likely due to the manufacturer's desire to use another company's proprietary approach without paying royalties for their invention, and also to avoid making public design details that could later be used against them in court. Whatever the reason, this lack of detail in previous discussions of how accelerator pedal sensor signals are digitized has hindered the search for an electronic cause of sudden unintended acceleration.

sensor is digitized, which happens approximately every 10 milliseconds or so, providing 100 samples per second. Instead, one should be able to digitize and store the 5V supply voltage only once every 10 milliseconds or so and then use the stored value of the supply voltage to correct all the sensor voltages digitized at the same time.

A related decision is whether one can digitize the sensor supply voltage at a rate slower than the rate used for the analog sensor outputs. The analog sensor outputs are digitized once every 10 milliseconds or so because this is the rate needed by the engine control algorithms. But the 5V sensor supply voltage is produced by a voltage regulator that changes its voltage very slowly as a result of variations in the temperature of the regulator in the ECU. And these temperature variations usually occur as the ECU heats up after the vehicle's engine is started. Therefore, an ADC programmer may decide to digitize the sensor supply voltage at a lower rate, like maybe once every minute, or once every five minutes, in order to save computation time for other ADC operations. This decision is acceptable as long as voltage dips are not present on the sensor supply line. If voltage dips are present, then problems can arise. [Footnote 3]

If the ADC software programmer decides to sample the sensor supply voltage at a rate slower than once every 10 milliseconds or so, then he introduces a cause of sudden unintended acceleration into the vehicle. This can happen because when voltage dips are present on the sensor voltage supply line, the ADC can sample the sensor voltage supply line during one of these voltage dips, and an incorrect voltage lower than the normal supply voltage will be digitized and stored. This stored incorrect lower voltage sample will then be used for correcting all the sensor voltage samples over the next minute or so, which are acquired while the supply voltage is higher. This means that for the next minute, all the incoming analog sensor signals that should be compared to the correct higher supply voltage are now compared to the incorrect lower supply voltage, which is used as an ADC reference (Figure 8).

Since the digitized sensor voltages are divided by the sensor supply voltage, which is now significantly lower, the resulting digitized sensor outputs after voltage correction will be <u>increased</u> over their normal values. This happens even though the <u>analog</u> sensor voltages remain unchanged from their normal values, which may be those of an un-pressed accelerator pedal if the vehicle is at idle. The vehicle's control system will recognize no difference between this larger digitized sensor voltage and one produced by the driver stepping on the accelerator pedal. The result is sudden unintended acceleration even though the driver does not press on the accelerator pedal. And the increased %pedal value resulting from this larger digitized sensor signal value will get sent to the EDR just like a normal released %pedal value, causing investigators to conclude that the driver stepped on the accelerator pedal when the driver did not step on the accelerator pedal. Instead, the increased %pedal value was caused by a change in the sensor supply voltage as a result of sampling the supply voltage during a transient voltage dip. The driver is then blamed for the sudden unintended acceleration caused by the vehicle.

This happens even though no hardware fault occurs in the vehicle. The hardware works perfectly while the increased accelerator pedal sensor outputs and %pedal values occur. This is why no DCT is ever found. The only vehicle fault is a design fault that fails to account for voltage dips that can lower the digitized sensor supply voltage to cause a change in the accelerator pedal sensor value. The changes in pedal sensor value that are produced by dips in the supply voltage can be avoided if the software tests the value of the supply voltage after digitization, in the same manner that the software tests the sensor output voltages after digitization. The only reason this

[3] Software programmers rarely have an expert knowledge about the electrical environment on a motor vehicle. So a decision like the one just described easily could have occurred during the development of the first electronic throttle ECU. Also, ECU's are provided to auto manufacturers by ECU suppliers, who tend to copy each other and compete on cost to put their own ECU's into as many vehicle models as possible. Therefore, if the above decision was made during development of the first electronic throttle ECU, it easily could have been repeated in later electronic throttle ECU's by the same supplier and by copycat suppliers.

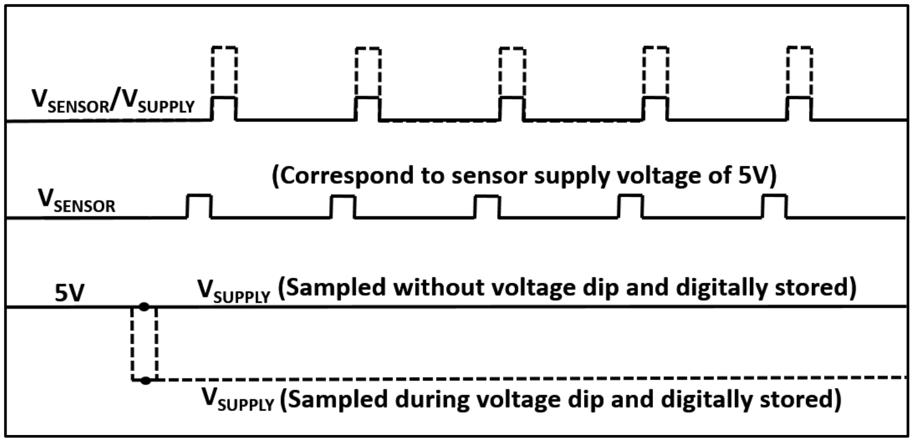


Fig. 8. If the sensor supply voltage is sampled during a voltage dip, then the digitized sensor voltages V_{SENSOR} that assume a 5V supply voltage will increase significantly when divided by a stored supply voltage V_{SUPPLY} less than 5V to yield the digital values V_{SENSOR}/V_{SUPPLY} free of supply voltage variations. This significant increase does not occur when the sensor supply voltage is sampled without a voltage dip, when a digitized and stored value of V_{SUPPLY} close to the normal 5V is obtained.

does not happen is because the ADC software programmer was unaware that large dips on the 12V supply line can randomly occur. Therefore, his assumption that the sensor supply voltage changes only very slowly was incorrect because these voltage dips create sudden changes in the sensor supply voltage. If the ADC software is changed to add a test of the supply voltage after digitization, then this problem can be averted.

Many drivers have found that when they have a sudden acceleration, if they turn the engine off and then turn it back on again, the problem goes away. They may not realize that this happens because the incorrect supply voltage that is stored in memory, which causes the sudden acceleration, gets replaced by a new supply voltage when the engine is restarted. By chance, the new supply voltage that is obtained after restarting is usually obtained by sampling the supply voltage while no voltage dip is occurring. So it is usually a correct value. But not always.

Negative slope ratiometric sensors are affected by voltage dips in the same way as positive slope ratiometric sensors because the voltage dips produce the same increase in the ratio of the sensor output to the supply voltage in both sensor types. It is just that the equation used by negative slope ratiometric sensors subtracts this ratio as the as the sensor input increases while the equation used by positive slope ratiometric sensors adds this ratio as the as the sensor input increases. In both cases, the voltage dip causes the apparent sensor input to increase.

Sudden acceleration requires voltage dips in the sensor supply line that get digitized and stored in memory, which are then used to divide sensor inputs that get digitized later while the sensor supply reverts back to a normal higher supply voltage. If the dips in the supply voltage are less than 10 milliseconds long, then it is possible that no more than one sample of the analog sensor signal gets digitized at the same time that a dip in the supply voltage is occurring. This means that this one signal sample has an incorrect supply voltage, so when it is divided by the stored incorrect supply voltage, a correct output voltage will occur. However, all subsequent signal samples corrected by the stored incorrect supply voltage will be changed to a higher incorrect output voltage. If the dips in the supply voltage are less than 20 milliseconds long, then at most two samples of the analog sensor signal can get digitized at the same time that a dip in the supply voltage is occurring, which might then yield a normal output after they are corrected by the stored sensor supply voltage. Then all subsequent signal samples corrected by the stored incorrect supply voltage will be changed to a higher incorrect output voltage. This thought process can be repeated with longer voltage dips to conclude that the voltage dip causing sudden acceleration may be N x 10 milliseconds long, with (N x 10 milliseconds) being less than the storage time of the supply voltage digitized during a voltage dip. In this case, N analog sensor samples can get digitized at the same time that a dip in the sensor supply voltage is occurring, which will then yield a normal output after they are corrected by the stored incorrect sensor supply voltage. But all subsequent signal samples divided by the stored incorrect supply voltage will be changed to a higher incorrect output voltage. These subsequent signal samples can last for a duration of seconds to minutes, depending on the storage time of the supply voltage samples, until a new sample of the supply voltage is taken.

Sudden acceleration requires voltage dips in the 12V supply line that cause voltage dips in the 5V supply line. The voltage dips in the 12V supply line must go down to about 3V or less that can produce dips in the 5V supply line down to about 2V or less to get % pedal values close to 100%. We will now look at how these voltage dips are produced.

V. How Voltage Dips are Produced

Before discussing voltage dips, we urge any readers who do not believe in transients or voltage dips in automobiles (perhaps because they think that they would see lights flicker on automobiles if voltage dips existed), to read the following NASA report on transients in space vehicles and an Army paper on a transient in an Armored Fighting Vehicle. The NASA report states: [8]

> *"There have been several instances of susceptibility to switching transients [in NASA vehicles]:*
> - *The Space Shuttle Spacelab Remote Acquisition Unit [RAU - a standard interface between Spacelab payloads and the Shuttle communications system] will shut down if the input 28 VDC bus drops below 22 volts for more than 80 microseconds. …*
> - *A heavy payload on one aircraft sags the 28 Volt bus below 20 Volts for milliseconds.*
> - *Vacuum cleaners which plugged into the Space Lab 400 Hz bus sagged the line voltage enough that computers also powered by 400 Hz crashed."*

The NASA report discusses in great detail how to measure and avoid these switching transients. The Army paper [9] states:

> *"[On an Armored Fighting Vehicle] … the 24V DC bus voltage drops down to 16 V during starting of a heavy load [namely, the hydraulic pump motor that rotates the turret]. As the entire mission-related sensitive systems are also connected to this same 24V DC bus, the voltage sag in the DC bus creates undesirable effects [namely, the failure of a computer used in the fire control system]."*

These references provide strong evidence for the existence of transients on vehicle supply lines, and specifically for voltage sags or dips on these supply lines.

Our objective here is to show how similar voltage dips are produced on the 12V supply line of an automobile and how they can create voltage dips in the 5V supply lines. We will first discuss vehicles with internal combustion engines (ICE). Then we will discuss battery-powered electric vehicles (BeV's).

<u>Vehicles with Internal Combustion Engines (ICE Vehicles).</u>

Figure 9 shows the power distribution system in a typical ICE vehicle. All actuators are powered directly by the 12V supply bus. All sensors are powered by multiple 5V supply lines. The 5V supplies are generated by a power management integrated circuit (PMIC) that also generates lower voltages like 3.3V and 1.5V to power the digital signal processor (DSP) device and other low power circuitry in the engine control unit (ECU).

The alternator operates at a constant output voltage of 14.1V, which is set by the voltage needed to charge a lead acid battery. Its current varies with engine RPM, with a current of less than 10 amps at 800 RPM (idle) and increasing to a maximum of about 100 amps above 3000 RPM. The battery, however, operates at a voltage of approximately 12.8V and can deliver almost any amount of current as needed.[Footnote 4] However, the battery is capacity limited, meaning it can only deliver current until its stored charge is depleted, at which time it can't deliver any more current. This is because charge is the integral of the current over time. And the battery's voltage is determined by the battery's state of charge (SOC), so as the battery's state of charge decreases, the battery's voltage also decreases.

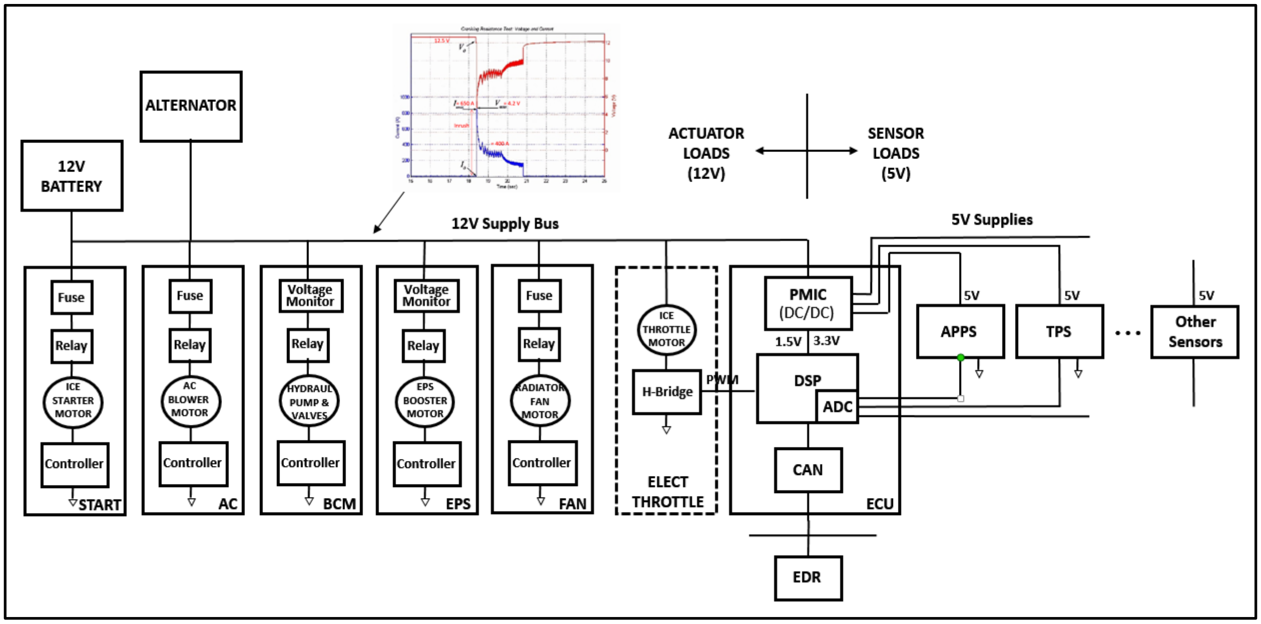


Fig. 9. Power distribution system in a typical ICE vehicle. Power is supplied by the 12V battery kept charged by an alternator operating at 14.4V. Loads having the highest current requirements are shown in order of decreasing current. The AC compressor is powered by the engine, but the large AC blower is electrically-powered. All of these high current loads are electric motors whose currents are fused for safety purposes. When one of these high-current loads is turned on, the electric motor creates an inrush current that is three to five times the magnitude of the DC current needed for continuous operation. The figure shows the waveforms for the inrush current and voltage associated with the starter motor. Similar waveforms are produced when the other electric motors turn on.

Now, one cannot add the battery current to the alternator current to obtain a higher current for to meet vehicle needs. While the battery is being charged by the alternator, it cannot supply any current (because current either goes into the battery or comes out of the battery), so all the current for charging the battery and for other vehicle needs must come from the alternator. And while the battery is being discharged, the alternator cannot supply current to the battery or to any other vehicle systems because the alternator has been turned off by its controller until the battery voltage decreases to a point where the controller decides by monitoring the battery voltage that the battery must be recharged, at which time the alternator is turned on again by its controller. This point is usually about 12.4V or so. So, if the supply voltage is 14.1V with the engine running, the alternator is charging the battery and supplying current to other vehicle needs while the battery is not supplying current. And if the supply voltage is anything less than 14.1V with the engine running, the battery is supplying current for all the vehicle's needs, while the alternator is turned off.

The main limitation on current, then, comes from the alternator when it is charging the battery at low vehicle speeds. If there is insufficient current to supply all the vehicle's needs, then the alternator will not be able to charge the battery, and the battery will soon lose its state of charge and be unable to supply the current demand when it is being discharged. This will cause a dead

4 The maximum current that a battery can produce is limited by the battery's temperature and by its internal resistance. This maximum current limit is measured by the cold cranking amps (CCA) figure of merit, which varies with battery type from 300 CCA to 1000 CCA at 0°C.

battery, with the only solution being to charge the battery from an external source or to change the alternator to one having a higher output current. For this reason, to satisfy the vehicle's needs for more current to support an increasing amount of electronics, some auto manufacturers have started to replace their standard 150 amp alternators with more robust alternators having outputs of 250 amps. Even higher output alternators are obtainable directly from alternator suppliers. The only limitation is cost and space available under the hood.

A second and more subtle limitation on current comes from the alternator's output time constant. This time constant limits the rise time and fall time of the alternator's current output to between 100 and 200 milliseconds. Therefore, if some load turns on suddenly while the alternator is charging the battery, then the alternator cannot instantly supply the needed current. So the voltage to the load falls and the battery changes from charging to discharging and supplies the needed current. This can continue even when the battery voltage falls below the level at which the alternator controller would normally turn on the alternator, because the alternator is already turned on. In this case the condition continues until either the load is turned off or until the alternator current can increase to satisfy the load. And while the battery is supplying the needed current, the supply voltage changes from 14.1V to the battery voltage. Loads that can change suddenly in this fashion include starter motors, transients caused by the inrush currents of electric motors turning on, sampling of the supply voltage by an ADC, and PWM'd motor loads. The latter become more of a problem as the PWM rate increases (PWM rates can vary from 2 Hz to over 20 kHz), although the amount that the supply voltage drops in this case is limited to the drop from 14.1V to the normal battery voltage (12.4V to 12.8V).

In Figure 9 only loads having the highest current requirements are shown in order of decreasing current. The air conditioning (AC) compressor is powered by the engine through an electromagnetic clutch. But the large AC blower is electrically powered and can draw nearly 100 amps. Other smaller loads like headlights, heaters, windshield wipers, etc, are present but not shown. All DC loads must be included in the total DC current that the battery must supply. All of the high-current loads are electric motors whose currents are fused for safety purposes, except the starter motor. For safety-critical loads the supply voltage is also monitored and controlled by a power relay.

When an electric starter motor is turned on, the motor windings suddenly see the full battery supply voltage. Before the motor starts turning, the motor windings produce no magnetic field and thus essentially become a passive resistor that sees the full battery voltage. The voltage and resistance at this time determine the inrush current, which is three to five times the DC current needed for continuous motor operation. As soon as the motor starts to turn, it produces a back-EMF across the windings that opposes the applied supply voltage. This reduces the voltage drop across the windings, which causes the current through the windings to drop. As the motor spins faster the current and voltage continue to drop. At some point after about 200 milliseconds the alternator current begins to produce ripples on the current waveforms created by the battery current. These ripples eventually level off and continue until engine combustion begins, which causes a further increase in the motor spin rate and the rate at which the motor voltage and current decrease. Finally, as the engine reaches the desired idle rate of around 800 RPM, the ignition switch is turned off, with the motor current going to zero and the motor voltage going to the battery supply voltage. The time for this to happen is between 400 milliseconds and 2.5 seconds, depending on how long the engine must be cranked before it begins running on its own. The initial inrush current occurs during the first 15 milliseconds or so, reaching currents of many hundreds of amps and causing dips in the supply voltage down to 8V or less, and even to 4V. This assumes an average engine with a fully charged battery. The current and voltage dips are larger with more powerful engines, increasing as the compression ratio of the engine increases. Diesel engines have such high compression ratios and are thus hard to start. Their starters have the highest currents and the largest voltage dips. A decrease in the state of charge of the battery can also cause larger voltage dips because the battery has less charge to contribute to support the current draw.

Figures 10 thru 13 show four typical cold crank waveforms with voltage dips down to 8.6V, 8.0V, 8.6V to 5.8V, and 4.2V. Voltages of about 8V are often caused by an inrush current reduction technique that adds a fixed resistance in series with the motor to cause a lower inrush current that yields a voltage of around 8V. Since a lower inrush current causes a lower starting torque, this resistance gets shorted out by a relay after about 10 milliseconds, allowing the current to increase once more. The variations in voltage from 8.6V to 5.8V in Figure 13 are produced by differences in the corrosion of the battery grid, which are caused by the same battery having different levels of charge (SOC).

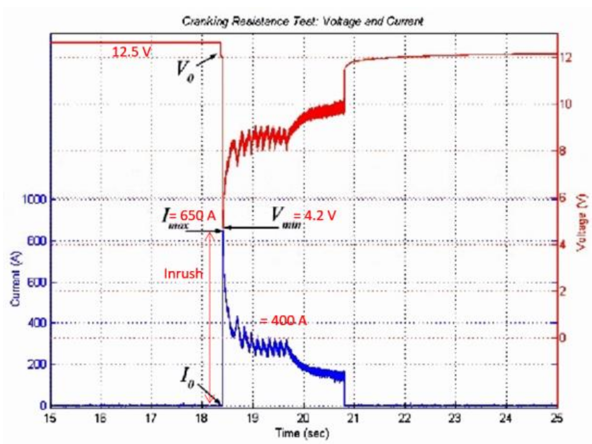


Fig. 10. Cold crank waveform with a dip in the 12V supply voltage down to 4.2V.[10]

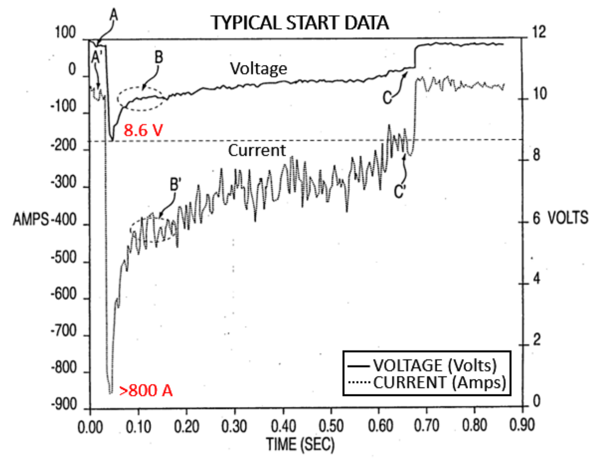


Fig. 11. Cold crank waveform with a dip in the 12V supply voltage down to 8.6V.[11]

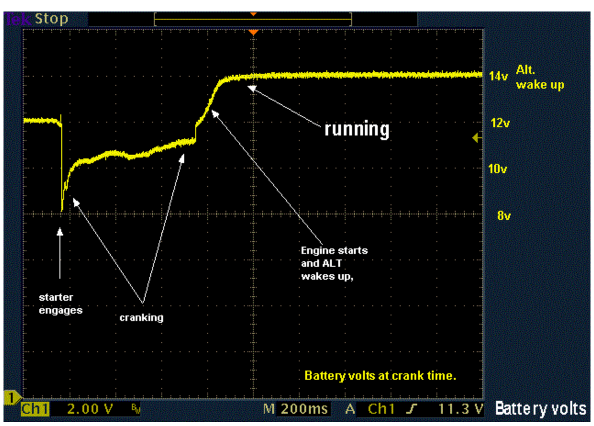


Fig. 12. Cold crank waveform with a dip in the 12V supply voltage down to 8.0V.[12]

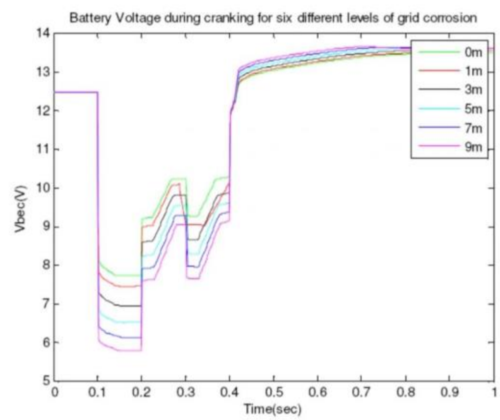


Fig. 13. Cold crank waveforms showing how voltage dips increase by 2V as the battery internal resistance increases with age.[13]

Experience has shown that the currents and voltage dips produced during cold cranking are determined only by the internal resistance of the battery, the resistance of the starter motor, and the battery voltage and current. Therefore, we can create a model of the starter circuit using simple resistances for the battery internal resistance and the starter resistance and determine the approximate starter current and battery supply voltage drop. Figure 14 shows some limiting cases of these modeled circuits along with the battery currents and voltage drops found.

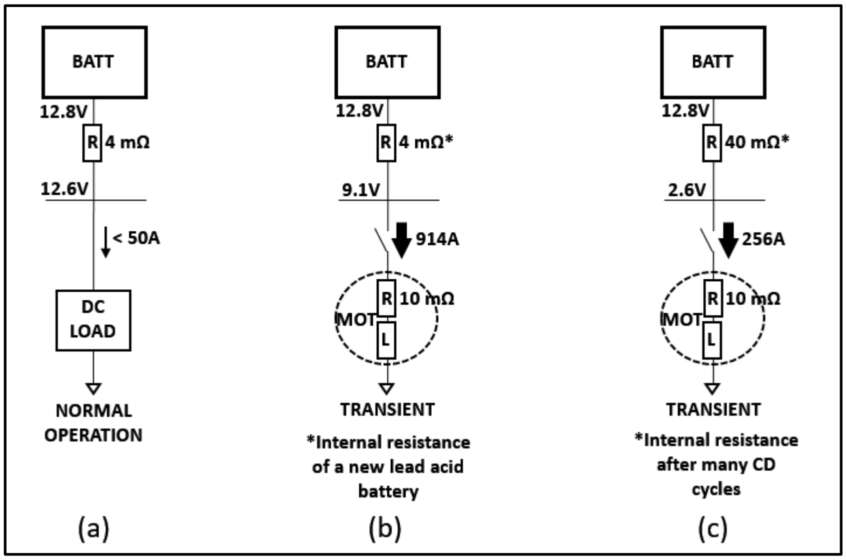


Figure 14. Three limiting cases of battery operation: (a) operation of a new lead acid battery with a typical DC load of 50 amps causes a dip in the supply voltage to only 12.6V, (b) operation of the same new lead acid battery when a starter having a resistance of 10 mΩ is engaged causes a dip in the supply voltage to only 9.1V, and (c) operation of a deteriorated lead acid battery with an internal resistance of 40 mΩ when a starter with the same resistance of 10 mΩ is engaged causes a dip in the supply voltage to 2.6V.

If we model several of these circuits for different battery internal resistances, we can graph the results for the battery currents and supply voltage dips as shown in Figure 15.

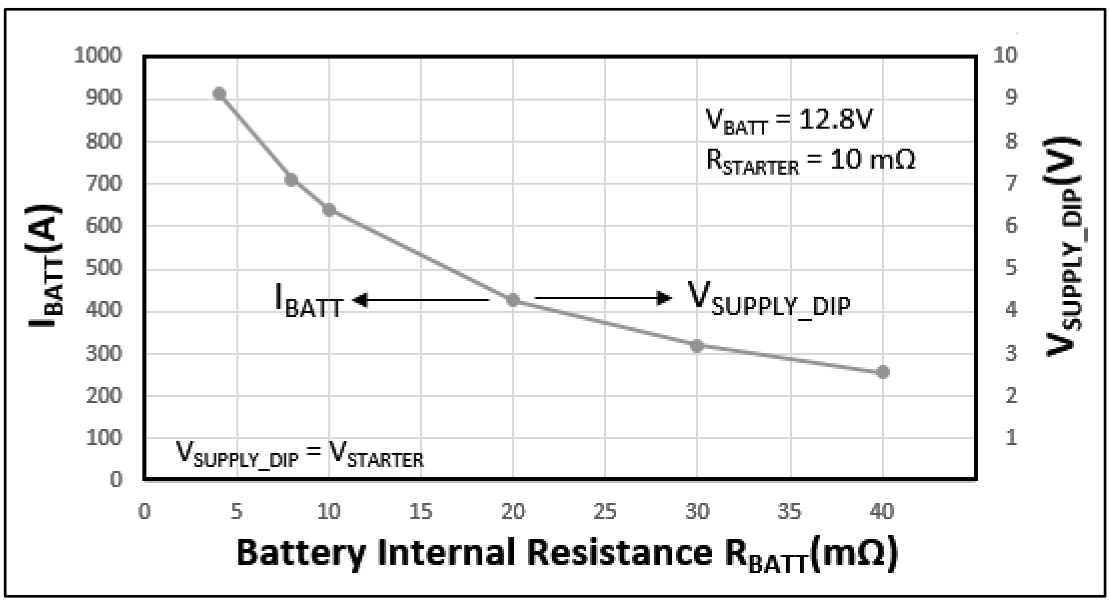


Figure 15. Battery current and supply voltage dip for varying values of battery internal resistance. A starter motor resistance of 10 mΩ has been assumed, and remains constant for all cases. Only the battery internal resistance varies, from a value of 4 mΩ for a new lead acid battery, to a value of 40 mΩ for a deteriorated lead acid battery.

The following conclusions can be drawn from this simple modeling exercise:

1) The dip in the supply voltage increases with an increase in the battery internal resistance. Battery experts have noted that the battery internal resistance does not vary strictly with time or with on/off ignition cycles. But it does vary with charge/discharge

cycles, and particularly when the charge/discharge cycles have large amounts of discharge (deep discharge). During these cycles, large dendrites can form in lead acid batteries that cause sulfation, which increases the battery's internal resistance. Increases up to 20 to 30 mΩ in have been measured in lead acid batteries. Battery internal resistance also increases at lower temperatures, especially temperatures below 0°C.

2) The dips in the supply voltage also increase with a decrease in the battery state of charge (SOC). Usually, the battery state of charge decreases when vehicle accessories that draw low battery currents are left on for a long amount of time before the alternator can recharge the battery. However, the battery state of charge can also decrease more rapidly when larger battery currents are drawn for shorter periods of time. With battery currents of 500 to 1000 amps the battery state of charge can be reduced to zero in mere minutes, as drivers have found out when trying to start their vehicle multiple times without driving in between to recharge the battery.

3) The starter resistance does not vary with time. It does vary, however, with starter motor torque, increasing with engine size and starter circuit details, such as cable sizes and lengths, and starter relay resistance. The variations with engine size can have a particularly large effect on the battery current and the supply voltage dip.

4) The inrush current produced during starting decreases with an increase in the battery internal resistance. Since this inrush current is directly related to the starter motor torque, this means that as the inrush current decreases, the engine becomes harder to start because less torque is applied.

5) The above conclusions assume a lead acid battery having an internal resistance of 4 mΩ when new. If one switches to an AGM battery, which has an internal resistance of only 1 mΩ when new, this can reduce the supply voltage dip both during normal loads and during starting, while increasing the starter motor current and torque, which can improve the starting capability. An AGM battery is also less susceptible to sulfation, which increases the battery internal resistance. Thus, an AGM battery will last longer.

6) The above conclusions, and the similarity of the inrush currents produced during sudden acceleration with the inrush currents produced during engine cranking, lead one to expect that the increased susceptibility of a vehicle to sudden acceleration will correlate with:
    a. increasing battery internal resistance
    b. increasing battery charge/discharge cycles
    c. decreasing battery temperature, especially below 0°C,
    d. increasing starter motor torque
    e. increasing engine size
    f. increasing resistance in the starter motor cables, relays, and connections
    g. decreasing levels of the battery state of charge (SOC)
    h. frequent short trips with low vehicle speeds that do not allow the alternator to recharge the battery, causing lower levels of battery SOC.
    i. alternator defects that do not allow the alternator to recharge the battery
    j. parasitic low current drains which discharge the battery while the engine is off
    k. increasing difficulty in starting the engine (longer crank times).

As a result of industry experience with these cold crank waveforms and how they vary with engine compression, the automobile industry has adopted test waveforms to test the EMI resistance of other vehicle circuitry affected by these cold cranking waveforms. These test waveforms are shown in Figures 14 and 15. The waveforms can be varied by the auto manufacturer to adapt them to their own specific circuit needs. But the voltage dips in the recommended test waveforms go all the way down to 3.2V with a full battery voltage. This means that some cold crank waveforms have been verified to cause voltage dips of this value.

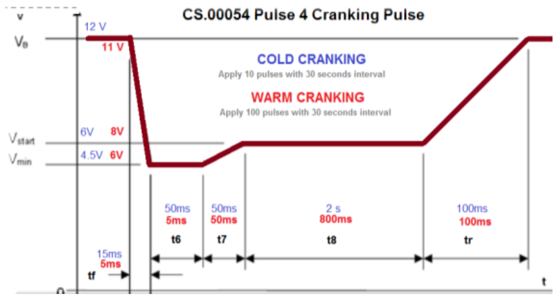


Fig. 16. Cold crank test pulse per Stellantis spec CS.00054 dips the 12V supply to 4.5V. Rise time is less than 15 milliseconds.[14]

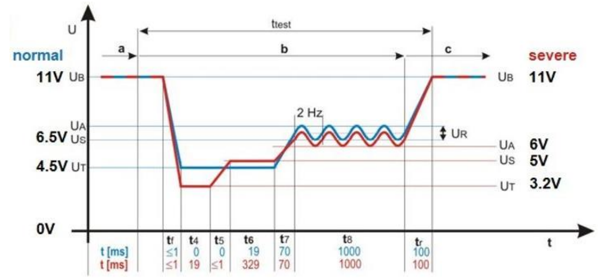


Fig. 17. Cold crank test pulse per German standard LV124 dips the 12V supply to 3.2V. Rise time is less than 1 millisecond.[15]

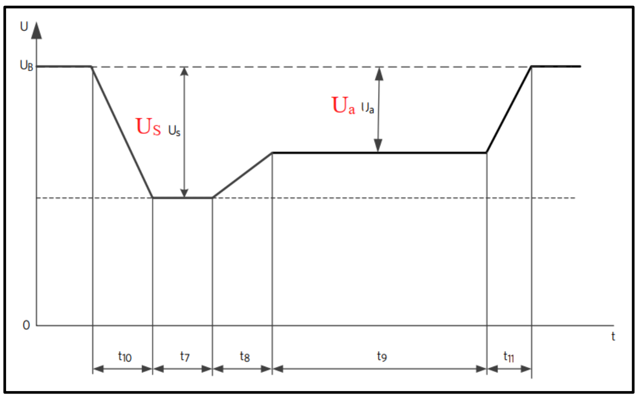


Fig. 18. LV124 voltage waveform for automotive cold crank.[16]

Parameter	12V System	24V System
U_s dip	-6V to -7V From 12V to 6V or 5V	-12V to -16V
U_a dip	-2.5V to -6V with $\lvert U_a \rvert \leq \lvert U_s \rvert$	-5V to -12V with $\lvert U_a \rvert \leq \lvert U_s \rvert$
R_i	0Ω to 0.02Ω	
t_7	15ms to 40ms[a]	50ms to 100ms[a]
t_8	≤ 50ms	
t_9	0.5s to 20s[a]	
t_{10}	5ms	10ms
t_{11}	5ms to 100ms[b]	10ms to 100ms[b]

[a] The value used should be agreed between the vehicle manufacturer and the equipment supplier to suit the proposed application.
[b] t_{11} = 5ms is typical of the case when engine starts at the end of the cranking period, while t_{11} = 100ms is typical of the case when the engine does not start.
[c] t_{11} = 10ms is typical of the case when engine starts at the end of the cranking period, while t_{11} = 100ms is typical of the case when the engine does not start.

Fig. 19. Voltage and timing specification for automotive cold crank.[11]

Now the cold crank waveform does not cause sudden unintended acceleration because it does not occur while the engine is running. But it is identical to an inrush current waveform of an electric motor. And all the other loads in Figure 9 are electric motors that have inrush currents and voltages just like the cold crank waveform. Fewer of these other transient inrush current waveforms have been measured. But we can estimate what these other transient startup waveforms must look like:

1) They will be shorter in duration because the other motors can spin up faster than the engine can spin up with its cold crank waveform. This means that the decay rate for the startup waveforms of the other transient-inducing motors is faster than the decay rate for the cold crank waveform. Therefore, even though the rise time of the inrush current is approximately the same for the two types of motors, the total waveform duration for the transient-inducing motors is shorter than it is for the cold crank waveform. This is because the starter motor must react to the changing engine torque load that ramps up slowly due to many factors such as fuel flow and engine speed. The other motors can adjust to their load torques much more rapidly. This means that the startup waveforms for the other motors can be as short as 5 to 10 milliseconds, with the peak inrush current occurring at 1 to 5 milliseconds.
2) The inrush currents for the other transient-inducing electric motors can be just as high as for the cold cranking waveform if we consider that the battery may be depleted while the other motors are started. This means that the voltage dips on the 12V supply line can go down to 3V or less for the transient-inducing electric motors.

It should be noted here that the alternator cannot supply any current for these short transient-inducing waveforms because the alternator output has a high output impedance that limits the rise time of its output current pulses to about 200 milliseconds. However, the battery has a low output impedance of a few tens of milliohms that allows it to change its output current nearly instantaneously. Therefore, the inrush currents are supplied only by the battery, causing the applied voltage to start with the DC battery voltage of 12.6V for a healthy battery. This is why the waveforms start at the DC battery voltage of 12.6V and not the alternator voltage of 14.4V. This applied DC battery voltage can go down to 11.0V for a nearly dead battery and down to 10.5V for a defective battery with one of its cells non-functional. The voltage dips in these cases will be lower by the corresponding drop in the DC battery voltage.

The next largest load in an ICE vehicle after the cold crank start waveform is the air conditioner blower motor. This is a large motor because it must distribute the cold air rapidly throughout the whole vehicle. In some larger vehicles this motor can have a DC current of nearly 100 amps. The associated inrush current is three to five times this DC current, or between 300 to 500 amps. This compares to the 600 amps to 800 amps for the cold crank waveforms in Figures 10 and 11 above.

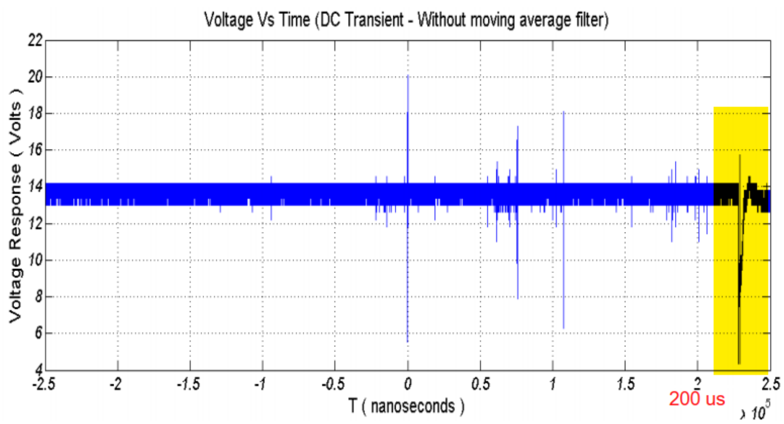


Fig. 20. Voltage waveform for the startup current from an automotive air conditioner showing a dip in the 12V supply to nearly 4V that lasts less than 50 us.[17] The dip is produced by the AC blower motor because the AC compressor is driven by the engine through an electromagnetic clutch.

So, is it reasonable to believe that the inrush current from the air conditioner blower motor can cause sudden unintended acceleration? The answer is a strong yes. Back in 2010 many drivers noticed that their vehicles could have sudden lurching events when the air conditioner turned on, but not when it turned off. When the air conditioner turned on, the AC blower motor is turned on along with the AC compressor. Therefore, an inrush current is created when the AC is turned on. This inrush current can occur at random times without the driver's intervention because the AC is controlled by a thermostat that actuates the AC when the temperature rises above a selected temperature setting.

It is interesting that back in 2010 James E. Lentz, president of Toyota Motor Sales USA, admitted that sudden acceleration in Toyota vehicles with electronic throttles had many causes and may be correlated with the air conditioner turning on.[18] Yet, there was no sudden acceleration in similar vehicles for thirty years prior to 2010 when similar air conditioning compressors and blowers were used in vehicles without electronic throttles. This leads one to suspect that the problem of sudden acceleration is not with the air conditioner per se, but with the enhanced susceptibility of the electronic throttle circuitry to something already produced by the air conditioners. At first, this was thought to arise from the inability of the electronic throttle to control engine torque when the air conditioner is turned on, which was done using an idle air control valve in earlier vehicles with a carburetor. However, this explanation is unlikely because this flaw would have been fixed during the normal design process. It is now suspected that the problem could be the inability of the electronic throttle circuitry to tolerate the inrush current dips produced by the blower motor compared with using an idle control valve for this purpose with a carburetor. This is more likely because it is difficult to model transient current dips and they may not have been considered during the normal design process.

This same air conditioner blower motor can produce problems with other systems on a vehicle. Back in 2006, NHTSA received over 519 consumer complaints of power steering malfunctions on the MiniCooper.[19] An engineering analysis by NHTSA found that a malfunctioning cooling fan caused an undervoltage condition in the Cooper's electric power steering system that caused as many as 60,000 Minis from the 2004 and 2005 model years to have power steering issues. NHTSA also believed that five minor collisions and three electrical fires were linked to the power steering issue with the Mini Cooper.[20]

After the air conditioning blower motor, the next largest inrush currents in an ICE vehicle are caused by the ABS brakes, and specifically by the hydraulic pump motor inside the hydraulic brake unit. This motor is known to heat up very rapidly when the ABS brakes are used because the pump must rapidly return the hydraulic brake fluid to the brake fluid reservoir as the brake valves open to remove braking force from the wheels during wheel lock-up. Finally, the inrush currents from the electronic power steering (EPS) motor in ICE vehicles have the lowest inrush currents in ICE vehicles. They are lower in ICE vehicles than in electric vehicles because ICE vehicles with electronic power steering are smaller vehicles with lower weight, resulting in the need for less steering torque in ICE vehicles. But as electronic power steering gets used in larger and heavier ICE vehicles, the EPS motors in these ICE vehicles will grow in the future and use higher currents, causing their inrush currents to increase until they become comparable to or exceed the air conditioner blower motor in current ICE vehicles.

We have now shown that voltage dips down to 3V can be produced on the 12V supply line of an ICE vehicle by the starter motor and that similar voltage dips down to 3V can be caused by transients created by the inrush current of an air conditioner fan motor turning on. We will now show that similar voltage dips can be produced in battery-powered electric vehicles by a different electric motor turning on.

Battery-Powered Electric Vehicles (BeV’s).

Figure 17 shows the power distribution system in a typical battery-powered electric vehicle. All actuators are powered directly by the 12V supply bus. All sensors are powered by multiple 5V supply lines. The 5V supplies are generated by a power management integrated circuit (PMIC) that also generates lower voltages like 3.3V and 1.5V to power the digital signal processor (DSP) device and other low power circuitry in the engine control unit (ECU).

The DC/DC converter in a BeV’s operates much like the alternator in an ICE vehicle. It operates at a constant output voltage of 14.1V, which is set by the voltage needed to charge a lead acid battery. However, its output current is constant, with a maximum current of about 200 amps, and does not vary with vehicle speed. The battery operates at a voltage of 12.8V or lower and can deliver almost any amount of current as needed [Footnote 5]. However, the battery is capacity limited, meaning it can only deliver current until its charge capacity is depleted, at which time it can’t deliver any more current. This is because charge is the integral of the current over time. And the battery’s voltage is determined by the battery’s state of charge (SOC), so as the battery’s state of charge decreases, the battery’s voltage also decreases.

[5] The maximum current that a battery can produce is limited by the battery’s temperature and by its internal resistance. This maximum current limit is measured by the cold cranking amps (CCA) figure of merit, which varies with battery type from 300 CCA to 1000 CCA at 0°C.

Just as with ICE vehicles, in a BeV one cannot add the battery current to the DC/DC converter current to obtain a higher current for more vehicle needs. While the battery is being charged, it cannot supply any current (because current either goes into the battery or comes out of the battery), so all the current for charging the battery and for other vehicle needs must come from the DC//DC converter. And while the battery is being discharged, the DC/DC converter cannot supply current to the battery or to any other vehicle systems because the DC/DC converter has been turned off by its controller until the battery voltage decreases to a point where the controller decides by monitoring the battery voltage that the battery must be recharged, at which time the DC/DC converter is turned on again by its controller. This point is usually about 12.4V or so. So, if the supply voltage is 14.1V with the engine running, the DC/DC converter is charging the battery and supplying current to other vehicle needs while the battery is not supplying current. And if the supply voltage is anything less than 14.1V, the battery is supplying current for all the vehicle's needs, while the DC/DC converter is turned off.

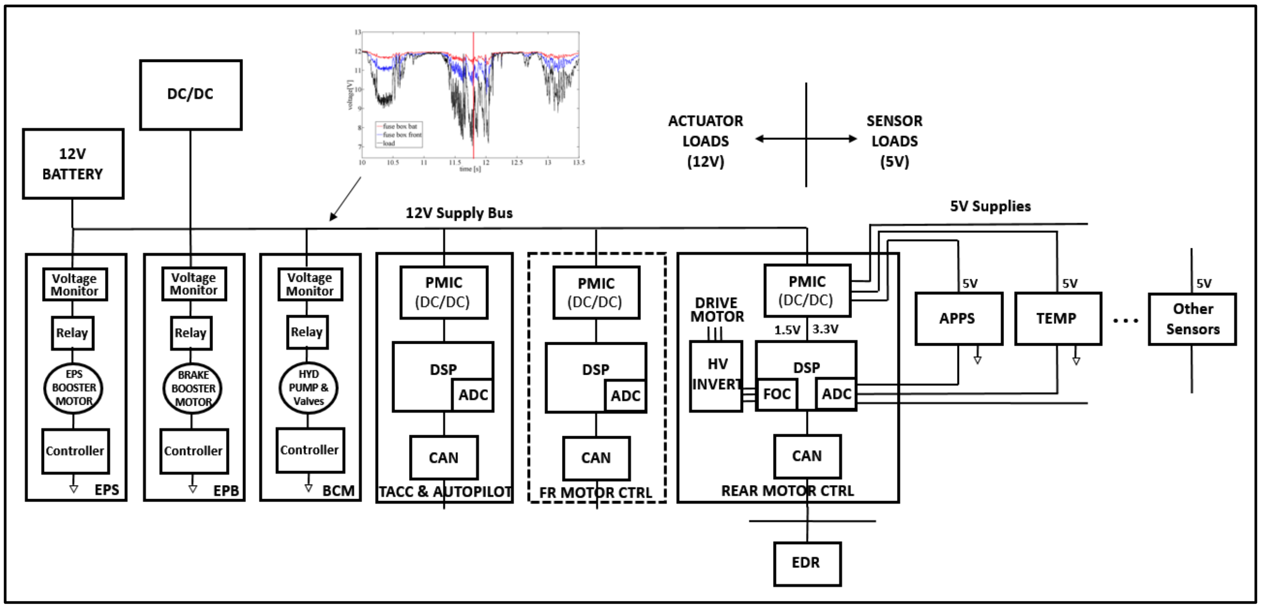


Fig. 21. Power distribution system in a typical battery-powered vehicle. Power is supplied by the 12V battery kept charged by a DC/DC converter operating at 14.4V. Loads having the highest currents are shown in order of decreasing current. The three largest loads are electric motors whose currents are fused for safety purposes. The largest load is the electronic power steering (EPS) system because it requires a high-torque motor to turn the steering wheels of a vehicle that is weighted down by a traction battery weighing over 1200 pounds. When one of these high-current loads is turned on, the electric motor creates an inrush current that is three to five times the magnitude of the DC current needed for continuous operation. The figure shows voltage waveforms for the inrush current produced by an EPS motor while the steering wheels are being turned during a slalom maneuver. Similar waveforms are produced when the other electric motors turn on.

The DC/DC converter can provide a constant current of 200 amps maximum in most electric vehicles. This current does not vary with vehicle speed as it does with the alternator current in an ICE vehicle. The DC/DC converter current output time constant is also very low, usually being less than 10 microseconds. Therefore, the DC/DC converter can deliver currents to all loads as fast as a battery, causing no problems with a failure to deliver current fast enough as with the alternator in an ICE vehicle.

Unlike in ICE vehicles in which the largest current load is associated with the air conditioner fan turning on, in battery-powered electric vehicles the largest current load is caused by the electronic power steering system (EPS). This system is larger in battery-powered electric vehicles than in ICE vehicles because electric vehicles are much heavier due to the weight of the battery, which adds nearly 1000 pounds of additional weight. This additional weight increases the force on the steering rack needed to turn the vehicle's front wheels, which necessitates an electric motor that provides more torque, leading to a greater physical size and a higher 12V DC current requirement, as shown in Table 2. In this table, a compact eV sedan weighs nearly 0.5 ton more than a compact ICE sedan of the same size, or nearly 1000 pounds more. This increases the DC current load of the EPS system from 40 to 60 amps in an ICE vehicle to 100 amps or more in an electric vehicle.

Table 2. EPS system 12V current needs increase with vehicle weight

	Full Size eV SUV	Full Size eV Sedan	Compact eV Sedan	Compact ICE Sedan	Subcompact ICE Sedan
Vehicle weight	3.5 tons	2.5 tons	2.0 tons	1.5 ton	1.0 ton
Steering force required	18 kN[1]	13 kN[1]	10 kN[1]	7 kN	4 kN
EPS type	Rack	Rack	Rack	Pinion	Column
Electric motor size	Lg coffee can	Coffee can	Coffee can	Lg soup can	Sm soup can
Electric power required	2000 W	1430 W	1150 W	750-950 W	500-720W
12V DC current required	170 A	120 A	100 A	60-80 A	40-60A

1) Only achievable with a rack-mounted EPS system.
2) Maximum 12V lead acid battery current is about 120A. Current for all vehicle loads in operation must be included in this limit.

The DC currents in an EPS system are highest when additional torque must be supplied under two conditions: 1) when the steering wheel is turned to its maximum left or right position while the vehicle is stationary, and 2) when the driver must make a sudden turn in response to an emergency situation. These conditions are shown in Figures 22 and 23.

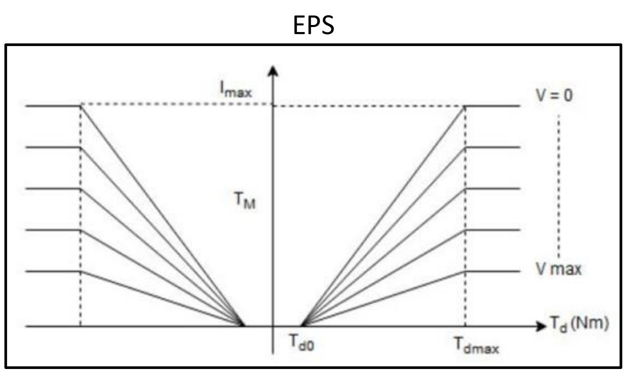


Fig. 22. EPS motor torque and DC current needs are highest when the steering wheel is turned to the maximum left or right position while the vehicle is stationary.

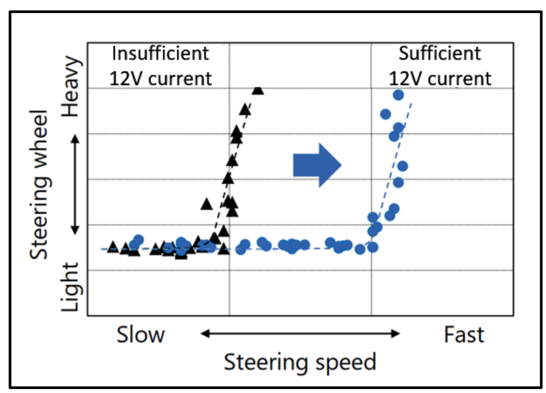


Fig. 23. Insufficient 12V DC current can also decrease the steering speed, making it harder to avoid emergency situations. This problem increases with vehicle weight.[21]

Now, just like any other electric motor, EPS motors can produce inrush currents that are three to five times higher than their sustained DC currents. An example of the inrush voltage waveform from an EPS system is shown in Figure 24. This example comes from a column-mounted power steering unit on an ICE vehicle because no one has yet published EPS waveforms for an electric vehicle. But this waveform from an ICE vehicle already shows a drop in the supply voltage down to about 7 volts during a slalom maneuver. A similar maneuver in an electric vehicle would cause a drop in the supply voltage much farther down than 7 volts, perhaps to 3 volts or less, due to the larger EPS motor with its higher current.

Figure 25 shows a conceptual current waveform for an EPS system during an abrupt steering event while the vehicle is moving or during turning while the vehicle is stationary. If the current demanded by the EPS motor is greater than the current that can be supplied by the battery, then the supply voltage will fall while the deficit occurs. This stops the motor from supplying steering torque, resulting in the steering getting very sluggish. This has led several companies to consider adding a supercapacitor or ultracapacitor in parallel with the battery to keep the supply voltage at its normal value at all times. And two auto manufacturers have gone even further, to include a supercapacitor in the production versions of their Prius hybrid and Leaf eV's, respectively.[22],[23] Now, this supercapacitor is intended to maintain EPS performance when EPS motor current is higher than what the battery can supply. But this is the same condition that produces transients that can cause the supply voltage to decrease. Therefore, these supercapacitors will also reduce transients that can cause sudden acceleration by keeping the supply voltage constant while it is being sampled by an ADC for use in compensating of an APP sensor output.

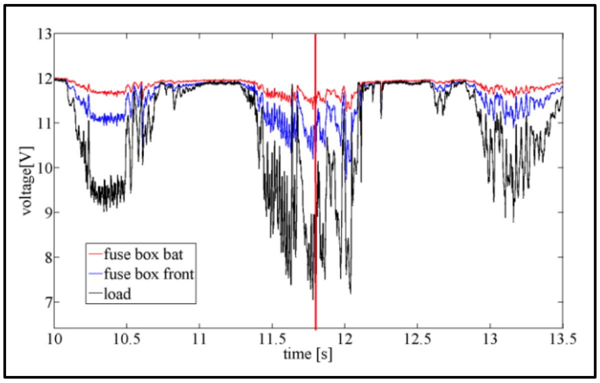


Fig. 24. Voltage waveforms produced by the inrush currents from a power steering motor during a slalom maneuver. Waveforms were measured at three different locations on the 12V power bus: at the battery (red), in the fuse box (blue), and at the load (black). The waveforms are from a column-mounted power steering unit that has a smaller electric motor than the rack-mounted unit on a battery-powered vehicle, which produces higher currents and lower voltage dips.[24]

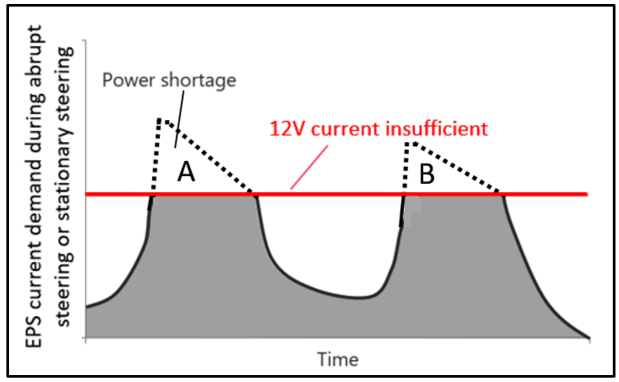


Fig. 25. Current demand during abrupt steering while the vehicle is moving or during turning while the vehicle stationary. With insufficient 12V current, the voltage will drop due to the high initial inrush current demand at the start of each action that cannot be met, and possibly even due to the sustained DC current demand that cannot be met.[25]

Figure 26 shows how effective a supercapacitor can be in stabilizing the"12v" supply voltage during engine cranking. This cranking transient is very similar to a transient caused by an EPS system.

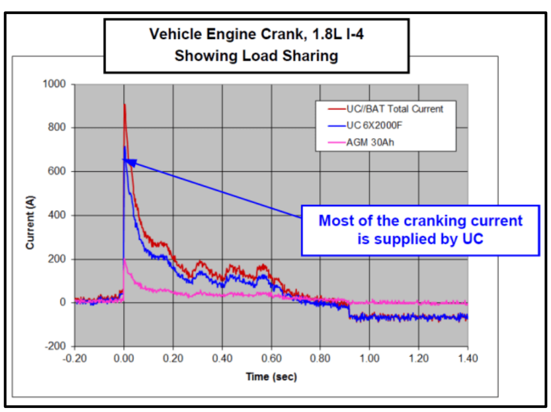


Fig. 26. Ultracapacitor peak-shaving of battery load as demonstrated on an actual vehicle during engine cranking.[26] In-rush (peak) currents are as follows: Pink curve is an AGM30 Ah battery with an internal resistance of 10 mΩ, providing 204 amps. Blue curve is a 6X200F ultracapacitor with a resistance of 2.5 mΩ, providing 716 amps. Red curve is the total of the two, showing 907 amps. Photo courtesy of Maxwell Technologies.

To further demonstrate that an EPS system can cause current deficits that temporarily shut down the EPS system as well as causing transients that can lead to sudden acceleration, Figure 27 shows a simulation done by engineers at Porsche, who pioneered EPS systems and is the recognized authority on EPS operation. The simulation shows DC/DC converter operation with a dynamic load of an EPS system superimposed on a DC base load of 80A. The purpose of the simulation was to show that merely matching the rated current output of the DC/DC converter (160A in this case) to the DC current load of an EPS system (160A in this case) is insufficient to guarantee operation of the EPS system under all conditions because this fails to consider the dynamic current load of the EPS system, which depends on the DC/DC converter temperature as well as its current output.

The results of the simulation can be read in the figure caption. The DC/DC converter was able to provide some of the additional current needed by operating above its rated value for a short time. But operation above the rated value heated up the DC/DC converter, so that it eventually was unable to operate in this fashion when another excursion above the rated value occurred. The converter then lost regulation and its output voltage plummeted to nearly zero volts. This clearly demonstrates that an EPS system can cause transients as low as zero volts.

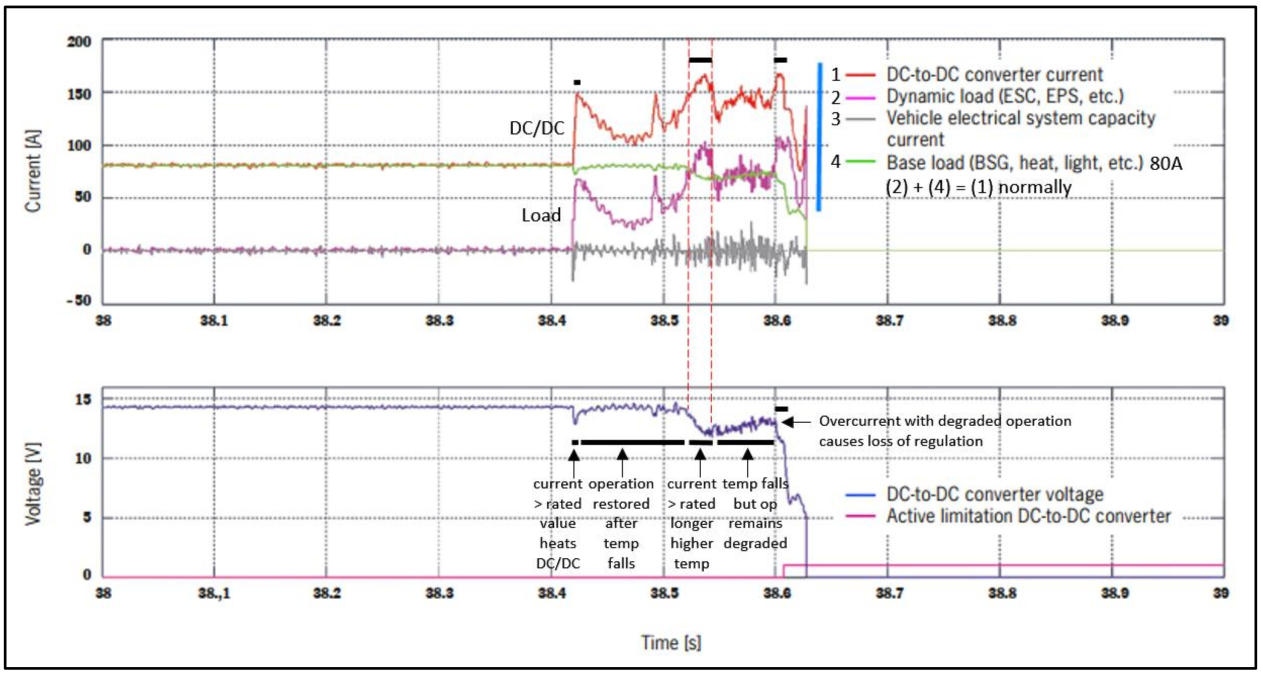


Fig. 27. Simulation of DC/DC converter operation with a dynamic load of an EPS system superimposed on a DC base load of 80A.[27] When the total current load exceeds the maximum rated DC/DC converter current of 160A, the DC/DC converter continues to operate above the rated current, which heats up the converter. The converter cools down quickly for a short excursion above the rated current, but takes longer to recover for a second longer excursion above the rated current. This degrades the operation of the DC/DC converter, so that when a third excursion occurs above the rated current while it is still recovering from the second thermal excursion, the converter cannot respond to the need for more current, causing the converter to go out of regulation and the voltage to drop rapidly. This simulation shows that merely matching the rated current output of the DC/DC converter (160A in this case) to the DC current load of an EPS system (160A in this case) is insufficient to guarantee operation of the EPS system under all conditions because this fails to consider the dynamic current load of the EPS system. And the dynamic current load of the EPS system should also include the inrush current of the EPS system motor, which was not modeled in this simulation.

Figure 28 shows that these EPS transients can be avoided by using a DC/DC converter whose rated current is high enough to provide a margin for an overcurrent situation. Now, the simulation in Figures 27 and 28 did not include the inrush current of the EPS motor. So a voltage dip caused by the inrush current of the EPS motor turning on was not modeled in this case. This inrush current would not greatly affect the operation of the EPS system. But its presence would cause a further dip in the voltage that could lead to sudden unintended acceleration.

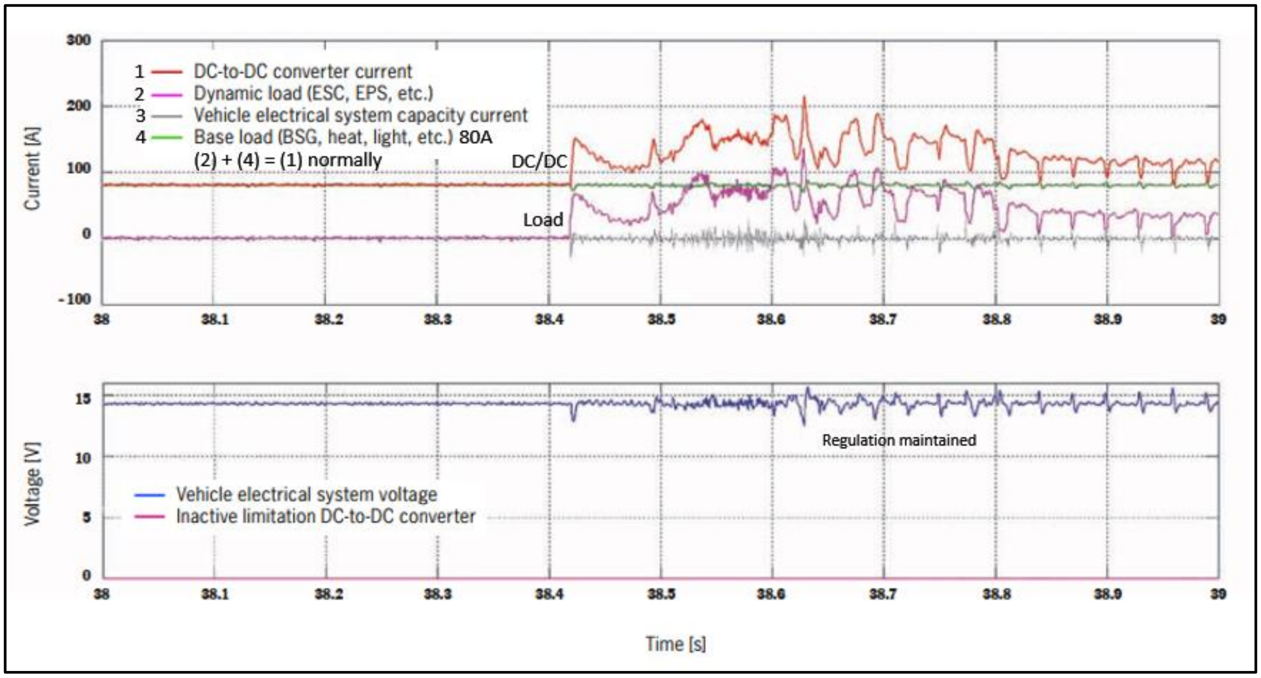


Fig. 28. Simulation of DC/DC converter operation with a dynamic load of an EPS system superimposed on a DC base load of 80A.[28] In this case, the rated current of the DC/DC converter is 240A, which provides sufficient margin for all dynamic EPS currents so that voltage regulation can be maintained. This simulation did not include the inrush current of the EPS motor, however. So a voltage dip caused by the inrush current of the EPS motor turning on would not be modeled in this case. This would not greatly affect the operation of the EPS system. But it would ignore the voltage dip that is believed to cause sudden unintended acceleration.

We have now shown that voltage dips down to 3V or less can be produced on the 12V supply line of an electric vehicle by the EPS system during situations that require high motor torque to overcome high steering loads. These situations include: 1) when the steering wheel is turned to its maximum left or right position while the vehicle is stationary, and 2) when the driver must make a sudden turn in response to an emergency situation. It is interesting that these conditions coincide with the conditions when many sudden acceleration events are claimed to occur; namely in parking lots, when pulling into a parking place in front of a store, or when the car tries to change lanes while in autopilot mode.

We will now consider how these transient voltage dips on the "12V" supply line can show up on the 5V supply line where they can cause a problem when reading the accelerator position sensors in both ICE vehicles and battery-powered electric vehicles.

How Voltage Dips are Transferred From the 12V Bus to the 5V Supplies

Both ICE vehicles and battery-powered electric vehicles require 5V, 3.3V, and 1.2V supplies for the operation of multiple devices such as sensors, DSP's, ADC's, keep-alive memory, and sensor interface circuitry. When the first electronic throttle control system was developed for direct injection engines in 1987, discrete voltage regulators were used for these supplies within an ECU, and the supply circuitry was designed by the ECU manufacturer. Later, after about 2010, these discrete voltage regulators were combined into a single integrated circuit called a power management integrated circuit, or PMIC, whose supply circuitry was designed by the integrated circuit manufacturer. This led to several improvements in the voltage supply circuitry.

We are unable to discuss the discrete versions of this supply circuitry because ECU manufacturers carefully guard the circuit diagrams for their ECU's. It is also likely that these circuit diagrams vary substantially from one ECU manufacturer to another. Therefore, we will limit the following discussion to the operation of the PMIC devices that are being used today in most ICE and electric vehicles.

Before we discuss the operation of PMIC integrated circuits, let's take a closer look at what a PMIC device does. Table 3 shows the functions that are performed by a PMIC device. Note that besides providing multiple supply voltages, it also provides the controlled power-up and power-down of these supply voltages, while monitoring the power rails for overvoltage, under-voltage, short-to-ground, and overcurrent. It can also shut down a faulty power rail if needed, or reset a questionable power rail back to a known safe voltage. Finally, it has a digital interface to a control device, like a microprocessor or DSP, that allows the control device to monitor all the operating functions and to diagnose the cause of any failures so that the control device can either restore safe operation or shut down the device safely. These latter functions constitute the improvements cited above over the discrete circuitry found in earlier ECU's.

Table 3. Functions of a power management integrated circuit (PMIC).

Functions of a PMIC:

1) Operate under all required conditions
    a. User application (e.g., powertrain, BMS, ADAS, camera, AFE, …)
    b. Temperature range (e.g., automotive, …)
    c. Operational lifetime (e.g., 10 years, …)
    d. Controller CPU interface compatibility (e.g., SPI, I^2C, DSP, GPIO, …)
    e. V_{IN} voltage range
        i. DC battery voltage range (e.g., 12V to 0V, …)
        ii. Load dump (i.e., battery disconnect) transient (e.g., up to 42V, …)
        iii. Cold crank transient voltage dip (e.g., down to 3V, …)
2) Provide multiple low-voltage power rails (e.g., 5V, 3.3V,1.2V, …)
3) Control external regulators and regulator components
4) Control power rail sequencing during power-on
5) Control power rail slew rates during power-off
6) Monitor the power rails and PMIC input voltage for incorrect conditions:
    a. Overvoltage (OV)
    b. Under-voltage (UV)
    c. Short-to-Ground (StG)
    d. Overcurrent (OC)
7) Take appropriate action when a fault condition exists
    a. Continue operation
    b. Shut down a power rail (temporarily or permanently)
        i. under-voltage lockout (UVLO)
        ii. overvoltage lockout (OVLO)
    c. Set a power rail to a safe voltage output
    d. Shut down the entire PMIC (temporarily or permanently)
8) Monitor PMIC temperature and warn if exceeded
9) Notify the user when a fault condition exists
    a. Controller interrupt
    b. Diagnostics
10) Other optional features:
    a. Safety features (e.g., reverse battery protection)
    b. Coulomb counting
    c. Battery charging capabilities
    d. Diagnostics

We will now discuss the operation of PMIC devices. These devices use two types of voltage regulators; namely, linear voltage regulators and switching mode voltage regulators. A typical linear regulator is shown in Figure 29. It operates by comparing its output voltage to a reference voltage and then turning on a pass element to allow the input signal V_i to pass to the output only when the output signal V_o remains above the reference voltage. Various pass elements and error amplifiers can be used to improve performance. Since feedback is involved in its operation, stable operation only occurs for applied frequencies that fall within a frequency band that provides amplitudes and phase shifts that support stable operation. We will not analyze any linear regulator designs for their stability because one must know the specific design of the elements of which they are made, and because such analyses are tedious. Instead, we note that most linear regulators can provide stable operation at frequencies of about ten kilohertz, which corresponds to a feedback time of 0.1 milliseconds. Therefore, most regulators can operate stably when the applied voltage pulses have a rise time of 0.1 milliseconds or greater. Since the transients involved in the preceding sections have rise times of one to ten milliseconds, this means that most linear regulators can provide their intended outputs during the rise and fall times of these transients.

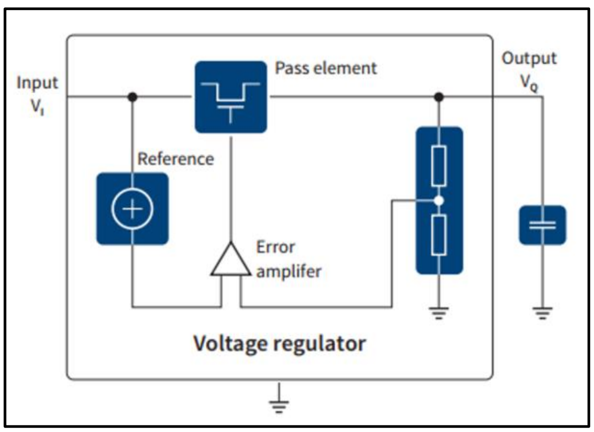


Fig. 29. A linear voltage regulator operates by comparing the output voltage to a reference voltage and then turning on a pass element to allow the input signal V_i to pass to the output only when the output signal V_o remains above the reference voltage. Various pass elements and error amplifiers can be used to improve performance. Switching regulators use similar feedback from the output voltage to a control element that raises or lowers the voltage of the discontinuous output voltage samples.

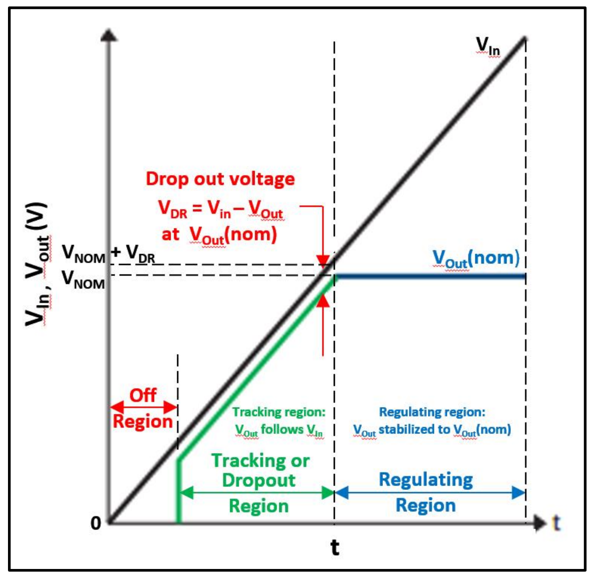


Fig. 30. All linear voltage regulators have a regulating region in which a regulated output voltage is provided when the input voltage exceeds the regulated voltage by some dropout voltage. When the input falls below this value, the regulator enters the dropout region in which the output voltage equals the input voltage minus the dropout voltage. At some point this tracking ceases, and the regulator output goes rapidly to zero, causing the regulator to turn off. Normal regulators have dropout voltages of one to three volts. Low dropout regulators (LDO) have dropout voltages of one hundred to four hundred millivolts.

Figure 30 shows the input/output behavior of a linear regulator. When the input voltage exceeds the regulated output voltage desired by some fixed dropout voltage, then the regulated voltage is obtained on the output. When the input falls below this value, the regulator enters the dropout region in which the output voltage equals the input voltage minus the dropout voltage. As the input voltage falls further, this tracking of the output voltage to the input voltage ceases, and the regulator output goes rapidly to zero, causing the regulator to turn off. Normal regulators have dropout voltages of one to three volts. Low dropout regulators (LDO) have dropout voltages of one hundred to four hundred millivolts.

Figure 31 shows the behavior of a linear regulator to an input pulse whose voltage varies from above the regulated output voltage to below the regulated output voltage. The part of the input pulse that lies above the regulated output plus a dropout voltage results in the desired regulated output voltage. This gives one the impression that this part of the input pulse is trimmed off. The part of the input pulse that lies below the regulated output plus a dropout voltage get passed to the regulator output at a lower voltage of $V_{in} – V_{DO}$. This continues until $V_{in} – V_{DO}$ reaches the off region of the regulator, when the output changes to zero.

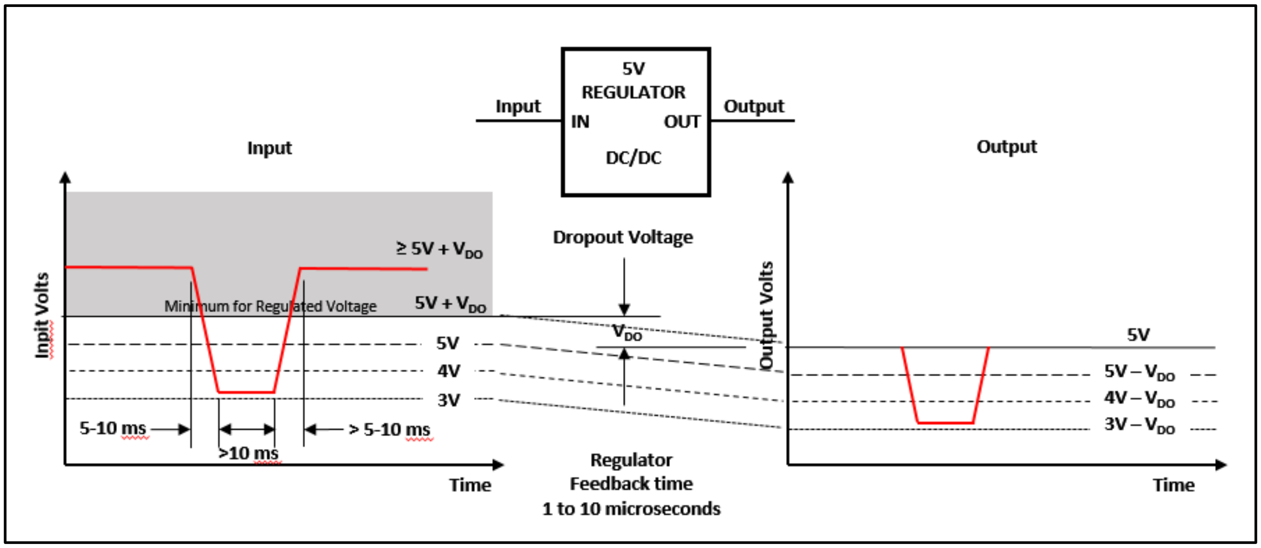


Fig. 31. Transient voltage dips with rise/fall times of 5 to 10 milliseconds are easily passed from the regulator input to the regulator output because the regulator feedback time of 1 to 10 microseconds is very short compared to the transient rise/fall times.

Switching regulators operate completely differently. There are many types of switching regulators, but we will discuss only two of them here: namely buck converters and boost converters. Buck converters can provide a lower voltage output from a higher voltage input. Boost converters can provide a higher voltage output from a lower voltage input.

A buck converter is shown in Figure 32. It operates by charging and discharging an inductor, which changes the voltage across the inductor as a result of using different times for charging and discharging. When the switch is closed, current is directed into the inductor, storing energy in the inductor's field and raising its voltage. When the switch is opened, current is directed out of the inductor through the diode and the load at a lower voltage. This transfers the energy stored in the inductor during the on-state into the load during the off state. The capacitor smoothes the switching spikes. The output voltage is less than the input voltage and decreases as the duty cycle D decreases from one: $V_{out} = D \bullet V_{in}$ for $0 \le D \le 1$.

A boost converter is shown in Figure 33. It also operates by charging and discharging an inductor, which changes the voltage across the inductor as a result of using different times for charging and discharging. When the switch is closed, current is directed into the inductor, storing energy in the inductor's field and raising its voltage. When the switch is opened, current is directed out of the inductor through the diode and the load at a higher voltage. This transfers the energy stored in the inductor during the on-state into the load during the off state. The capacitor smoothes the switching spikes. The output voltage is greater than the input voltage and increases as the duty cycle increases toward one: $V_{out} = V_{in} / (1 - D)$ for $0 \le D \le 1$.

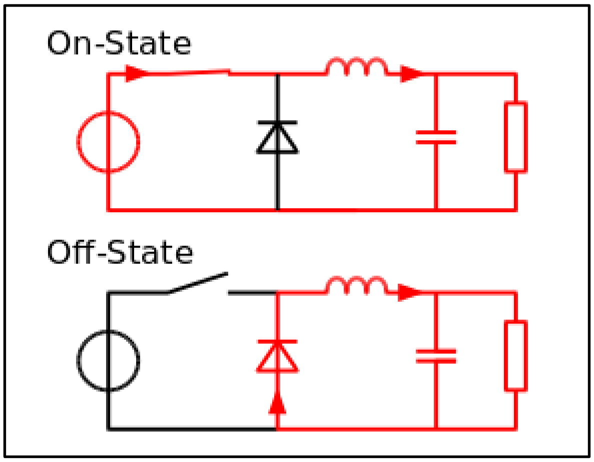


Fig. 32. Buck Converter. In the on-state, the switch is closed, resulting in an increase in the inductor current. In the off-state, the switch is open and inductor current discharges through the diode and the load. This transfers the energy stored in the inductor during the on-state into the load during the off state. The capacitor smoothes the switching spikes. The output is lower than the input and decreases as the duty cycle D decreases from one: $V_{out} = D \bullet V_{in}$ for $0 \leq D \leq 1$.

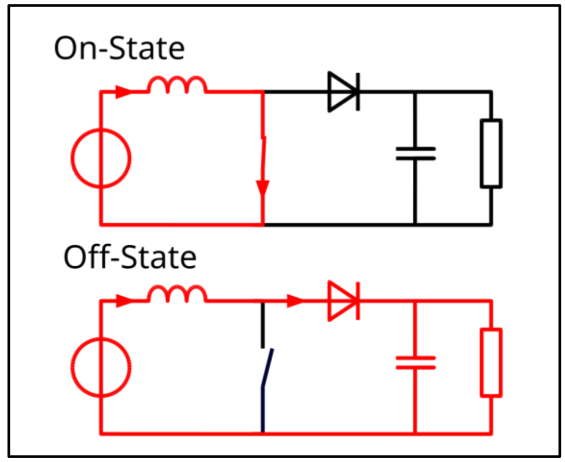


Fig. 33. Boost converter. In the on-state, the switch is closed, resulting in an increase in the inductor current. In the off-state, the switch is open and inductor current discharges through the diode and the load. This transfers the energy stored in the inductor during the on-state into the load during the off state. The capacitor smoothes the switching spikes. The output is higher than the input and increases as the duty cycle increases toward one: $V_{out} = V_{in} / (1 - D)$ for $0 \leq D \leq 1$.

Switching regulators also have characteristic feedback times. But these times are very short, being less than ten microseconds usually. Table 4 shows how rise and fall times of transient voltage dips compare to the feedback times of linear regulators and switching regulators. This comparison shows that both types of regulators will track the transient voltage dips without changing their rise and fall times and will provide the intended regulator outputs in response to the changes in the input voltage.

Table 4. Transient voltage dips compared to regulator feedback times

Event	Time
Electric motor inrush current transient	
- Rise time (motor inductance magnetic field builds up)	5 to 10 milliseconds
- Duration/fall time (EMF increases as rotor RPM increases with RPM limited by motor application)	
- Cold crank start waveform (limited by engine operation)	1 to 5 seconds
- Electronic power steering (limited by steering torque)	100 ms to 1 second
Linear regulator feedback time	< 0.1 milliseconds
Switching regulator feedback time	< 10 microseconds

With the above knowledge of regulator operation, we can now discuss PMIC device operation.

If one merely connects an assortment of 5V, 3.3V, and 1.2V regulators to the same 12V supply voltage, as shown in Figure 34, then all the regulators will operate as designed and provide their normal outputs. However, if a voltage dip occurs that temporarily drops the 12V supply voltage to below 5V plus a dropout voltage of 1V, or 6V, then the 5V regulator will cease to regulate properly and its output voltage will begin to drop while the other lower voltage regulators will continue to operate properly. Therefore, the functions powered by the 5V regulators will receive a lower unregulated voltage that will deteriorate their performance and maybe even turn them off. This design will only work when the battery voltage V_{BATT} is greater than 6V. There is also a problem if linear voltage regulators are used in this fashion, because they must drop the voltage all the way from 12V down to the regulator voltage, which increases their power dissipation and heats them up to high temperatures.

The power dissipation problem in this case can be fixed by using by using a switching mode buck regulator to drop the voltage from the 12V supply down to a regulated 6V output, which is then used to feed the linear regulators. This fix works because a switching mode buck regulator lowers the voltage from 12V down to the regulated voltage by a switching technique that does not dissipate any power like a linear regulator does. However, this 6V buck regulator still has the problem that it will cease to operate when the 12V supply voltage falls down below 6V plus the dropout voltage, or around 7V. Below this voltage the 6V regulator ceases to regulate, and the output of the 6V regulator begins to fall as its input falls further. The net result is that the 5V regulator will still go out of regulation when the 12V supply falls to 5V plus a dropout voltage, or 6V. So the 6V buck regulator in this case only lowers the power dissipation and provides no additional protection against voltage dips.[Footnote 6]

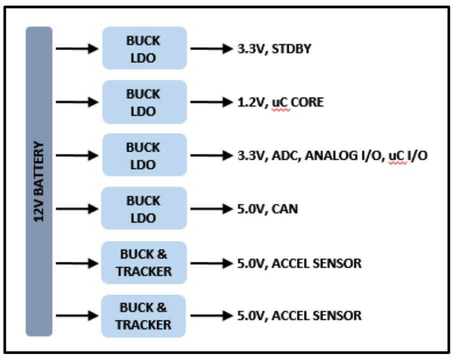


Fig. 34. If all regulators for lower voltages are supplied by the same 12V battery voltage, then as the battery voltage decreases, the 5V regulators will fall out of regulation first, with those having higher dropout voltages going before those having lower dropout voltages (LDO). This design works only when V_{BATT} > 6V to 7V.

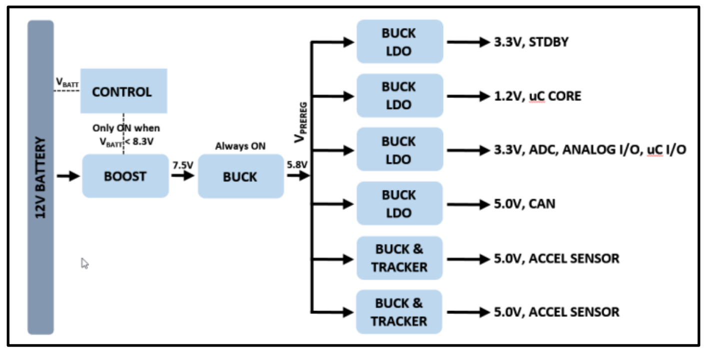


Fig. 35. If a boost regulator is used to raise the supply voltage for all the buck regulators, then as the battery voltage falls below some critical value, all the buck regulators will stay in regulation during a voltage dip on the 12V battery supply line, including the 5V regulators. Many PMIC chips allow all regulators to remain in regulation when the battery voltage falls as low as 3V.

One way to maintain regulation of the 5V linear regulator as the 12V supply falls below 6V is to add a boost converter whose output powers the 6V buck converter. Then, as the 12V supply falls below 6V, the boost converter can increase its output to maintain the input to the 6V converter at 6V plus a dropout voltage. On the other hand, when the 12V supply remains above 6V plus a dropout voltage, the boost converter can be switched out, allowing the 6V buck converter to lower the voltage from 12V down to 6V. This is the reason why the 6V converter is kept in the circuit in this case. It turns out that nearly all PMIC manufacturers use the circuit shown in Figure 35. A variation one manufacturer uses is to keep the boost converter gain at a constant high voltage. Another manufacturer uses a combined boost-buck converter in place of individual boost and buck converter. But the operation in all these cases is the same. And they all can maintain operation of the 5V regulator while the 12V supply dips down to 3 to 4V.

6 This power supply design with a buck mode pre-regulator operating at a regulated voltage of 6V may have been used in some or all of the vehicles investigated by NASA/NHTSA in 2011, as inferred from Fig B-6.1, "*Power Fishbone Diagram*" and Table B-6.1, "Power Fishbone Summary of Design Sensitivities with Postulated Faults", in NHTSA Toyota UA Investigation Report: Appendix B, p. 33-35. http://www.nhtsa.gov/UA .

Figure 36 shows a block diagram of a PMIC device made by Infineon. This device is known to be used by at least one electric vehicle manufacturer in several models of its vehicles. It may also be used by other electric vehicle manufacturers, as well as by other manufacturers of ICE vehicles, hybrid vehicles, and diesel vehicles. This is because Infineon is regarded as a reliable supplier to the automotive industry whose products are of excellent quality and whose supply will be maintained during the years of a vehicle's production. It is also because Infineon's device has a wide range of other features including monitoring the power rails for overvoltage, under-voltage, short-to-ground, and overcurrent. It can also shut down a faulty power rail if needed, or reset a questionable power rail back to a known safe voltage. Finally, it has a digital interface to a control device, like a microprocessor or DSP, that allows the control device to monitor all operating functions and to diagnose the cause of any failures so that the control device can either restore safe operation or shut down the device safely. We will now discuss Infineon's device in more detail.

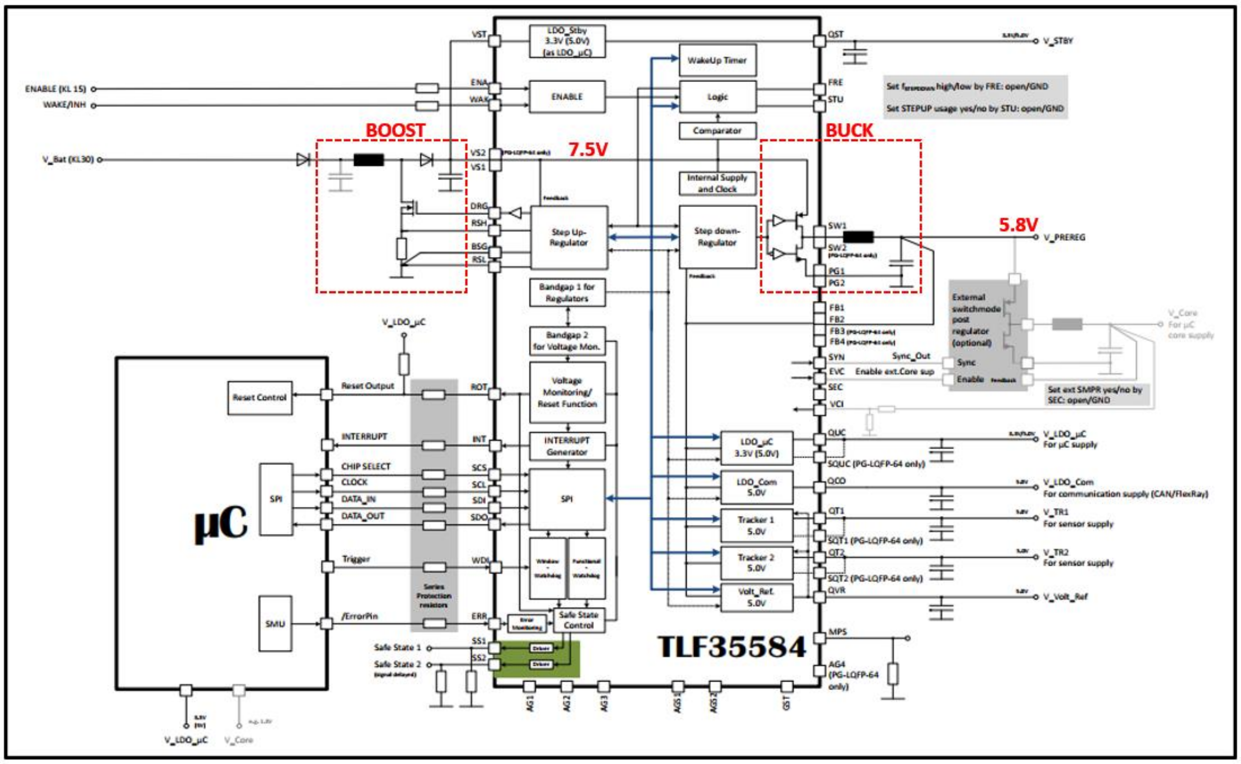


Fig. 36. Infineon's TLF35584 PMIC device operates with battery voltages as low as 3V while monitoring all output rails for overvoltage, under-voltage, and short to ground.[29] It is used by many automobile manufacturers because Infineon is a dedicated long-term supplier to the automotive industry with a reputation for high quality.

The way the regulators work in the TLF33584 PMIC can be described with the aid of Figure 37, which is simplified version of Figure 36 above. Normally, the input to the PMIC chip sees a battery voltage of 12.7V ±0.1V depending on the DC load corresponding to the actuators in use at the time. When the battery voltage stays high, the boost converter remains turned off, and the battery voltage gets passed directly to the input of the buck converter, which can then provide an output of 5.8V, which is sufficient for all the LDO regulators. However, when the battery voltage drops as a result of a transient voltage drop, then a voltage monitor detects when the battery voltage drops below its setting of 8.0V and turns on the boost converter. As the battery voltage drops further, the boost converter increases its output voltage to provide a constant 7.5V at its output while its input, which is tied to the battery voltage, continues drop. This allows the buck converter to output a constant 5.8V even when the battery voltage drops as low as 3V. With all the LDO regulators supplied by a constant 5.8V, all the 5V, 3.3V, and 1.5V regulators remain in regulation while the battery voltage can drop to 3V (but not less). This is demonstrated by Figure 38, which shows the 5V and 3.3V regulator outputs are still in regulation while the battery voltage is at 3.0V.

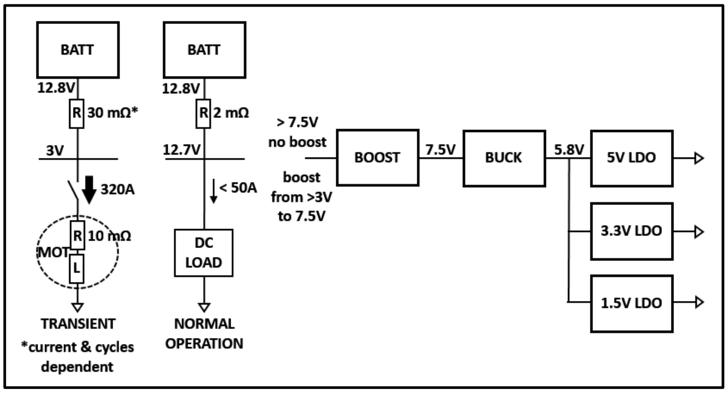


Fig. 37. Simplified diagram of Infineon's TLF33584 PMIC chip showing that it contains boost and buck switching converters that provide a solid 5.8 volt input to the low dropout linear regulators that supply the 5V, 3.3V, and 1.5V rails. The 5V regulator output remains in regulation when the PMIC input sees a transient voltage dip as low as 3V caused by starter cranking or by other electric motors turning on.

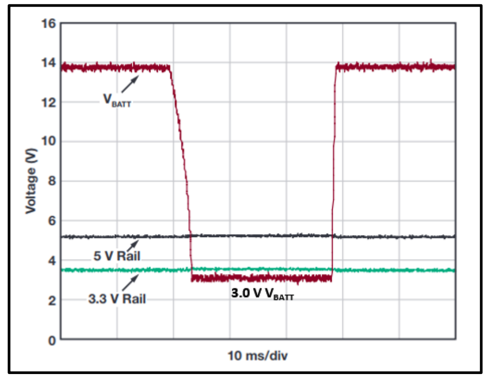


Fig. 38. This figure from Analog Devices shows that their LT8603 maintains 5V, 3.3V, and 1.2V output regulation with a V_{BATT} as low as 3V. [30] Infineon's TLF35583 provides similar performance. (Note that V_{BATT} is not the direct input to the two regulators).

One might ask what happens when the battery voltage falls below 3.0V? To answer this question, we need to know the voltage in the regulator chain when the battery voltage is at 3.0V.

Now the spec and test data show that when VBATT is 3.0V, the 5.0V regulator maintains regulation with an output voltage of 5.0V. It is safe to assume that the battery voltage cannot go any lower without the 5V rail dropping, or else the spec sheet would have claimed some battery voltage lower than 3V. This means that at a battery voltage of 3V the input voltage to the 5.0V regulator is at 5.0V plus its dropout voltage, which is the minimum input voltage the 5V regulator can have before it goes out of regulation below 5.0V. From the spec sheet we find that the dropout voltage of the 5V regulator is 0.4V. So we can assume that the input to the 5.0V regulator is at 5.4V when the battery voltage is 3.0V.

Now if we decrease battery voltage by N millivolts from 3.0V, this will produce a corresponding decrease in the 5.4V input to the 5V regulator by the same N millivolts. We can then create the following table:

Table 5. Operation of the TLF33584 5V regulator during dropout

V_{BATT}	5V regulator V_{IN}[1]	5V regulator V_{OUT}
>3V	>5.4V	5.0V
3.0V	5.4V	5.0V
2.9V	5.3V	4.9V
2.8V	5.2V	4.8V
2.7V	5.1V	4.7V
2.6V	5.0V	4.6V
2.5V	4.9V	4.5V[2]
2.4V	4.8V	4.4V[3] or 0V[4]

[1] Dropout voltage is 0.4V per spec sheet.
[2] Under voltage threshold is 4.5V per spec sheet.

[3] Regulator continues operation if under voltage is shorter than 3 milliseconds.
[4] Regulator is shut down with output set to zero if under-voltage lasts longer than 3 milliseconds indicating short to ground .

Table 5 shows that when the battery voltage dips to 2.5V, the 5V regulator output will drop below 4.5V, which is the under-voltage threshold for the 5V tracker regulator (see Table 6). Below this threshold an interrupt is generated and a flag is set in the MONSF2 register showing that an under-voltage condition occurred in the 5V regulator output. The 5V regulator will continue to operate as before. If this under-voltage condition persists for 3 milliseconds or longer, another interrupt is generated and a second flag is set in the MONSF0 register showing that a short-to-ground has occurred in the 5V regulator output. Simultaneously, the 5V regulator is turned off and its output is set to zero.

Table 6. Characteristics of TLF33584 voltage regulators[31]

Function	Drop-out Voltage	Output Voltage	Output Under-voltage Threshold	Under-voltage Threshold Signal
Boost PreReg		7.5V	8.3V (input)	$V_{PRE\_REG,boost,UV}$
Buck PreReg	0.6V	5.8V	5.1V	$V_{RT,FB,low}$
LDO COM (CAN)	0.4V	5V	4.5V	$V_{RT,QCO,low}$
VREF	0.4V	5V	4.3V	$V_{RT,QVR,low}$
Tracker1	0.4V	5V	4.5V	$V_{RT,QT1,low}$
Tracker2	0.4V	5V	4.5V	$V_{RT,QT2,low}$
LDO_uC Dig I/O	0.4V	5V	4.3V	$V_{RT,QUC,low}$(VS1)
LDO_uC Dig I/O	0.5V	3.3V	2.97V	$V_{RT,QUC,low}$(VS2)
uC Core		1.2V	728 mV	$V_{RT,VCI,low}$
LowVRESET			0.7V/0.4V	$V_{ROT,low}$(VS1)

When the output of the 5V regulator is set to zero, this turns off the supply voltage for one of the two APP sensors. This means that one of the APP sensors has no output signals. But this condition lasts only until the short-to-ground interrupt is serviced, which is normally less than a few hundred milliseconds. The interrupt service routine may then turn the regulator back on, restoring both sensors again. This will cause only a short hiccup in the operation of an electronic throttle.

Now, while the short-to-ground event occurs, the input to the 5V regulator stays at 4.8V. The inputs to the 3.3V regulator and the 1.5V regulator are therefore at this same voltage of 4.8V. This voltage is well above the voltage at which dropout occurs in these regulators, so the ADC remains in operation while the 5V regulator is turned off.

If the ADC then samples the voltage of the 5V supply to the APP sensors while the 5V regulator is turned off, then the ADC obtains a digital output of zero volts for the supply voltage. When this digitized supply voltage is used to correct subsequent APP sensor outputs for variations in their supply voltage, the sensor outputs will increase to their maximum values. This causes sudden acceleration without the driver pressing on the accelerator pedal.

The conclusion is that when the battery supply voltage dips below 2.5V, then the 5V regulator output goes below its under-voltage threshold of 4.5V, causing an under-voltage flag to be set while the 5V regulator remains on. If this under-voltage condition persists for 3 milliseconds or longer, a second short-to-ground flag is set, and the 5V regulator is turned off with its output set to zero. If the 5V output is now sampled in this condition by an ADC, then the ADC obtains a digital output of zero volts for the supply voltage. When this zero volt output is used to correct subsequent APP sensor outputs for variations in their supply voltage, the sensor outputs will increase to their maximum values. This causes sudden acceleration without the driver pressing on the accelerator pedal. So we have just proven that any vehicle that uses Infineon's TLF 33584 PMIC device can undergo sudden acceleration when the battery supply voltage falls below 2.5V and when the ADC samples the battery supply voltage in this condition.

Here are some further conclusions that can be drawn from this discussion:

1) If sudden acceleration occurs, it occurs without a defect in the TLF 33584 device. The PMIC device always works according to spec, which states that the device will operate correctly with a battery voltage 3.0V or above. The condition that produces sudden acceleration is operation of the TLF 33584 device with a battery voltage below 3.0V, which is outside the device specification.
2) Is it possible that battery voltage dips below 3V will occur? Yes. The PMIC device manufacturer thought so because they determined what the chip should do when under-voltages occur, which can happen when battery voltage dips lower than 3V occur.
3) Is this a problem with just the Infineon device? Can a better PMIC be obtained? Answer: The PMIC chips from other manufacturers have a similar limitation of battery voltage dips to around 3V or less. (See Table 7 below). What causes this limitation is not known at this time. But it is suspected that it is caused by a limitation in the maximum gain of the boost converter.

Table 7. PMIC's similar to Infineon's TLF 33584

Company	P/N	Boost	V_{REG}'s	Lowest V_{BATT}	$V_{BOOSTOut}$	V_{PreReg}
Infineon	TLF35584	Yes	5V, 3.3V, 1,2V	3V	8.3V	5.8V
Bosch	CY329	Yes	5V, 3.3V, 1,2V	3V	---	6V
Analog Devices	LT8603	Yes	5V, 3.3V, 1,2V	2V	8.0V	---
ST Microelectronics	L9758	Yes	5V, 3.3V, 1,2V	4V	8.5V-10V	6V
Allegro	ARG82800	Yes	5V, 3.3V, 1,2V	3.8V		5.3V
Motorola/NXP	MC33394	Yes	5V, 3.3V, 2.6V	4.0V	6.0V	5.6V

4) Now, the vehicle manufacturer, in addition to the PMIC manufacturer, must be aware that some events can produce dips in the battery voltage below 3V because they must write the interrupt service routines that respond to the under-voltage interrupts and the short-to-ground interrupts so they can restore the normal PMIC device operation. These interrupt routines are part of the software that runs on the DSP that also reads the APP sensor signals and that controls the drive motor in response to the APP sensor signals. This means that the vehicle manufacturer must know, not only in general that dips below a battery voltage of 3V can occur, but also that by reading the PMIC interrupt registers before they are reset they can know specifically if and when an under-voltage has occurred. Therefore, when a sudden acceleration occurs, the PMIC interrupt registers can be inspected to determine whether a transient occurred to cause the sudden acceleration.

In summary, it has been shown in this section that transient voltage dips on the 12V supply line can pass through the 5V regulators in a PMIC device and show up on the 5V supply line. The companies that supply these PMIC devices know this because their device architectures assume this fact as evidenced by monitoring the outputs of the 5V regulators and providing interrupts when these outputs have an under-voltage or a short-to-ground. Auto manufacturers also know this because they must write the software routines for the DSP's in their powertrain ECU's that services these interrupts.

So we now know that transient voltage dips on the 12V supply line can pass through the 5V regulators in a PMIC device and show up on the 5V supply line. If an ADC then digitizes the voltage of the 5V supply line while a transient voltage dip is present, the ADC digital output will be not 5V, but the lower voltage of the transient voltage dip. And when this lower digital supply voltage is used to divide the digitized output of a ratiometric APP sensor to compensate for changes in supply voltage with temperature, the result will be a larger digital sensor output even though the analog output of the APP sensor remains small because the accelerator pedal has not been pushed. The result will be sudden acceleration with the EDR data showing a large digital APP sensor % reading even though the accelerator pedal has not been pressed.

VI. Another SUA Mechanism in ICE Vehicles

There is another mechanism in ICE vehicles that can cause sudden acceleration. Figure 39 shows a block diagram of the electronic throttle control system in all ICE vehicles, and explains how the duty cycle input to the H-bridge is multiplied by the ratio $12V/V_{12V}$(ADC) to make the to make the output of the H-bridge, or the input to the throttle motor, independent of any changes in the 12V supply voltage. This is a normal adjustment made by all automobile manufacturers to prevent changes in the throttle opening from occurring as the 12V battery state of charge changes during vehicle operation. This adjustment works well as the value of the supply voltage V_{12V}(ADC) is updated periodically on the order of once every minute or so.

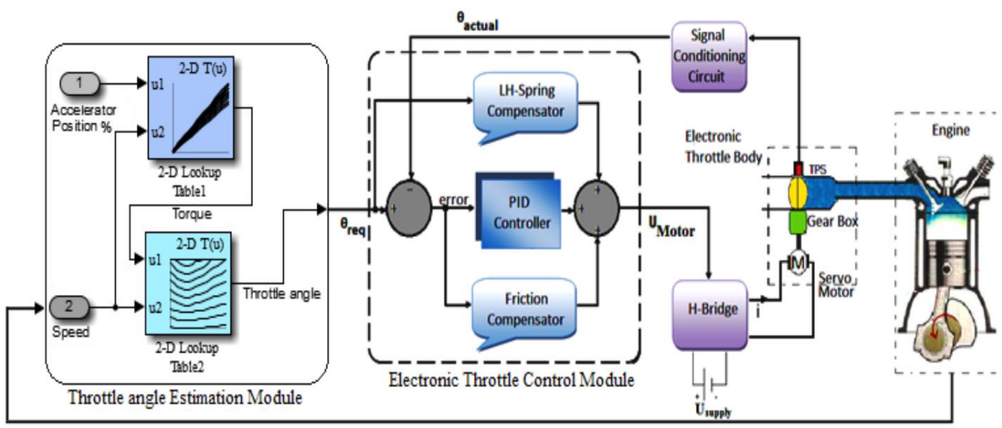


Figure 39. Block diagram of the electronic throttle control system in all ICE vehicles.[32] Note that the H-bridge operates with the supply voltage as an input, making the throttle motor torque, and therefore the throttle opening, dependent upon changes in the 12V supply voltage. This dependence is removed by multiplying the duty cycle input to the H-bridge by the ratio $12V/V_{12V}$(ADC) where V_{12V}(ADC) periodically samples the 12V supply line and the ratio increases as the supply line voltage decreases. Therefore, increases in the duty cycle offset decreases in the supply line voltage, to make the output of the H-bridge, or the input to the throttle motor, independent of any changes in the supply voltage.

Now, if a transient voltage dip occurs while the ADC is sampling the 12V supply voltage during this routine adjustment, then the ADC digital output will have a value close to 0V instead of a normal value close to 12.8V. In this case, the normal adjustment to the duty cycle, i.e., the ratio $12V/V_{12V}$(ADC), has a value much larger than one, which increases the H-bridge output voltage to increase the throttle motor torque and increase the throttle motor opening. The result is sudden acceleration without the driver pressing on the accelerator pedal.

This mechanism differs from the APP sensor mechanism discussed earlier in this paper because it involves sampling the voltage of the 12V supply line during a transient voltage dip instead of sampling the voltage of the 5V supply line during a transient voltage dip. And while both of these mechanisms can cause an increase in the throttle opening without the driver pressing on the accelerator pedal, this mechanism results in the EDR showing an APP sensor value of 0%

while the previous mechanism results in the EDR showing an APP sensor value greater than 0%, and often up to 100% while the driver has not pressed the accelerator pedal. Another difference is that this mechanism can result in throttle sensor opening values that exceed the normal values (i.e., TPS sensor output values) while the previous mechanism always provides throttle openings within the normal values.

Further details on this SUA mechanism in ICE vehicles can be obtained by reading the following papers by this author:

1) A Clear Explanation of Belt's Theory of Sudden Unintended Acceleration – 5/15/18
2) Answers to Some Remaining Questions On Belt's Theory of Sudden Acceleration – 12/1/15
3) Sudden Acceleration in Vehicles with Mechanical Throttles and Idle Speed Actuators – 7/1/15
4) Simulation of Sudden Acceleration in a Torque-Based Electronic Throttle Controller – 1/30/15
5) Dr. Ronald A. Belt: Comparison of Two Electronic Theories of Sudden Acceleration – 9/30/14
6) Further Details on an Electronic Mechanism for Sudden Unintended Acceleration – 1/6/14
7) A More Detailed Electronic Mechanism for Sudden Unintended Acceleration – 8/4/13
8) Sudden Acceleration Without an Accelerator Input – 11/1/12
9) A Detailed Electronic Mechanism for Sudden Unintended Acceleration – 8/2/12

All these papers are available from the Center for Auto Safety website at https://www.autosafety.org/dr-ronald-a-belts-sudden-acceleration-papers/ or by clicking on the title of each paper.

VII. Another SUA Mechanism in BeV's

There is another mechanism in battery-powered electric vehicles that can cause sudden acceleration. Figure 40 shows that the vehicle torque and power curves shift to lower motor speeds as the state of charge of the high voltage battery decreases. This requires that an adjustment be made in all algorithms that depend upon the battery voltage explicitly or upon any variable that is dependent upon the battery voltage. Motor speed is one of these variables. If an adjustment is not made, then as the battery voltage or motor speed changes, errors will be made in estimating the magnetic flux and current of the drive motor that will cause incorrect operation of the FOC control algorithms. The solution is to multiply the battery voltage and motor speed in these algorithms by the ratio $V_{BATTnorm}/V_{BATT}(ADC)$ where $V_{BATTnorm}$ is the normal high voltage battery voltage of 400V and $V_{BATT}(ADC)$ is the actual voltage of the battery at any given time as measured by a voltage sensor and digitized by an ADC. An example of how this is done is shown in Figure 41. This adjustment works well as the value of the high voltage battery voltage $V_{BATT}(ADC)$ is updated periodically on the order of once every minute or so.

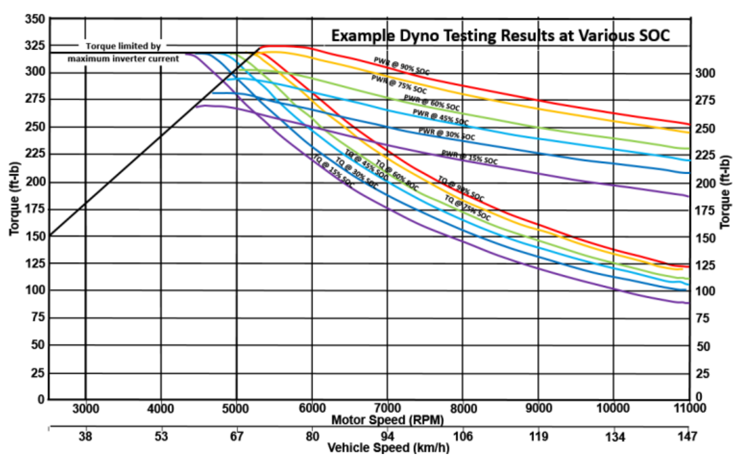


Figure 40. Dynamometer testing results[33] on a battery-powered electric vehicle show that the vehicle torque and power curves shift to lower motor speeds as the state of charge of the high voltage battery decreases. The maximum torque for all curves remains constant because it is limited by the inverter current.

Now, the sensor used in measuring the voltage of the high voltage battery is a special sensor that isolates the high voltage input from the low voltage output, as shown in Figure 42. The output of this sensor is proportional to both the high voltage being measured and the 5V supply voltage. This makes it a ratiometric sensor, just like the APP sensors discussed earlier in this paper. Therefore, the 5V supply voltage is used to correct the output of the high voltage sensor for changes in the 5V supply voltage. When this is done, normally everything works well and the resulting high voltage value can be used to correct the estimates of the magnetic flux and speed of the drive motor as shown in Figure 41. But if a transient voltage dip occurs while the ADC is sampling the 5V supply voltage during this routine adjustment, then the ADC digital output will have a value close to 0V instead of a normal value close to 5V. When this is used to correct the high voltage sensor output, the sensor output will increase to a much higher voltage. This will cause the estimates of the magnetic flux and speed of the drive motor to increase, causing the FOC algorithm to increase the speed of the drive motor. The result is sudden acceleration.

This mechanism differs from the APP sensor mechanism discussed earlier in this paper because it involves changes in the measured voltage of the high voltage supply to the drive motor. These changes are associated with a voltage sensor, and not the APP sensor as discussed earlier. And while both of these mechanisms can cause an increase in the throttle opening without the driver pressing on the accelerator pedal, this mechanism results in the EDR showing an APP sensor value of 0% while the previous mechanism results in the EDR showing an APP sensor value greater than 0%, and often up to 100% while the driver has not pressed the accelerator pedal.

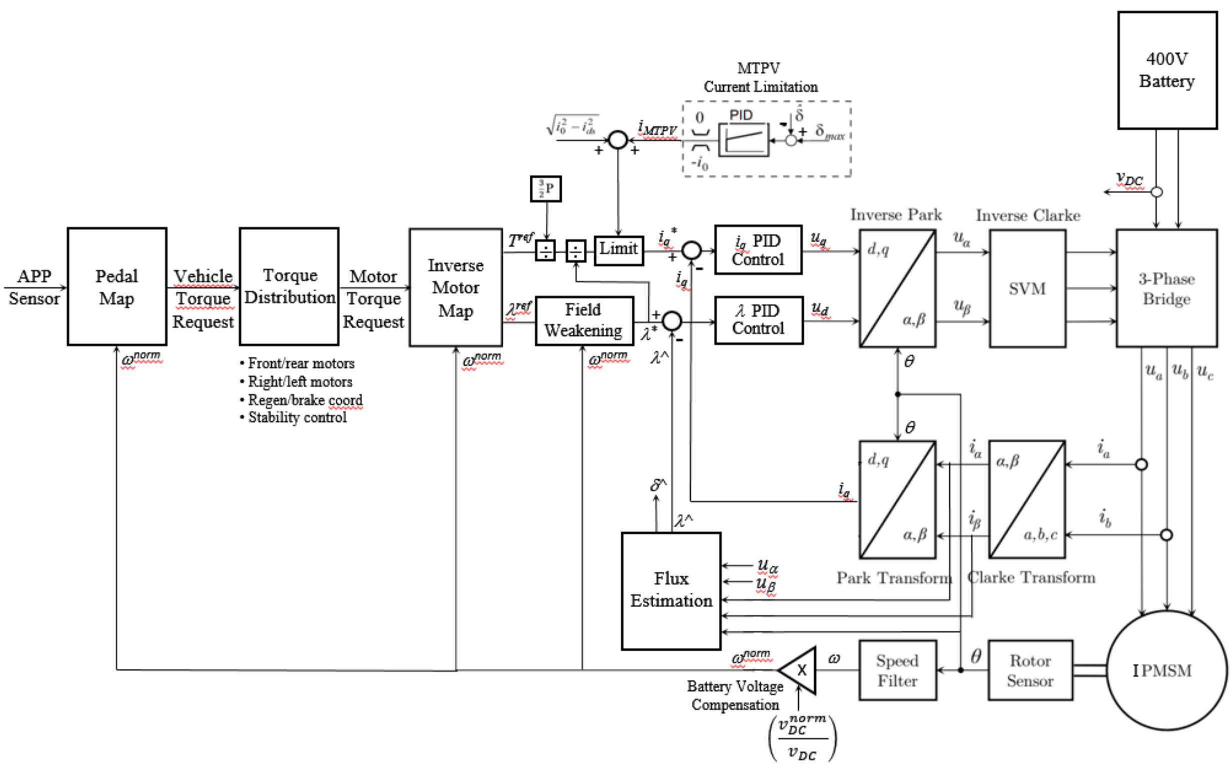


Figure 41. Block diagram of the control system of a typical battery-powered electric vehicle showing how the motor speed and flux are corrected for changes in the voltage of the high voltage battery.

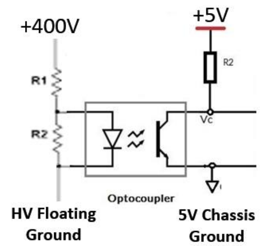


Fig 42. A high voltage sensor can isolate the high voltage input from the low voltage output by using an opto-coupler. The resulting sensor output is proportional to both the high voltage being measured and the 5V supply voltage.

Further details on this SUA mechanism in battery-powered electric vehicles can be obtained by reading the following paper by this author:

1) A Cause of Sudden Acceleration in Battery Powered Electric Vehicles

This paper is available from the Center for Auto Safety website at https://www.autosafety.org/dr-ronald-a-belts-sudden-acceleration-papers/ or by clicking on the title of the paper.

VIII. Why EMI Testing has Failed to Find the Cause of Sudden Acceleration

One may ask why EMI testing has failed to find any sudden acceleration in automobiles when applying voltage dips to the 12V supply as recommended by EMI standards. The answer is that the vehicle is not susceptible to any voltage dips on the 12V supply or the 5V supply unless an ADC is sampling the voltage of the 12V bus or the 5V bus at the same time the voltage dips are being applied. The test of whether the vehicle is susceptible is to look at the output of the ADC after the supply voltage is digitized. This is a difficult test to do when one has no control over the time of digitization. In this case one can only apply voltage dips continuously and hope for a random coincidence between the voltage dips and the ADC acquisition of a voltage sample. The only other alternatives are to hold the 12V bus low for a long time during which the ADC eventually will acquire a voltage sample, or to establish control over the timing of the ADC digitization so one can synchronize it with a voltage dip pulse. None of these last three alternatives has been used in EMI testing to date.

One may ask why we don't see the vehicle lights dim when a voltage dips occurs on the 12V power bus. The answer is that most lights are incandescent, so they are current sensitive, and not voltage sensitive. With incandescent lighting one must supply enough current to heat up the filament of the light bulb. This heating is an integral of the current, so the light from an incandescent bulb is sensitive only to current over time, and not to the current during a very short voltage dip lasting a few tens of milliseconds.

One may follow up the last question by noting that one can see the headlights dim when starting a car, so why can't one see headlights dim when a transient occurs? After all, the point was made earlier that the transients that cause sudden acceleration are similar to a starter crank waveform. The answer is that a starter crank waveform lasts for one to three seconds, because the engine takes time to fire up. This makes it easier to notice the dimming of headlights than for a transient that lasts only a few tens of milliseconds. When the crank waveform is averaged over the eye integration time of a few tenths of a second, the crank waveform contributes to the entire eye integration time. When a transient waveform is integrated over the same eye integration time, the shorter transient waveform contributes to only a small part of the eye integration time.

Finally, one may say that the contactors in an electric vehicle would open if a voltage dip occurs on the 12V supply line, causing the vehicle to come to a sudden stop. Therefore, the reason the contactors stay closed is because there are no voltage dips on the 12V supply line. In response to this statement, it is noted that a contactor is essentially a relay that has inductance because it has many turns of wire. This makes it sensitive to currents, and not to voltages. This is why a contactor has a hold current and not a hold voltage. This current dissipates heat and requires power. So all contactors come with an economizer that supplies the minimum safe current that holds the contactor closed. An economizer uses PWM control with a 20 kHz PWM frequency to supply the hold current, just like the current to a throttle motor. This means that the 12V supply current is pulsed fully on and fully off every 50 microseconds to provide the hold current for the contactor. So, contactor manufacturers wouldn't use a PWM controller if a contactor would open every time the hold voltage is switched to zero. The reason contactors don't open during PWM operation is that they average the current over a longer time period during which the electric field in the contactor stays high and the contactor stays on. And if the hold current decreases for any reason, the PWM controller increases the PWM duty cycle to increase the hold current back to its original value.

IX. Elimination of Sudden Acceleration

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

1) Add a second 12V supply line with its own battery and use it only for powering the APP sensors and the ADC's to provide clean power to these functions free of negative-going voltage spikes from electric motors and solenoids. Use the existing 12V supply with its battery for all other 12V applications (dirty power).
    a. The battery for the APP sensors and the ADC's may tolerate a smaller capacity because its drain current will be lower as a result of other loads being removed.
    b. A battery for the APP sensors and the ADC's having the same capacity or larger may be used because it retains charge longer. In this case, a study may reveal that charging the battery once a day is sufficient.
2) Modify the software routine for sampling the supply voltage by testing the digitized supply voltage before using it and then doing one of the following:
    a. If the digitized supply voltage is found to be less than the normal supply voltage, then don't change the calibration voltage from the previous value.
    b. If the digitized supply voltage is found to be less than the normal calibration voltage, then use some default supply voltage instead.
    c. If the digitized supply voltage is found to be less than the normal supply 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.

X. Test Results from Exponent Report

This section summarizes the results of a report by Exponent entitled "*Analysis of Toyota ETCS-i System Hardware and Software*", published in 2012.

The report examined the ETCS-i system hardware from a 2002 V6 Camry and a 2007 V6 Camry. It measured the transfer functions of the APP sensors and either analyzed or measured the limiting conditions for the DC operation of the following subsystems: accelerator pedal and APP sensors, processors (main processor and sub-processor), throttle motor driver, throttle body (including the throttle motor, and throttle position (TPS) sensors), A/D converter, power supply, wiring and connectors. It tested the sensors operating with the ECU only while at idle. These tests essentially considered only stuck-at faults. The report did not supply a circuit diagram for any ECU circuitry, did not hypothesize any cause for sudden acceleration, and ultimately concluded that all the electronics worked as designed with no cause of sudden acceleration being found.

The following paragraphs discuss some of the report's findings, along with some comments by this author regarding these findings.

Figures 3 to 11 in the report explain how the study was divided into hardware faults, software faults, and system level faults, and gives details of how these faults would be searched for. Figure 12 summarizes the search strategy for the entire investigation. Yet, if one reviews Exponent's search strategy described in these figures while having in mind this author's explanation of sudden acceleration as provided in Sections I through V of this paper, one is challenged to find which test or analysis in Exponent's study would have discovered the author's proposed cause of sudden acceleration. For example, the author's proposed cause of sudden acceleration does not require any hardware faults during the sudden acceleration. It states that the hardware works as intended at all times; before, during, and after the sudden acceleration. Therefore, none of Exponent's proposed or actual hardware tests would have discovered this cause of sudden acceleration. A similar case can be made for Exponent's software tests, because this author's proposed cause of sudden acceleration does not require any software faults during the sudden acceleration. It states that the software works as intended at all times; before, during, and after the sudden acceleration. The only thing that changes in the author's proposed cause of sudden acceleration is the <u>value</u> of the sensor supply voltage at the time it is digitized by an ADC and stored in memory. This value is changed because of a transient voltage dip on the 12V supply bus that causes the digitized supply voltage to be lower than normal. When all the subsequent APP sensor outputs are digitized and compensated to remove their dependence on the supply voltage, this lower value of the supply voltage causes the APP sensor outputs to increase in the same way that would happen if the driver stepped on the accelerator pedal.

So, it is a change in the <u>data</u> that causes sudden acceleration by the author's proposed cause of sudden acceleration, and not a hardware fault or software fault. So, if one includes guaranteeing the integrity of the data as part of software design, then one might consider a change in the data to be a software fault. However, this fault is only one of omission to guarantee the integrity of the data, and not one of commission that constitutes an error in the software. Therefore, this changes what one looks for in the software tests. The closest tests that Exponent proposed that could have found this fault of omission are the following:

a) Line-by-line source code review to trace signals from the pedal to the throttle angle,
b) Flow analysis to study information flow and throttle motor control system, and
c) Analysis of bounds applied by software on various inputs.

It appears that these tests were not done in sufficient detail to discover the author's proposed cause of sudden acceleration.

Now, since a change in the data is caused by a transient voltage dip on the 12V supply line, one might expect that a proper hardware test might have discovered the author's proposed cause of sudden acceleration. The closest tests that Exponent proposed that could have found this hardware operation are the following tests that might simulate a transient voltage dip on the 12V supply line:

a) Bulk current EMI testing, and
b) Chatterbox testing.

Because the vehicle is susceptible to a transient voltage dip only while the ADC is sampling the 12V supply or the 5V supply, these two tests would be successful only if repeated enough times to allow a random coincidence of the ADC sample with the transient test pulse. It appears that these tests were not done a sufficient number of times to discover the author's proposed cause of sudden acceleration.

Exponent's test results obtained from these two EMI tests are given in their report entitled "*Evaluation of the Effects of Electromagnetic Fields On the Behavior of Electronic Throttle*

Control Technology Used in Toyota Vehicles", dated September 2012.[34] Table 9 of their report shows the tests that they planned to run:

Table 9. Tested wires and vehicles[25]

	Pedal to ECU Harness	TPS signal VTA	APP signal 1 VPA	APP signal 2 VPA2	5V supply VCPA	5V Supply GND EPA
2002 Camry	X	X	X	X		X
2004 Camry	X	X	X	X	X	X
2005 Camry		X	X			X
2007 Camry [a]	X	X	X (Denso) X (CTS)	X (Denso) X (CTS)	X (Denso) X (CTS)	X (Denso) X (CTS)
2007 ES350	X	X	X	X	X	X

[a] RF tests for pedal signals on the 2007 Camry were performed using both Denso and CTS pedals. The remaining tests were performed with the make of pedal originally installed in the vehicle.

Table 9b summarizes the results of their bulk current EMI testing in the same format as Table 9. It shows that some injected RF currents produced RPM increases as high as 1500 RPM when injected into the 5V supply rail. And in one case, an RPM increase up to 6000 RPM was obtained when RF currents were injected into the 5V ground line. But Exponent discounted these increases because they were not permanent and because the driver could reduce the RPM's by lifting his foot off the accelerator pedal.

Table 9b. RF inductive injection tests in PARK at idle

	Pedal to ECU Harness	TPS signal VTA		APP signal 1 VPA	APP signal 2 VPA2	5V supply VCPA	5V Supply GND EPA
2002 Camry	-----------	Burned TPS trace		No malfunction observed	No malfunction observed	-----------	700 RPM
2004 Camry	+200 RPM	+400 RPM		200 RPM	200 RPM	500 RPM	6000 RPM
2005 Camry	-----------	DTC		DTC	-----------	-----------	Burned APP trace
2007 Camry	+500 RPM	+500 RPM	Denso	No malfunction observed	1000 RPM	+500 RPM	+500 RPM
			CTS	No malfunction observed	1800 RPM	+1500 RPM	+1500 RPM
2007 ES350	No malfunction observed	No malfunction observed	Denso	1000 RPM	1400 RPM	1400 RPM	No malfunction observed

Table 10 summarizes the results of their chatterbox testing in the same format as Table 9. Exponent notes that none of the conducted disturbance tests resulted in a significant engine RPM increase or setting of a DTC code. The vehicle either continued to function normally during and after the test, or the engine shut off immediately in response to the applied disturbances. The conducted disturbance testing did not identify any realistic EM exposure that would result in substantial, un-commanded increases in throttle position or engine speed.

Table 10. Chatterbox disturbance tests in PARK at idle

	Coupled disturbance						Conducted disturbance
	TPS signals VTA/VTA2	+5V VCTA	GND ETA	APP signals VPA/VPA2	+5V VCPA	GND EPA	+12V +B supply
2002 Camry	----	-------	------	----	----	----	None of the conducted disturbance tests resulted in a significant engine RPM increase or setting of a DTC code. The vehicle either continued to function normally during and after the test, or the engine shut off immediately in response to the applied disturbances. The conducted disturbance testing did not identify any realistic EM exposure that would result in substantial, uncommanded increases in throttle position or engine speed.
2004 Camry	No	A2-2	A2-2	No	No	No	
2005 Camry	No	A2-2	A2-2	No	No	No	
2007 Camry	No	A2-2	A2-2	No	No	No	
2009 Camry	No	A2-2	A2-2	No	No	A2-2	
2006 IS350	No	A2-2	A2-2	No	No	No	

No means not sensitive to A2-1 and A2-2 pulses.
A2-2 means sensitive only to A2-2 pulse with <600 RPM increase.

It is interesting that Exponent never used the standard EMI tests described in ISO standard 16750, which was available since 2003. This standard has a test pulse for testing vehicle susceptibility to upset during cold cranking/starting (test pulse 2), that nearly perfectly mimics the upsets caused by transient voltage dips. This standard was even updated in 2010 to give better pulse parameters, along with a method of creating the pulses. If Exponent had used this standard, instead of Chatterbox testing, they might have found a cause of sudden acceleration in Toyota vehicles if they tested long enough.

Finally, one might expect that if a change in the APP sensor data is caused by a transient voltage dip on the 12V supply line, resulting in a potential sudden acceleration, then this would be detected by the three system guards discussed in Exponent's report starting on page 223. However, this is not true because the change in the APP sensor data caused by this author's proposed mechanism is indistinguishable from a change in the sensor data caused by the driver stepping on the accelerator pedal. Therefore, if the three system guards allow the driver to accelerate the vehicle without stopping him, then these same system guards will allow the APP sensor changes caused by a transient voltage dip to accelerate the vehicle as proposed by this author.

In summary, Exponent's two reports describe a plethora of hardware, software, system, and EMI tests and analyses on five or more models of Toyota vehicles that required over a dozen researchers full time for up to a year or more, and costing several millions of dollars for vehicles, parts, test facilities, and manpower. Yet, Exponent found no defect in Toyota electronics and software that could be responsible for causing unintended acceleration in Toyota and Lexus vehicles. They concluded that Toyota's robust network of safety features and overall system design will trigger failsafe responses that would prevent any such occurrence. Exponent also found no real world conditions where EMI could result in substantial, un-commanded increases in throttle position or engine speed.

This Exponent study provided a thorough assessment of Toyota vehicle operation independent of the studies done by NASA/NHTSA, yet achieved the same results. It is interesting, however, that a later study of Toyota's software done by Barr and his associates were able to find a cause of sudden acceleration in the Toyota software that the Exponent study and the NASA/NHTSA study did not. This paper attempts to repeat Barr's success by investigating the ETC hardware and its susceptibility to voltage dips instead of the software.

Here are a few additional comments on the Exponent report that may be of interest.

On page 125, the report states the following for a 2002 V6 Camry tested at idle:
"The supply voltage for the circuit generating the VTA1 and VTA2 drops due to a series resistance fault. Since the potentiometer sensors are ratiometric, a drop in the supply voltage to

the sensors results in a drop in VTA1 and VTA2. The algorithm in the ECM compensates by opening the throttle further. This was observed during testing."
Comment: This finding confirms that the potentiometer type throttle position sensors (TPS sensors) are ratiometric, and that the ADC circuitry eliminates changes in the TPS outputs caused by changes in the 5V supply voltage by multiplying the TPS outputs by the inverse of the TPS supply voltage.

On page 126, the report states the following for a 2007 V6 Camry tested at idle:
"The supply voltage for the circuit generating the VTA1 and VTA2 drops due to a series resistance fault. Since the Hall Effect sensors are ratiometric, a drop in the supply voltage to the sensors results in a drop in VTA1 and VTA2. The algorithm in the ECM compensates by opening the throttle further. This was observed during testing. The engine RPM when the vehicle was at idle rose"
Comment: This finding confirms that the Hall effect type throttle position sensors (TPS sensors) are ratiometric, and that the ADC circuitry eliminates changes in the TPS outputs caused by changes in the 5V supply voltage by multiplying the TPS outputs by the inverse of the TPS supply voltage.

On page 150, the report states:
"6.6.3.3 Under-Voltage
A low voltage output may result due to an output overload condition (section 6.6.3.1), or a failure of the power supply IC. Testing performed on a 2009 V6 Camry to simulate an output under-voltage indicated that the vehicle continued to work as normal until the power supply output voltage dropped to approximately 3.5V, at which point the vehicle's engine shut down. In addition, because the Hall Effect sensors in both the accelerator pedal and the throttle assembly are powered by the main +5Vdc power supply and are ratiometric, no increase in vehicle RPM occurs (either when the vehicle is at idle or being driven) as the power supply voltage drops from +5V to +3.5V."
Comment: This paragraph confirms that the ratiometric Hall effect APP sensor outputs remain unaffected by changes in the 5V power supply as discussed earlier in this paper. Operation of the 5V supply is as expected for a PMIC chip available today. But we don't know if the 2009 V6 Camry used a PMIC chip or if its power supply design was the same as for the 2002 V6 Camry and the 2007 V6 Camry tested elsewhere. There must be some difference between the power supply designs in these three vehicles, or they would not have selected a later model vehicle for this test. Nevertheless, this under-voltage operation says nothing related to the cause of sudden acceleration.

On page 170, the report states:
"6.8 Analog to Digital Converter
The A/D converter is located on the sub-processor ASIC. The A/D converter is a ♦–bit converter that digitizes signals from both the throttle and the [accelerator] pedal, in addition to signals from other sensors. The A/D converter communicates with the serial communications block on the ASIC, which interfaces with the main processor.
The A/D converter module is composed of a digital control block and an analog control block and includes a multiplexer to selectively switch the sensor signals to the input of the A/D converter. The A/D conversion is performed sequentially using a pre-set priority system.
The converter is powered by the same regulated +5Vdc (Vc) power supply that supplies DC power to the main and sub processors, the sensors on both the pedal and the throttle body, and a number of other sensors (MAF sensor, IAT sensor, oxygen sensor, etc.) in the vehicle.

> 86. A momentary failure of the A/D converter that affects the operation of the A/D converter for a short period of time is not expected to have an effect on the operation of the vehicle. This is because the A/D converter digitizes critical signals such as the pedal position signal (VPA1 and VPA2) and the throttle position signals (VTA1 and VTA2) every ♦ ms. (VTA1 is converted every ♦ ms). The vehicle's engine will not respond to a momentary failure of the A/D converter that results in erroneous digitization of these signals for a few cycles (i.e., for tens of ms). This section

discusses the possible consequences of abnormal operation of the A/D converter that is sustained for several seconds.

<u>Comment</u>: Footnote 86 essentially says that the engine will keep running even when erroneous signals are provided to it for several cycles (i.e., a few tens of milliseconds). This means for two or three consecutive powertrain control samples at around 10 milliseconds per sample. This may provide an answer to why the engine keeps running when the outputs of multiple sensors are degraded by a loss of a 5V power supply if we suppose the loss of the power supply lasts only a few tens of milliseconds.

On page 172, the report states:
“Variations (such as drifts or fluctuations) in the A/D reference voltage will not result in UA.
-- A change in the +5 Vdc signal used by the A/D converter as a reference voltage will also affect the pedal and throttle position signals by the same proportion. Consequently, the A/D converter output will accurately reflect the signals from both the pedal and the throttle.
-- If the variation results in a permanent failure of the A/D converter, the engine will shut down.
-- A fault in the A/D converter which affects the conversion of all input signals can result in an erroneous conversion (e.g., raising all signals by a fixed amount). This fault will also result in a similarly erroneous conversion for all other input signals (e.g., VPA2, VTA2, MAF sensor signal, oxygen sensor, etc.) Numerous scenarios are possible in this condition: These include …”
<u>Comment</u>: The last dashed remark comes very close to finding a cause for sudden acceleration. But the Exponent report appears to be focussed on finding a stuck-at fault in the hardware that causes a DC shift in the signal levels, and not on a temporary change in the reference voltage that could cause a gain change in the signal levels.

XI. Test Results from Zhang Paper

This section summarizes the results of a paper by Dexin Zhang and Todd H. Hubing, entitled "*Comparison of the Accelerator-Pedal-to-Engine-Control-Module Interfaces on Vehicles With Low and High Reported Rates of Unintended Acceleration*," published in *IEEE Access*, vol. 3, pp. 852-863, 2015. This paper is obtainable from:
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7124409.

The paper gives the results of applying power dips to the supply circuitry in ECU’s from four different automobiles having varying rates of sudden acceleration incidents. The ECMs and the throttle bodies were identical to the parts found on the investigated vehicles. A power supply functioned as the vehicle battery. The input signals from the APP sensors to the ECM were simulated using two or three analog output ports of a DAQ controlled by LabVIEW software. Figure 43 shows the power supplies tested on each automobile; namely, the 12V supply to the ECU (VB), the 5V supply to the CPU (VC), the 5V supplies to the two APP sensors (VS1 & VS2), and the 5V supply to the memory (VM).

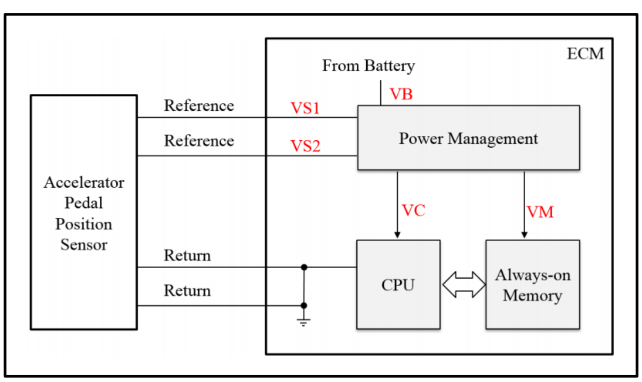


Fig. 43. Power supplies of the AP-to-ECM diagnostic interface.

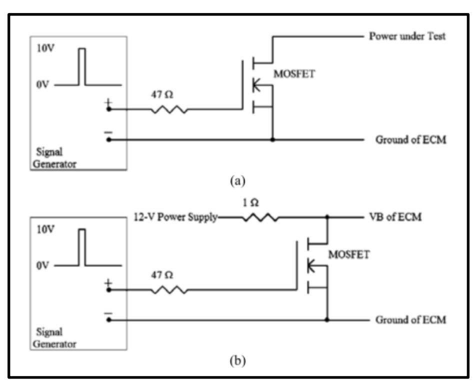


Fig. 44. Power dip test circuits. (a) Power dip test circuit for VC (5V supply to CPU), VS1 & VS2 (5V supplies to APP sensors), and VM (5V

supply to memory). (b) Power dip test circuit for VB (12V supply to ECU).

Figure 44 shows the test circuits that generated the power dips. These circuits are essentially switches that connect the output of the power supply directly to ground, causing the voltage to drop from its nominal value to a very small value during the presence of the dip. The duration of the power dips was 20 µs and 120 µs for one vehicle, and 50 µs for the other three vehicles.

Figure 45 shows the methodology for the Type I tests that applied power dips to the five supplies. The Type I tests started by erasing all DTC's in memory and then performed an engine on/off cycle in which a throttle learning step was performed using the foot-off values of the APP signals. This was followed by a second engine on/off cycle in which the power was applied to the CPU and the APP sensors, the APP signals were set to the given test point, and the application of the accelerator pedal was simulated. Power dips to the five supply outputs were then applied, after which the throttle position signals and APP-related DTC's were recorded. Finally, the power to the CPU and the APP sensors was turned off and the data was logged. Type II and Type III tests will not be discussed here because they did not include any power dip tests.

Fig 45. Methodology used for varying the APP sensor signals and for applying power dips to the supplies.

Figure 46 shows how the data was plotted. The results of each test were plotted on a diagnostic map having the values of the two APP signals as the coordinates. At each point on the map a symbol was placed to indicate whether DTC's were created or a WOT value was obtained. The points where no DTC's were found were shown by a green symbol, and the green areas were designated as operational lanes. The widths of these operational lanes were then placed into a table along with the WOT test results to compare these values for all vehicles tested. Table 11 shows this table of operational lane widths and WOT test results.

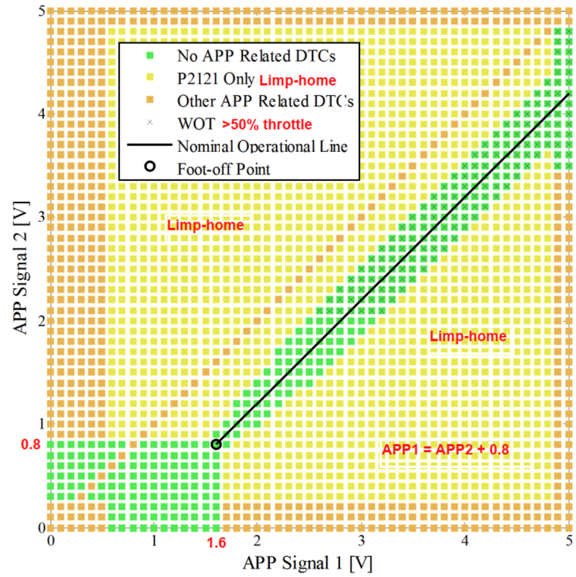


Fig. 46. Diagnostic map for a 2005 Camry. Width of operational lane is the width of the green area. This is a Type 1 map in which the APP signals were changed while power was on.

Table 11. Summary of results showing widths of operational lanes and WOT caused by power dips

Diagnostic map	APP Signal	2005 Camry 4.31 UA complaints per 10,000 vehicles	2005 Mustang 1.30 UA's per 10,000	2008 Sierra 0.06 UA's per 10,000	2001 Jetta 0.21 UA's per 10,000
Type I APPs changed pwr ON	1	0.7 V	0.4 V	0.5 V max.	0.7 V
	2			0.2 V to 0.3 V max.	0.3 V to 0.4 V
Type II APPs changed pwr OFF	1	1.6 V	0.4 V	0.5 V max.	0.7 V
	2			0.2 V to 0.3 V Max.	0.3 V to 0.4 V
Type III APPs changed pwr ON	1	1.6 V	0.4 V	0.5 V	0.7 V
	2			0.2 V to 0.3 V	0.3 V to 0.4 V
Power dip on VC 5V to CPU	1	0.7 V w/o DTC and 1.6 V w. WOT	0.4 V	0.5 V Max.	0.7 V
	2	20 & 120 µs	50 µs	0.2 V to 0.3 V Max.	0.3 V to 0.4 V
Power dip on VS1 5V to APP1	1	VS1 = VS2 = VC -	VS1 = VS2 ≠ VC 0.4 V	VS1 ≠ VS2 ≠ VC 0.5 V max.	VS1 ≠ VS2 ≠ VC 0.7 V
	2		50 µs	50 µs 0.2 V to 0.3 V Max.	50 µs 0.3 V to 0.4 V
Power dip on VS2 5V to APP2	1	VS1 = VS2 = VC -	VS1 = VS2 ≠ VC -	VS1 ≠ VS2 ≠ VC 0.5 V max.	VS1 ≠ VS2 ≠ VC 0.7 V
	2			0.2 V to 0.3 V Max.	0.3 V to 0.4 V
Power dip on VM 5V to Memory	1	0.7 V w/o DTC and 1.6 V w. WOT (20-µsec); 1.6 V (120-µsec)	0.4 V	0.5 V max.	0.7 V
	2	20 & 120 µs	50 µs	50 µs 0.2 V to 0.3 V Max.	50 µs 0.3 V to 0.4 V
Power dip on VB 12V to ECU	1	0.7 V w/o DTC and 1.6 V w. WOT	0.4 V	0.5 V max.	0.7 V
	2	13.2 ms	15 ms	15 ms 0.2 V to 0.3 V Max.	15 ms 0.3 V to 0.4 V
Adaption to the foot-off position	1	0.7 V	0.3 V w/o DTC and 0.6 V w. WOT	0.5 V	0.7 V
	2			0.2 V to 0.3 V	0.3 V to 0.4 V

Table 11 shows the widths of operational lanes for all vehicles. The shaded boxes show conditions where WOT was found during power dip tests. WOT in these tests was considered to be a throttle opening greater than 50%, as indicated by the throttle position sensor.

For the 2005 Camry, WOT was found for power dips of 20 µs and 120 µs on the VC = 5V CPU supply. These WOT events appeared in areas of the diagnostic map that did not have WOT events without voltage dip testing. The same results were found for power dips of 13.2 ms on the VB = 12V supply and for power dips of 20 µs on the VM = 5V memory supply. For power dips of 120 µs on the VM = 5V memory supply, the power dips caused WOT events in areas of the diagnostic map that did not have WOT events before, which widened the width of the operational lane. [This author, but not the original authors of this work, has noticed that the power dips on the VM = 5V memory supply also <u>removed WOT events</u> in areas of the diagnostic map <u>that did have WOT events before</u>. This may mean that the power dips on the memory supply flipped the original WOT values back to their non-WOT state, while flipping non-WOT values to WOT values. No DTC's were produced because the changes were made to the values in memory without causing the APP sensor values to change.]

For the 2005 Mustang, a 50-μsec power dip on the VM = 5V memory power supply sometimes generated more DTCs and disabled the throttle response. But it did not cause WOT. However, WOT did occur during the adaption to the foot-off position.

In summary:

1) The throttle on a 2005 Camry is capable of being opened widely with DTCs after power dips on the VB = 12V ECU supply, the VC = 5V CPU supply, and the VM = 5V memory supply. Significant variations of the operational areas of the diagnostic maps can be observed for the 2005 Camry.
2) In the 2005 Camry, it was possible to open the throttle even when DTC's that normally triggered a limp mode were set.
3) The vehicles from three other manufacturers had narrower operational lane widths and showed no sensitivity to power dips that could cause a wide open throttle.
4) The 2005 Camry with high rates of UA had a APP1 = APP2 + 0.8 relationship between the APP1 and APP2 sensor voltages. Vehicles from other manufacturers with lower reported rates of unintended acceleration employed a nominal 1:2 ratio between the APP1 and APP2 sensor voltages.

Conclusions of the present author:

1. WOT means >50% throttle.
2. On the 2005 Camry:
   a. WOT was created by pulling the VB = 12V ECU supply down with 13.2 ms dips
   b. WOT was created by pulling the VC = 5V CPU supply down with 20 us & 120 us dips
   c. WOT was created by pulling VM = 5V memory supply down with 20 us & 120 us dips
3. These conditions were enough to take the throttle into WOT out of the limp-home position.
4. These results for WOT may be explained by assuming that the battery voltage compensation of the APP sensors gets changed when a voltage dip occurs on the supply voltage VC = VS1 = VS2 = 5V while VC is being sampled by the ADC. The same explanation applies to the battery voltage VB = 12V while VB is being sampled by the ADC for use in compensating the PWM duty cycle of the throttle motor for changes in the 12V supply voltage.
5. Could not induce WOT in Ford, GM, or VW vehicles.
   a. This may be because GM samples the power supply voltage while the vehicle ignition is off.
   b. Ford and VW may sample the power supply voltage at a different time, like when the vehicle ignition is turned on but before starting.
   c. Toyota appears to sample the power supply voltage at startup and at regular intervals during operation.
6. On the 2005 Mustang, WOT was created by using a different foot-off position with APP1 = 1.3 V, APP2 = 1.1 V, and APP3 = 4.0 V

This paper by Zhang and Hubing clearly shows that power dips on the 12V and 5V supply lines can cause a wide open throttle in the 2005 Camry, which had over 186 complaints to NHTSA alleging unintended acceleration between 2005 and 2015. This work supports the explanations proposed by this author that sudden acceleration is caused by voltage dips on the 12V and 5V supply lines produced by the inrush currents of electric motors turning that lower the supply voltage reading obtained when a voltage dip occurs during ADC sampling. When this incorrect voltage reading is used to compensate either the APP sensor signals or the PWM duty cycle of the throttle motor, it raises the values of the APP sensor signals or the duty cycle of the throttle motor, causing them to be higher than normal. This produces sudden acceleration without the driver pressing on the accelerator pedal.

XII. Test Results from ChipShouter EMP Tester

This section summarizes the findings of Mr. Colin O'Flynn, EMP researcher and creator of several small EMP test units, who used his latest PicoEMP tester called the ChipShouter to test the electronic throttle system of a 2005 Toyota Corolla. His findings were published in the following two papers:

1. "*Finding a $Billion Dollar Fault Mode*" by Colin O'Flynn, 2021. https://circuitcellar.com/research-design-hub/design-solutions/finding-a-billion-dollar-fault-mode/ , and
2. "*EMFI for Safety-Critical Testing of Automotive Systems*" by Colin O'Flynn, 2021, https://www.researchgate.net/publication/355238790.

The following figures and text are extracted from these papers, with the text in Mr. O'Flynn's original words. Text in brackets has been added by this author.

I found a locally wrecked 2005 Toyota Corolla, which allowed me to remove the ECU and related devices (throttle body, pedal sensor and so forth). This ECU uses a different architecture than the one used in a law suit against Toyota. The ECU I purchased and tested has an NXP MPC565 based main microcontroller (MCU) with a PowerPC architecture.

Figure 47. A photo of the main ECU from a 2005 Toyota Corolla. The large BGA on the upper right is a Freescale (NXP) MPC565. A secondary Microchip device in TQFP package to the upper left of that BGA is assumed to be a PIC device [Peripheral Interface Controller, later called a Programmable Intelligent Computer], but a custom part number does not lend itself to a specific cross reference.

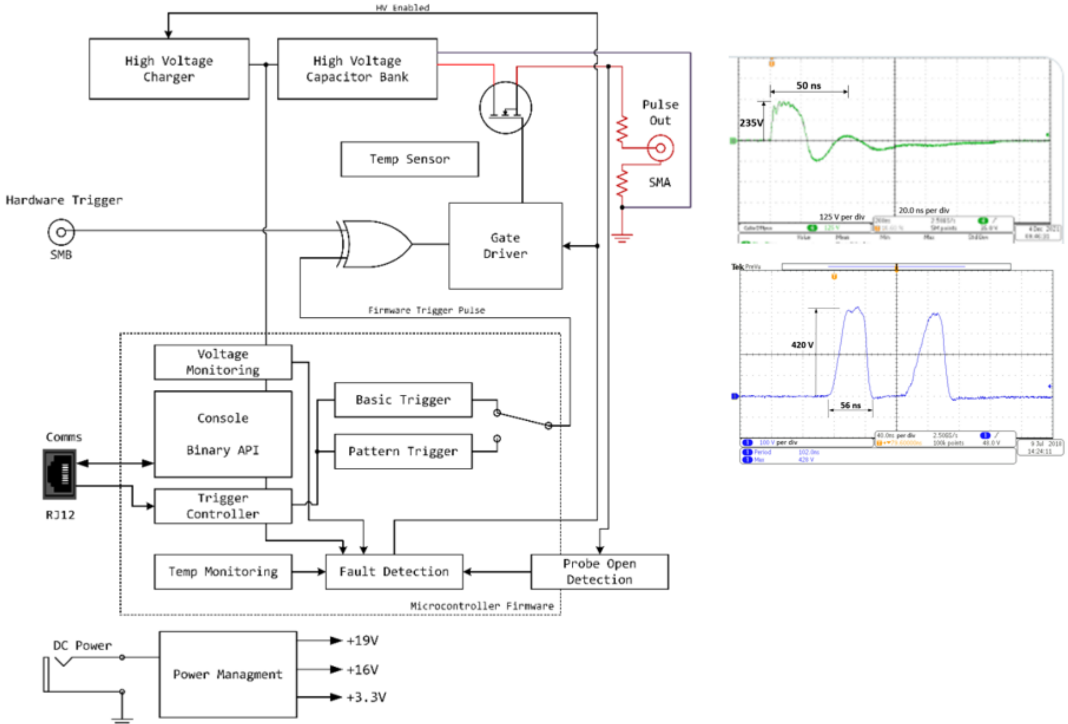


Figure 48. The ChipShouter PicoEMP unit can provide programmable EMP pulses [of 100V to 500V for times of 10 to 100 ns.]

[Electromagnetic fault injection (EMFI) is performed by generating a localized short-duration high-intensity electromagnetic pulse that induces currents within the internal chip circuitry. ChipShouter uses EMFI glitching, and not voltage glitching, which is done by direct injection of short and fast voltage pulses into the chip supply lines.]

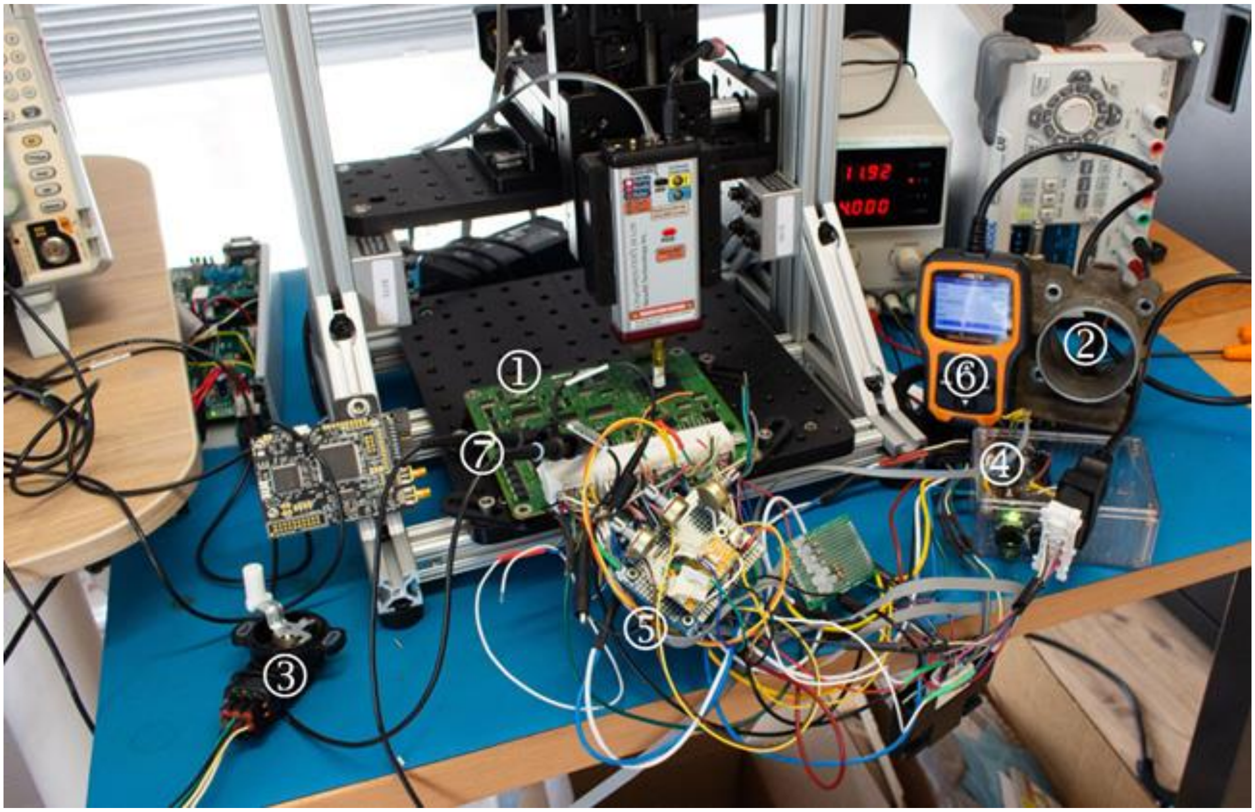


Figure 49. This test bench enables me to use the ECU with a physical throttle body and acceleration pedal sensor, with several other sensors “faked out” to try and keep the ECU operating somewhat normally. A standard automotive diagnostic tool (6) is used to confirm operation. Shown here: (1) the main ECU, (2) throttle body, (3) accelerator pedal sensor, (4) ignition switch and start button, (5) simulator to generate the CAM and crank signals, which the ECU expects during the engine operation, (6) OBD-II reader which can be used to read data from the ECU and confirm overall operation and (7) oscilloscope to monitor drive signals.

After a single [induced EMI] injection at one location, I noticed that the throttle motor suddenly became noisier. You can see the normal PWM drive signal (pre-fault injection) in Figure 50, and compare this to the PWM drive signal (post-fault injection) in Figure 51, and you can see that there is a drastic change in the drive waveforms. The incorrect drive waveforms caused an increase in current draw. The [current] draw becomes erratic but spikes beyond 5A and averages around 3.5A, whereas when operating normally, the system averaged at 1.5A. The control loop is still controlling the throttle, such that it follows the expected value. It simply appears to be “struggling” to control it now.

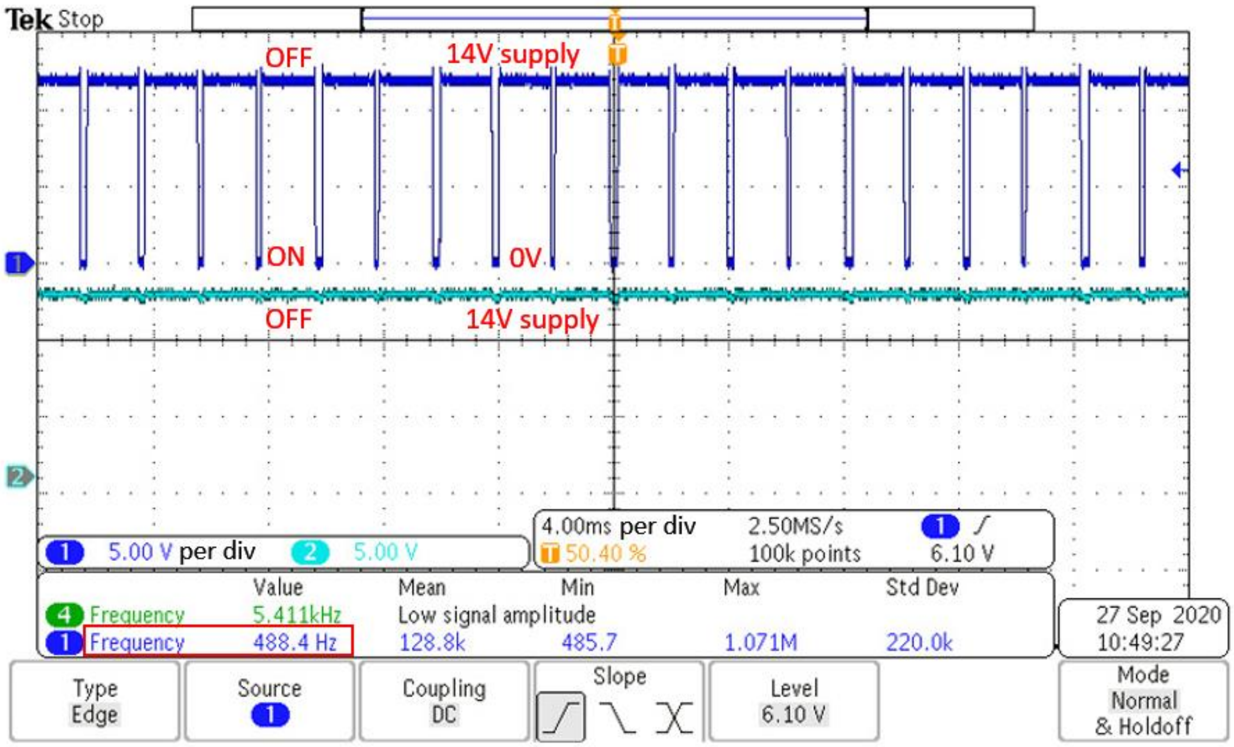


Figure 50. The two throttle body motor wires show a PWM signal operating normally, where one signal is pulsing low at a constant duty cycle, and the other signal is a constant high value. [This is normal operation with motor rotation in one direction at a low duty cycle.]

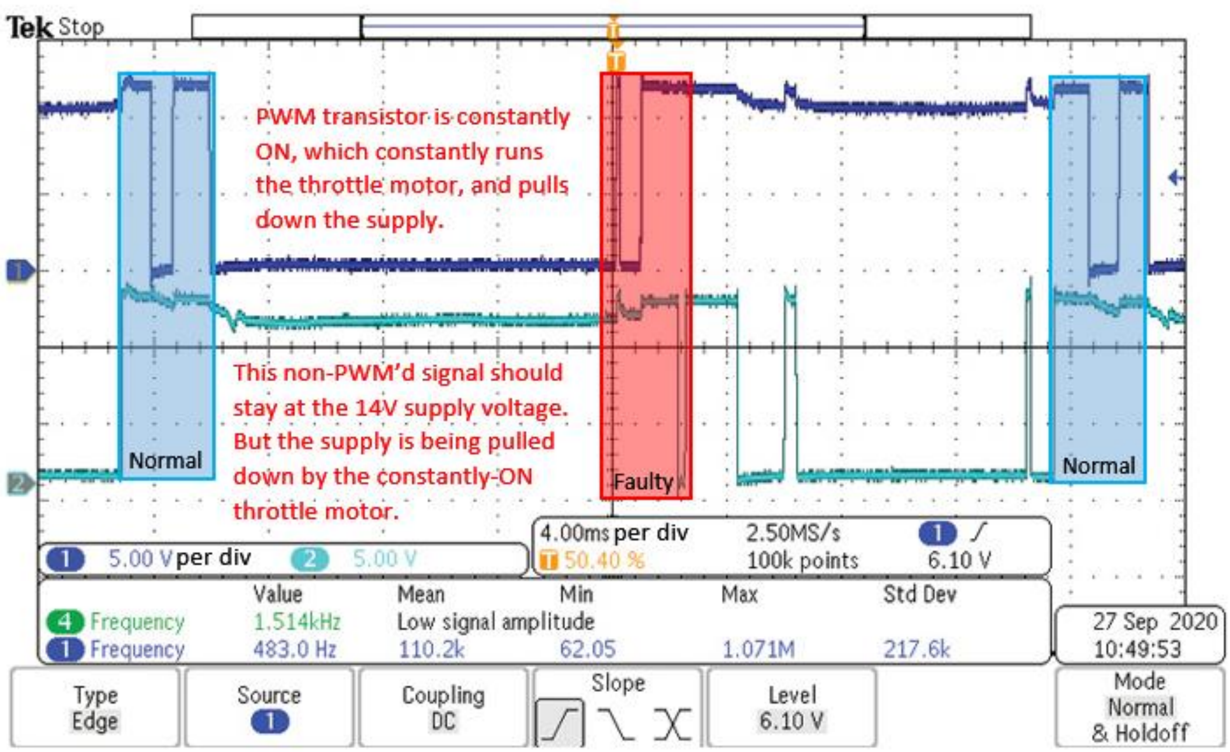


Figure 51. Chattery operation. The same throttle body motor wires are used as in Figure 4, but under erratic operation after fault, where the waveform does not match an expected square wave used in PWM.

[There is a lot happening in Figure 51:

1) The PWM waveforms show the motor first running in a forward direction at a higher duty cycle than in Figure 50, then the direction of the motor rotation changing with the motor running at a lower duty cycle than in Figure 50.
2) The PWM waveforms show the PWM transistor initially operating at a low duty cycle in each direction, followed by the PWM transistor stopping its ON/OFF action and staying ON, either due to some control failure or due to the duty cycle going to 100%. When the PWM pulses stay ON, the current through the motor increases, which pulls down the 12V power supply by about 2 volts as shown on the other trace.
3) The oscilloscope traces show that the PWM frequency changes from 488.4Hz during normal operation to 483.0 Hz during erratic operation. This may have something to do with changing the generation and synchronization of the PWM pulses.

Now, it would be helpful to know which of these conditions is included in the term "erratic operation". This is because condition 1) above might be the normal result of the experimenter pressing the accelerator pedal to create a throttle opening above idle, followed by the experimenter suddenly releasing the accelerator pedal, with the oscilloscope catching one PWM period with an increased duty cycle before releasing the accelerator pedal and a second PWM period with a decreased duty cycle after releasing the accelerator pedal. In this case, it is normal for the motor controller to drive the motor downward after the accelerator pedal is released; ie, to drive the motor in the return direction rather than turning the motor off and letting the spring return the motor to its idle state.
Therefore, if condition 1) is caused by the experimenter, the remaining two conditions become less complicated, which might allow someone to figure out how they originate. If condition 1) is not caused by the experimenter, then explaining all the changes gets very complicated.]

Interestingly, this erratic mode remains a problem after turning the ignition off and on again. As the car maintains some power to the ECU, even when the ignition is switched off normally, it is assumed some calibration or similar variable has been corrupted. It also could be a register which is not initialized within the MCU, except on a full reset or power cycle (such as a PWM control register). I found that only a total power cycle (removing all power from the ECU) caused the system to return to normal operation.

The final objective is to find a situation where the throttle appears to stick open. This erratic mode appeared to be the gateway. After some time in this mode (normally about 30 seconds to 2 minutes), the throttle body did jam either fully open or fully closed. The problem seems to be accelerated by reducing the current limit of the power supply, causing the voltage to dip during the current spikes. [These current spikes and voltage dips on the 12V supply are not being generated by the continual application of EMP pulses. Only one EMP pulse started the erratic operation, after which a long-duration voltage dip was produced by manually limiting the 12V supply current]. This instance of the voltage dip having an effect on the throttle matches the work published in 2016 on the topic by Park et al [6]. In this previous research, the throttle changes were not permanent (only changing during the voltage dips). But in my work here it appears to stick fully open—more closely matching some of the claims from consumers.

Once the throttle is stuck (open in this case), the ECU will continue to communicate with my ODB-II tool, and appears to be controlling the spark igniters in response to my simulated crank and cam signals. Adjusting the [APP] signal input creates a corresponding change in the igniter signals for example. Using the ODB-II tool, I can confirm that the throttle position is commanded to be fully open [during these changes], as in Figure 52. Note that the set TPS position of 88% is above the "allowed" regular operating range that is reached with the accelerator pedal. The throttle seems to remain in this state until the ignition is switched off. I only waited a few minutes before shutting off system power, but the fault does not clear within a few seconds as it should if the watchdog or similar kicked in.

Figure 52 – Wide Open Throttle and ODB-II reader showing that the throttle is commanded to 88%. The motor is being actively driven with a constant "on" voltage (no PWM operation is observed). [This constant "on" voltage may be just a 100% PWM duty cycle].

While the throttle body appeared to be maintaining the requested position, the throttle body now had a noticeable "chatter". In addition, the power consumption jumped from the normal 1.6A to 3 – 5A (the current draw became less constant). This sudden jump in current consumption results in additional voltage drops on the ECU power rail, which also aligns with the previous work demonstrating wide open throttle condition during voltage fluctuations.

1) Stuck Throttle Results: Once in the incorrect PWM mode, the throttle would eventually stick either fully closed or fully open, and the accelerator pedal sensor changes no longer have any impact on the throttle position. In this case the current draw increased further, and viewing the PWM waveforms it was clear the output signal was now constant. Once this mode was entered, a power cycle was required to exit this mode.

While in this mode, the ECU continued to provide ignition output signals that responded to changes in the cam & crank signals, and the OBD-II scan tool could continue to provide diagnostics information. A photo of the throttle stuck open is shown in Figure 8. Note the throttle is shown commanded to 88% opening here. During regular operation, the maximum throttle opening on the test bench is only 81%, thus the 88% throttle position commanded here appears to be even beyond regular operating values.

Comments:

1. **Colin O'Flynn found: The throttle sticking was accelerated by reducing the current limit of the 12V power supply, causing the voltage to dip lower during the simulater current spike.**
   Belt's comment: The load in this case is the throttle motor. Reducing the current limit of the 12V supply essentially simulates a voltage dip on the 12V supply line similar to one created by an electric motor from an AC fan motor turning on while the battery is unable to supply the inrush current of the fan motor because it is depleted of charge by a reduced SOC. If the 12V supply voltage is sampled in this state by an ADC, then the digitized voltage value will be much lower than 12V. When this lower 12V supply voltage

voltage is used to compensate the PWM duty cycle to the throttle motor by multiplying it by the ratio $V_{12Vsupply}$(normal)/$V_{12Vsupply}$(low) = 12V/3V = 4, then the duty cycle will be multiplied by a factor of 4, which increases the voltage and current to the throttle motor by a factor of 4 above its normal values, which opens the throttle to full open.

2. **Colin O'Flynn found: Once the throttle is stuck open, it remains stuck open until the ignition is switched off and then on again.**
Belt's comment: This correlates with having the digitized 12V supply voltage stored in memory with its value remaining unchanged until a new sample of the 12V supply voltage is stored.

3. **Colin O'Flynn found: The throttle is commanded to 88% opening when stuck open. During regular operation, the maximum throttle opening on the test bench is only 81%, thus the 88% throttle position commanded here appears to be even beyond regular operating values.**
Belt's comment: An 88% throttle opening is beyond the normal throttle opening limit of 81% and cannot be explained by normal electronic throttle system operation in which the accelerator pedal is pressed instead of the brake pedal. This eliminates driver confusion as an explanation. In fact, it also eliminates this author's latest theory in which the digitized APP sensor output increases because it is compensated by an incorrect 5V supply voltage. However, it may be explained by this author's previous theory of sudden acceleration discussed in Section VI of this paper. The only way the throttle opening can be increased above its normal limit is by increasing the throttle motor PWM duty cycle to correct the voltage and current to the throttle motor in response to changes in the supply voltage. If the 12V supply voltage is sampled by an ADC during a voltage dip, then the digitized voltage value will be much lower than 12V. When this lower 12V supply voltage is used to compensate the PWM duty cycle to the throttle motor by multiplying it by the ratio $V_{12Vsupply}$(normal)/$V_{12Vsupply}$(low) = 12V/3V = 4, then the duty cycle will be multiplied by a factor of 4, which increases the voltage and current to the throttle motor by a factor of 4 above its normal values, which opens the throttle to full open.

4. **Colin O'Flynn speculates that a wide open throttle is caused by memory corruption induced by voltage drops on the ECU 12V power rail.**
Belt's comment: I agree that voltage drops on the ECU 12V supply voltage can induce a wide open throttle. But I don't believe that memory corruption is needed to cause a wide open throttle. My papers have discussed how a wide open throttle can be caused by a voltage dip occurring on the ECU 12V power rail while the ADC is sampling the voltage of the power rail, which causes an incorrect power rail voltage to be stored that produces a wide open throttle condition when this incorrect rail voltage is used later to compensate the duty cycle for battery voltage variation. So, Mr. O'Flynn and I agree that somehow a value stored in memory gets corrupted to cause a wide open throttle. The difference is that Mr. O'Flynn believes that memory corruption is the cause of the signal change, but does not identify which signal gets corrupted in memory. However, I believe that an incorrect value of the signal is created before it is stored in memory without later corruption of the memory value after it has been stored. And I believe that this signal is the 12V supply voltage. So while memory corruption may be possible, it may not be needed.

In summary, these two papers by Colin O'Flynn clearly show that the throttle of a 2005 Toyota Corolla can be opened to a wide open throttle condition by a combination of an EMP pulse followed by a voltage drop on the ECU power rail. The throttle remains open in this condition after the EMP pulse and the voltage drop are removed. This work supports the explanation proposed by this author that sudden acceleration is caused by a voltage dip on the 12V supply rail produced by the inrush current of an electric motor turning that lowers the supply voltage reading obtained when a voltage dip occurs during ADC sampling. When this incorrect voltage reading is used to compensate the PWM duty cycle of the throttle motor, it raises the value of the duty cycle of the throttle motor, causing it to be higher than normal. This produces sudden acceleration without the driver pressing on the accelerator pedal.

XIII. Loss of Braking During SUA

This paper will not address the loss of braking during sudden acceleration because the paper is already getting too long. However, a loss of braking during SUA can be explained not by a loss of the mechanical brakes, but by the loss of braking assist, which makes it harder for the driver to apply the brakes. In some cases, the loss of braking assist increases the pedal force needed on the brake pedal above the maximum of 112 lbs required by government regulations, which already exceeds the force that 18% of the female population can provide. In some cases, the required pedal force can approach 170 lbs without braking assist.

With vehicles having electronic brake assist, the loss of brake assist can happen because of a voltage dip on the 12V supply line, which may be the same voltage dip that causes sudden acceleration. This is because the brake assist unit contains a voltage monitor that can turn off the braking system's electric assist motor when the supply voltage drops lower than some voltage that can cause reduced operation, such as 9V. With vehicles having pneumatic brake assist, the loss of brake assist can happen because of a loss of manifold pressure as a result of pulsing the brakes too often. This has been shown to cause pedal forces that exceed 170 lbs.

XIV. A Way to Verify New SUA Mechanism

One way to prove that sudden acceleration is caused by the vehicle and not by the driver is to have a video camera watch the driver's feet to see if he steps on the accelerator pedal instead of the brake pedal. Then, if the EDR data shows that the accelerator pedal was pressed during an incident, the video recording can be used to clarify whether the driver caused the accelerator pedal to be pressed or whether the vehicle caused the accelerator pedal reading to increase while the driver did not press the accelerator pedal. Video cameras of this type have been installed in many vehicles in Korea. But their installation is difficult as a result of the lighting conditions, and the cost is high because of the installation costs.

A better way to prove that sudden acceleration is caused by the vehicle and not by the driver is to periodically monitor the analog outputs of the accelerator pedal position (APP) sensor using a battery-powered analog-to-digital converter with a rotating digital memory that can hold several day's worth of ADC readings. This can be done without changing the analog APP sensor outputs that the vehicle's ADC uses, and the monitoring ADC can use a different voltage reference that the vehicle uses while not correcting its ADC outputs for changes in the APP sensor supply voltage. This battery-operated monitoring ADC and memory can be installed in a vehicle by the vehicle owner by merely unplugging the accelerator pedal connector and inserting the unit in between the two vehicle connectors by mating them to the connectors provided with the monitoring unit. A monitoring unit that can provide the necessary functions is obtainable for less than $70 from Novus Automation (See Fig. 53). When the cost of the two additional connectors is included, the total cost can be less than $100. This unit is less expensive than a video camera with memory. It is also easily installed by the vehicle owner and can survive wider temperature extremes than a video camera, as well as being less sensitive to changing light conditions.

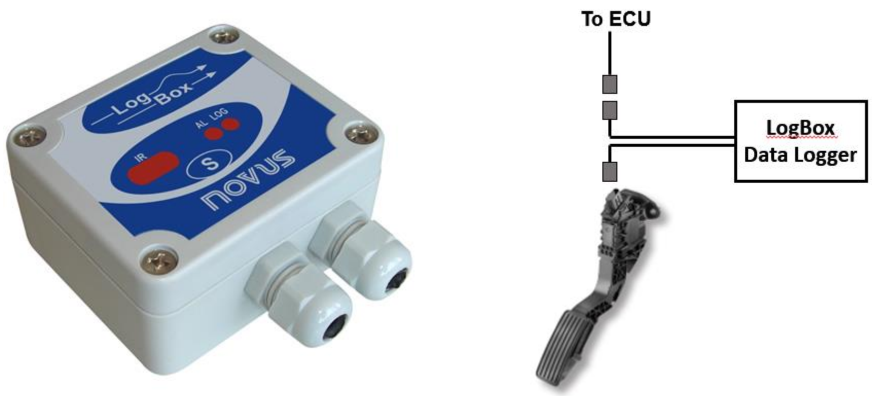


Fig. 53. Novus Automation (www.novusautomation.com) makes a data logger called "LogBox AA" that can digitize and store two or three analog signals for up to 18 hours and is battery-powered. This product can provide all the functions required by a Pedal Monitor, while being less expensive than a video camera with memory. It is also easier to install and can survive wider temperature extremes than a video camera, as well as being less sensitive to changing light conditions.

XV. Summary and Conclusion

A new cause of sudden acceleration has been described that can occur in all vehicles with electronic throttles, including cars with gasoline engines, diesel engines, and electric drive motors, along with trucks, buses, motorcycles, possibly even electric bicycles. The cause involves a dip in the APP sensor supply voltage while it is being digitized for later use in compensating the APP sensor outputs for variations in the supply voltage due to thermal fluctuations. When a dip occurs, the digitized outputs of the APP sensors increase even though the analog sensor outputs remain unchanged. This causes sudden acceleration with the EDR data showing that the driver pressed the accelerator pedal even though the driver may have never put his foot on the accelerator pedal. This change in the APP sensor outputs is not caused by a hardware fault or a software fault, but by a change in the APP sensor data caused by a voltage dip. This explains why no DTC's are ever found after a sudden acceleration incident. This voltage dip can be produced by the inrush current of an electric motor turning on, just like the voltage dip produced by an electric starter on an ICE vehicle.

The paper points out that this new cause of sudden acceleration is in addition to the causes of sudden acceleration in ICE vehicles and in electric vehicles that have been already discussed by this author. It explains why EMI testing has failed to find any of these causes of sudden acceleration in studies by both Exponent and NASA/NHTSA. It then discusses two experimental studies of electronic throttle hardware that prove that the throttle can be opened by dips in the 12V battery supply voltage or by dips in the 5V APP sensor supply voltage. This is followed by an explanation of how to eliminate sudden acceleration by testing the digitized supply voltage before using it to compensate either the APP sensor outputs for changes in the 5V supply voltage or the duty cycle of the throttle motor for changes in the 12V supply voltage. Finally, a way to verify this cause of sudden acceleration is provided by identifying an inexpensive attachment to the accelerator pedal that can monitor the APP sensor outputs for comparison with the EDR data. This inexpensive voltage monitor can be installed easily by the vehicle owner and can survive wider temperature extremes than a video camera, as well as being less sensitive to changing light conditions.

Appendix 1. Typical Accelerator Pedal Characteristics Determined by Manufacturer Usage

In the following discussion the names of specific auto manufacturers are omitted in order to avoid cease and desist orders arising from possible errors in the description of a specific manufacturer's designs.

Accelerator Pedal Position (APP) Sensor Assemblies

- Nearly all auto manufacturers use an accelerator pedal assembly that has at least two accelerator pedal position sensors.
    - Most auto manufacturers now use a standard accelerator pedal assembly with two analog pedal position sensors having A=2B (aka half-scale) analog outputs
    - However, early accelerator pedal assemblies (e.g., before 2004) used potentiometer type sensors whose outputs had the same slope but different offsets. Later, sensors with outputs having different slopes were used.
    - One auto manufacturer has used two pedal sensors that break up the range of pedal travel into two or three regions with different gain factors for each region.
    - Some auto manufacturers add a third sensor whose output starts at a high voltage and then decreases as the accelerator pedal is depressed.
    - Some auto manufacturers add an idle switch to the accelerator pedal assembly to detect whether the pedal is pressed or not pressed.
- The 5V supply voltages are usually provided by different 5V regulators.
    - However, some manufacturers may use only one 5V regulator to power both sensors.
- All sensor outputs are digitized by an ADC at a rate of about 10 kHz, or 100 samples per second, which is the sample rate of the control algorithms in the vehicle.
- Diagnostic tests are performed on the digital outputs of both sensors to determine whether either of the two sensors is bad. The vehicle's response to a bad sensor varies with the auto manufacturer. For example:
    - If only one sensor is bad a diagnostic test code (DTC) is set while engine operation continues with the output power of the engine limited.
    - If both sensors are bad a diagnostic test code (DTC) is set and power to the throttle is shut off, causing the throttle to go into the limp home mode.
    - A DTC is usually erased if the defect condition does not appear during the next ignition cycle.
    - A DTC usually remains if the defect condition persists for two or more ignition cycles.
- The digitized outputs of both sensors are used to calculate a single percent pedal value that represents how far down the accelerator pedal is pressed.
    - The percent pedal values are calculated at a rate of about 100 samples per second.
    - The percent pedal values are used by the control system to control the throttle, or engine speed.
- The percent pedal values taken at 100 samples per second are subsampled at a lower rate and sent to the EDR. They are constantly updated in the EDR until a crash occurs, at which time the values are frozen so that they can be read out after an accident.
    - NHTSA EDR regulations currently require a sample rate of 1 sample per second for 5 seconds before a crash. Most auto manufacturers use this rate.
    - Some auto manufacturers have increased the rate on their own to 2 samples per second for 5 or 10 seconds before a crash
    - New NHTSA EDR regulations that go into effect on 22 September 2024 will require 10 samples per second for 20 seconds (Federal Register / Vol. 87, No. 119 / Wednesday, June 22, 2022 / Proposed Rules p37289**)**

Typical APP sensor waveforms:

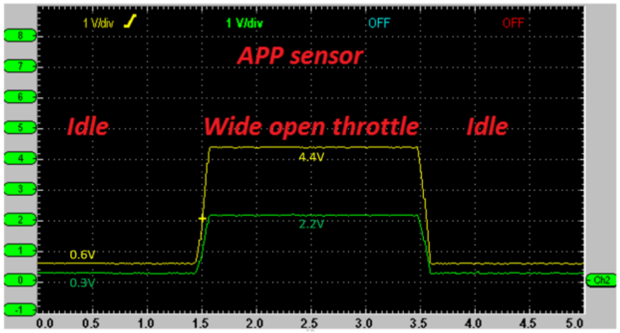


Fig. A1. APP sensors with A=2B outputs

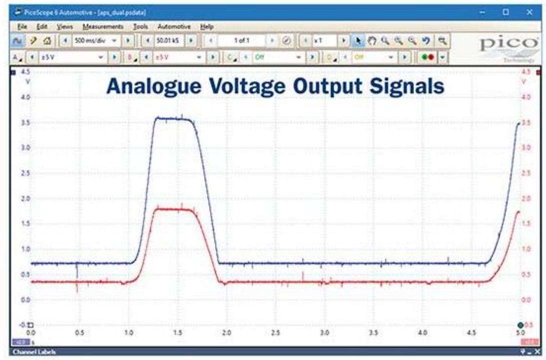


Fig. A2. APP sensors with A=2B outputs.

<u>Throttle Position Sensor (TPS) Assemblies</u>

Throttle position sensors differ from accelerator pedal position sensors in the following ways:

- Nearly all vehicles with air throttles use only two throttle position sensors.
- Both sensors use a 5V supply voltage.
- Both sensors have linear outputs.
- The output of one sensor has a positive slope while the output of the output of the other sensor has a negative slope.

Typical APP sensor waveforms:

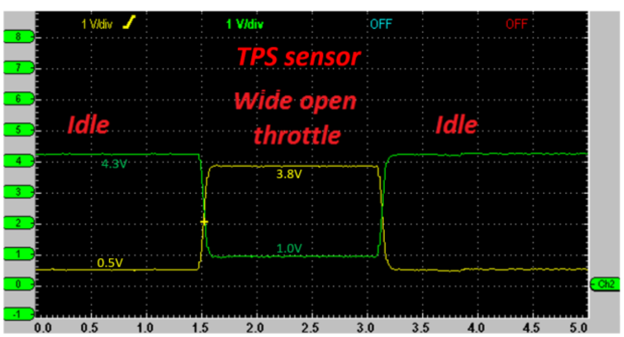
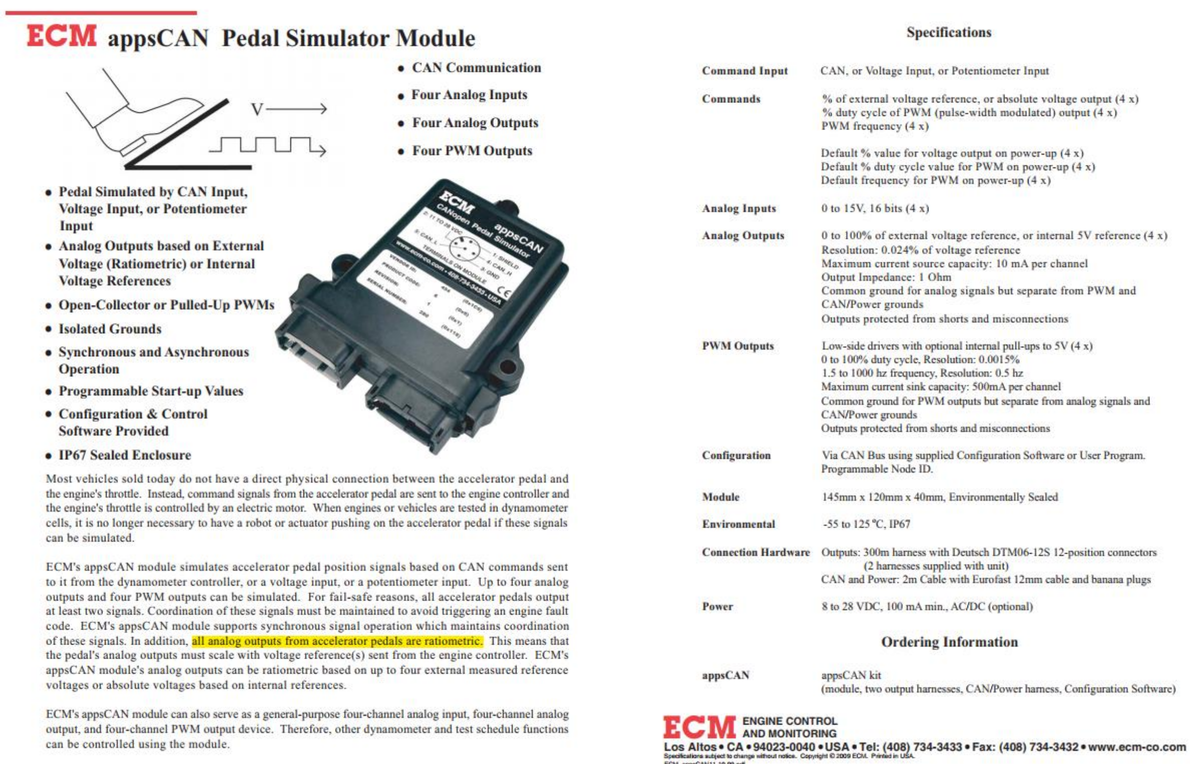


Fig. A3. TPS sensors with + and - slopes

References

1. In one incident a cab driver waiting in a queue with the engine at idle was smoking while sitting with both feet outside the vehicle. When the cabs in front of his vehicle moved forward to leave a gap, he attempted to move his vehicle forward by shifting the transmission from PARK into DRIVE while keeping his feet outside. The engine suddenly roared to high RPM's and the cab sprang forward, crashing into a bridge structure ahead.
   In another incident, a carwash employee entered a vehicle as it was exiting the carwash so he could park it to finish the job. As he shifted the transmission from NEUTRAL to DRIVE with the door still open and his seat belt unfastened the engine suddenly roared to high RPM's and the vehicle leapt forward at high speed. As the vehicle crossed a culvert before crossing a busy road, the driver was thrown out of the vehicle. After crossing the road, the vehicle continued on its own for over 100 yards across an empty field before crashing into an electrical structure outside an apartment building. Investigators later found nothing inside the vehicle that could have interfered with the accelerator pedal.
2. ECM Engine Control and Monitoring, "*Spec sheet for the appsCAN Pedal Simulator Module*", https://ecm-co.com/product/appscan-kit/. The spec sheet below clearly states that all analog outputs from accelerator pedals are ratiometric. The company is a supplier to many automobile testing facilities.



ECM appsCAN Pedal Simulator Module

- CAN Communication
- Four Analog Inputs
- Four Analog Outputs
- Four PWM Outputs

- Pedal Simulated by CAN Input, Voltage Input, or Potentiometer Input
- Analog Outputs based on External Voltage (Ratiometric) or Internal Voltage References
- Open-Collector or Pulled-Up PWMs
- Isolated Grounds
- Synchronous and Asynchronous Operation
- Programmable Start-up Values
- Configuration & Control Software Provided
- IP67 Sealed Enclosure

Most vehicles sold today do not have a direct physical connection between the accelerator pedal and the engine's throttle. Instead, command signals from the accelerator pedal are sent to the engine controller and the engine's throttle is controlled by an electric motor. When engines or vehicles are tested in dynamometer cells, it is no longer necessary to have a robot or actuator pushing on the accelerator pedal if these signals can be simulated.

ECM's appsCAN module simulates accelerator pedal position signals based on CAN commands sent to it from the dynamometer controller, or a voltage input, or a potentiometer input. Up to four analog outputs and four PWM outputs can be simulated. For fail-safe reasons, all accelerator pedals output at least two signals. Coordination of these signals must be maintained to avoid triggering an engine fault code. ECM's appsCAN module supports synchronous signal operation which maintains coordination of these signals. In addition, all analog outputs from accelerator pedals are ratiometric. This means that the pedal's analog outputs must scale with voltage reference(s) sent from the engine controller. ECM's appsCAN module's analog outputs can be ratiometric based on up to four external measured reference voltages or absolute voltages based on internal references.

ECM's appsCAN module can also serve as a general-purpose four-channel analog input, four-channel analog output, and four-channel PWM output device. Therefore, other dynamometer and test schedule functions can be controlled using the module.

Specifications

Command Input	CAN, or Voltage Input, or Potentiometer Input
Commands	% of external voltage reference, or absolute voltage output (4 x) % duty cycle of PWM (pulse-width modulated) output (4 x) PWM frequency (4 x) Default % value for voltage output on power-up (4 x) Default % duty cycle value for PWM on power-up (4 x) Default frequency for PWM on power-up (4 x)
Analog Inputs	0 to 15V, 16 bits (4 x)
Analog Outputs	0 to 100% of external voltage reference, or internal 5V reference (4 x) Resolution: 0.024% of voltage reference Maximum current source capacity: 10 mA per channel Output Impedance: 1 Ohm Common ground for analog signals but separate from PWM and CAN/Power grounds Outputs protected from shorts and misconnections
PWM Outputs	Low-side drivers with optional internal pull-ups to 5V (4 x) 0 to 100% duty cycle, Resolution: 0.0015% 1.5 to 1000 hz frequency, Resolution: 0.5 hz Maximum current sink capacity: 500mA per channel Common ground for PWM outputs but separate from analog signals and CAN/Power grounds Outputs protected from shorts and misconnections
Configuration	Via CAN Bus using supplied Configuration Software or User Program. Programmable Node ID.
Module	145mm x 120mm x 40mm, Environmentally Sealed
Environmental	-55 to 125 °C, IP67
Connection Hardware	Outputs: 300m harness with Deutsch DTM06-12S 12-position connectors (2 harnesses supplied with unit) CAN and Power: 2m Cable with Eurofast 12mm cable and banana plugs
Power	8 to 28 VDC, 100 mA min., AC/DC (optional)

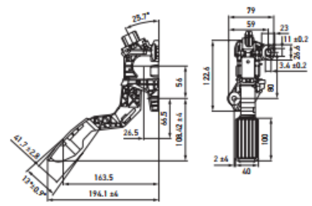
Ordering Information

appsCAN	appsCAN kit (module, two output harnesses, CAN/Power harness, Configuration Software)

ECM ENGINE CONTROL AND MONITORING
Los Altos • CA • 94023-0040 • USA • Tel: (408) 734-3433 • Fax: (408) 734-3432 • www.ecm-co.com
Specifications subject to change without notice. Copyright © 2009 ECM. Printed in USA.
ECM_appsCAN11-10-09.pdf

3. HELLA GmbH & Co. KGaA. https://www.hella.com/soe/assets/documents_global/1947_Gesamtbroschuere_Elektronik_SOE_HELLA_EN.pdf . Below are two pages from this supplier of accelerator pedal assemblies. The pages state that the output signals of their pedal assemblies are ratiometric. Catalogs from other companies show similar statements that their analog outputs are ratiometric.

SUSPENDED PEDALS



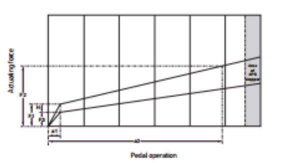
Design/function

Housing and operating lever are completely made of reusable, glass-fibre reinforced plastic. The actuating force is generated by two springs, each individually ensuring safe return to the initial position. The electrical output signal is obtained via the CIPOS® measuring principle. For this purpose, a sheet metal cursor is routed from the pedal arm via sensor paths on the measuring board. There, two metallically separated sensors each generate an output signal. Different output signals can be generated depending on the measuring board used. In addition, individual characteristic curves can be programmed on request.

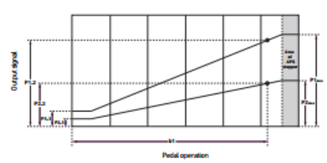
Technical data	
Operating voltage	5 V ± 10 %
Initial force	20 N
Final force	35 N
Actuation angle	13°
Output signal	2 x analogue ratiometric, 2nd channel half pitch
Idling voltage	15 % / 7,5 %
Full throttle voltage	88 % / 44 %
Operating temperature	-40°C to +80°C
Protection class (electronic)	IP 5K4
Mating connector[1]	Sumitomo Denso 6189-1083

[1] This accessory is not included in the scope of delivery. Available from Sumitomo.

Mechanical characteristic curve



Electrical characteristic curve



			Rated values
F1	Initial force	Newton (N)	20 ± 4
F2	Final force	Newton (N)	35 ± 5
F3	Restoring force	Newton (N)	> 5
H	Force hysteresis	Newton (N)	> 4
a1	Starting angle	Degree (°)	< 1.1
a2	End angle	Degree (°)	13

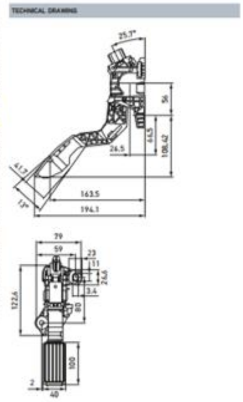
			Rated values
P1.1	Idling voltage S1	Percent (%)	15 ± 1
P2.1	Idling voltage S2	Percent (%)	7,5 ± 1
P1.2	Full throttle voltage S1	Percent (%)	88
P2.2	Full throttle voltage S2	Percent (%)	44
$P1_{max}$	Maximum voltage S1	Percent (%)	88
$P2_{max}$	Maximum voltage S2	Percent (%)	44
b1	Full throttle angle	Degree (°)	11.9 ± 0.6

Suspended accelerator pedals
On request

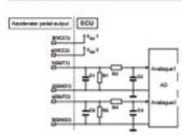
TECHNICAL DATA	
Operating voltage	5 V ± 10%
Power consumption per channel	max. 10 mA
Surge voltage withstand capability, duration t → ∞	14 V
Initial force	20 N
Final force	35 N
Actuation angle	13°
Resolution	0.04°
Output signal	2 x analogue ratiometric, 2nd channel half pitch
Linearity	± 3%
Synchronisation	± 2%
Idling voltage	15%/7.5%
Full throttle voltage	88%/44%
Load resistance	10 kΩ ± 1%
Load capacity	1 nF ± 5%
Filter constant in control unit	1 ms ± 5%
Signal output current	max. 0.55 mA
Operating temperature	-40°C to +80 °C
Storage temperature	-40°C to +80 °C
Protection class (electronic)	IP 5K4
Housing material	PA66-GF40
Mating connector[1]	6189-1083
Weight	≤ 290 g
Actuations	min. 2 million
EMV	CISPR 25, Class 5, electrical and magnetic fields
ESD	10 kV

[1] This accessory is not included in the scope of delivery. Available from Sumitomo Denso. Gold-plated contacts and single conductor insulation are required.

TECHNICAL DRAWING



RECOMMENDED WIRING IN THE CONTROL UNIT

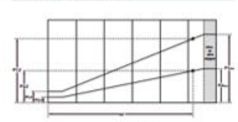


PIN ASSIGNMENT/ELECTRICAL CONNECTION

Pin 1: Analogue signal: Sensor 1
Pin 2: Ground: Sensor 1
Pin 3: 5 V supply: Sensor 1
Pin 4: Analogue signal: Sensor 2
Pin 5: Ground: Sensor 2
Pin 6: 5 V supply: Sensor 2

MECHANICAL CHARACTERISTIC CURVE

ELECTRICAL CHARACTERISTIC CURVE



RATED VALUES			
F1	Initial force	Newton (N)	20±4
F2	Final force	Newton (N)	35±5
F3	Restoring force	Newton (N)	> 5
H	Force hysteresis	Newton (N)	> 4
a1	Start angle	Degree (°)	< 1.1
a2	End angle	Degree (°)	13

RATED VALUES			
P1.1	Idling voltage S1	Percent (%)	15±1
P2.1	Idling voltage S2	Percent (%)	7.5±1
P1.2	Full throttle voltage S1	Percent (%)	88
P2.2	Full throttle voltage S2	Percent (%)	44
$P1_{max}$	Maximum voltage S1	Percent (%)	< 89
$P2_{max}$	Maximum voltage S2	Percent (%)	> 45
b1	Full throttle angle	Degrees (°)	11.9±0.6

PROGRAM OVERVIEW

Accelerator pedal material	Part number	PU*
Plastic	On request	-

4. Exponent, "Analysis of Toyota ETCS-i System Hardware and Software", September 2012, https://archive.org/details/AnalysisOfToyotaETCS-iSystemHardwareandSoftware . Also obtainable from: https://www.scribd.com/document/128038560/ETCSi-Report-Sept242012

Exponent®

Analysis of Toyota ETCS-i System Hardware and Software

Analysis of Toyota ETCS-i System Hardware and Software

Prepared for

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Georgetown, KY 40324

Prepared by

Exponent
149 Commonwealth Drive
Menlo Park, CA 94025

September 2012

5. The following table summarizes the statements about ratiometric APP sensors in the Exponent report:

Sensor Type	Vehicle Used On	References to Ratiometric Behavior
Potentiometer (Aisan, p58)	2002 Camry with L4 engine 2002-2006 Camry (p63)	p84, ratiometric p95, ratiometric p107, ratiometric p125, ratiometric
Potentiometer (Denso, p58)	2002 Camry with V6 engine 2002-2003 Lexus SC430 (p63) 2008 Corolla (p63)	
Hall effect (Denso, p61)	2007+ Camry with L4 engine (p63)	p86, ratiometric down to 3 VDC p95, ratiometric p150, ratiometric p216, ratiometric
Hall effect (CTS, p60)	2007+ Camry with V6 engine (p63)	p85, ratiometric down to 2.8 VDC p95, ratiometric p108, ratiometric p126, ratiometric p150, ratiometric p216, ratiometric

6. G. Gee and L. Hazelton, US patent 6359578, "*System for Externally Referenced Ratiometric Signal Processing*", March 19, 2002, assigned to Delphi Technologies, Troy, Michigan, https://patentimages.storage.googleapis.com/c5/f5/fe/cc3d9e3cb95041/US6359578.pdf
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10. Battery voltage sag during engine cranking, June 15, 2023. https://www.powerstream.com/voltage-sag-during-engine-starting.htm
11. Allied Signal Inc, European patent EP 1 135 840 B1, *"System and Method for Monitoring a Vehicle Battery"* , December 5, 2010. https://data.epo.org/publication-server/rest/v1.0/publication-dates/20100512/patents/EP1135840NWB1/document.html
12. https://www.fixkick.com/Charging/start-voltage-scope.GIF. See also, https://www.fixya.com/cars/t29902773-2003_passat_w8_fuelpump_wont_turn_pump
13. M. Abbas, A. Ferri, M. Orchard and G. Vachtsevanos, "*An Intelligent Diagnostic/Prognostic Framework for Automotive Electrical Systems",* *https://www.researchgate.net/publication/4268857_An_Intelligent_DiagnosticPrognostic_Framework_for_Automotive_Electrical_Systems*
14. EMC Flex Blog, Automotive cranking pulse, CS.00054 Pulse 4 cranking pulse, https://flexautomotive.net/EMCFLEXBLOG/post/2015/09/10/automotive-cranking-pulse
15. Monolithic Power Systems, "*Easy, Cost-Effective Pre-Booster for Automotive Cold Crank Conditions*", 2024. https://www.monolithicpower.com/pre-booster-for-automotive-cold-crank-conditions
16. Maxim Integrated, "*Power Management for Advanced Driver Assistance Systems*," Design Guide, p16. *www.maximintegrated.com/adas-power*
17. Earl Pannila and Mahesh Edirisinghe, "*Power System Switching Transients in Passenger Automobiles*", Dec 2014. https://www.researchgate.net/publication/352509512
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20. NHTSA Action Number: PE10038, Date Investigation Opened: September 24, 2010, Date Investigation Closed: May 10, 2011, Engineering analysis: EA11-005.
21. T. Mio et.al., "*Auxiliary Power Supply System for Electric Power Steering (EPS) and High-Heat-Resistant Lithium-Ion Capacitor*", World Electric Vehicle Journal **2019**, *10*, 27; https://www.mdpi.com/2032-6653/10/2/27
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