An Electronic Cause for Sudden Unintended Acceleration

by

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Abstract: An electronic cause for sudden unintended acceleration is presented. At low vehicle speeds, when the engine is at idle, the alternator cannot supply all the current required by the vehicle's electrical system. In this case, the battery must supply the additional current, and the system voltage is determined by the battery voltage. If the battery state of charge is weak, the battery voltage will be low, and the inrush current caused by one of the vehicle's electrical functions (e.g., an electric motor) starting up will cause a large negative voltage spike on the battery supply line. This voltage spike can pass through the ECM voltage regulators and lead to a brownout error in the CPUs if the CPUs are not properly held in reset by the ECM supply. The brownout error can cause faulty operation of the CPUs, keep-alive memory, and/or EEPROM memory, leading to a software error that causes unpredictable engine operation, such as sudden acceleration. At high vehicle speeds, when the alternator is setting the system voltage, worn or bouncing brushes inside the alternator can interrupt the alternator field current and produce a large negative voltage spike on the alternator output that causes a brownout error in the CPUs. These two causes provide an alternative explanation to driver error for many observations associated with sudden unintended acceleration in vehicles with electronically controlled throttles similar to Toyota's ETCS-i system.

I. Introduction

Sudden acceleration has ceased to make news headlines since the NHTSA-sponsored NASA study report appeared in February 2011. However, this does not mean that sudden acceleration events have stopped occurring. Safety Research & Strategies (SRS), a consumer safety watchdog organization, has identified 330 unintended acceleration complaints reported to the National Highway Traffic Safety Administration (NHTSA) for incidents occurring in 2011. And a separate SRS review of complaints filed with the NHTSA has identified 247 unique unintended acceleration incidents even after Toyota had applied their two fixes for pedal sticking and floor mat entrapment. Just what is sudden acceleration? A 1998 NHTSA study defined a "sudden acceleration incident" as an "unintended, unexpected, high-power acceleration from a stationary position or a very low initial speed accompanied by an apparent loss of braking effectiveness." For twenty years this definition has been used by the NHTSA to characterize data, perform investigations, and draw conclusions regarding sudden acceleration. It has also been used by automobile companies to make recalls and by the U.S. courts to settle suits brought against automobile manufacturers. Its dual requirements of: a) "acceleration from a stationary or very low initial speed position" and b) "loss of braking effectiveness", along with the results of several NHTSA-sponsored studies that no causal connection can made between throttle operation and brake operation, have influenced NHTSA to conclude that the only way a sudden acceleration event can happen is either by two independent faults causing phenomena a) and b) simultaneously, or by the driver himself causing the incident due to pedal misapplication. Since NHTSA believes that both such faults must leave physical evidence, and since no study has proven the existence of two such faults by means of physical evidence, NHTSA has concluded that all sudden acceleration incidents are the result of pedal misapplication by the driver.

A more recent NHTSA/NASA report in 2011 defines "unintended acceleration" as "the occurrence of any degree of acceleration that the driver did not purposely cause to occur." It is intended to be a broader term that encompasses "sudden acceleration incidents" as well as incidents where brakes are partially or fully effective, including occurrences such as pedal entrapment by floor mats at full throttle and high speeds and incidents of lesser throttle openings at various speeds. Despite this more general definition, NHTSA claims in their latest NASA report that "*No mechanism has been identified that could cause the throttle to open because of brake application and any engine power increases that may occur during a brake application should be easily controllable by the driver*".[1] Therefore, NHTSA concludes once more from this study that all sudden acceleration incidents are caused by pedal misapplication by the driver. Their conclusion disregards the claims of thousands of drivers that their foot was on the brake when sudden acceleration started, and effectively implies that the drivers were either unwittingly mistaken or knowingly lying about the location of their foot when sudden acceleration occurred. It also turns a blind eye to the fact that sudden acceleration incidents have happened to policemen, Toyota and other dealer repair technicians, and chauffeurs trained in emergency vehicle maneuvers.

It is difficult for this author to believe that such a large number of drivers are either mistaken or lying about the position of their foot. On the other hand, the author believes that, if such a large number of drivers are making the same claims about unintended acceleration, then perhaps there is some truth to these claims. If the claims are indeed true, they may be telling us something about how unintended acceleration begins. Therefore, this paper will start with drivers' first-hand observations about unintended acceleration and try to use these observations as clues to deduce the cause of sudden acceleration.

The following is a list of known observations and facts about sudden unintended acceleration as compiled by the author. The term "sudden unintended acceleration" has been used intentionally to avoid any categorization of the incidents according to either NHTSA's 1989 definition or NHTSA/NASA's 2011 definition.

1. During a sudden unintended acceleration incident, the engine RPM's suddenly increase above what the driver considers to be normal. Sometimes the RPM's increase to a wide open throttle state (>6000 RPM). But other times they increase to only 2000 to 3000 RPM or less.
2. The majority of sudden unintended acceleration incidents (92%) occur at low speeds (<15 mph)[2]. (Fig 1).
3. More low-speed sudden unintended acceleration incidents (49%) occur when entering a parking space than when leaving a parking space (12%).[3] (Fig 2).

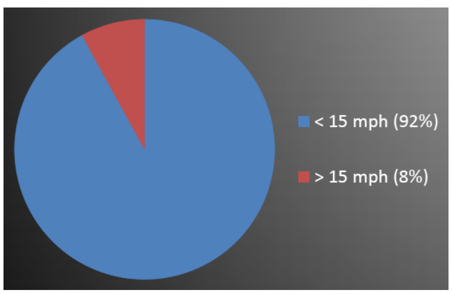


Fig 1. MY2002 – 2006 consumer complaints by initiation speed: Pre-5-Oct-09[2]

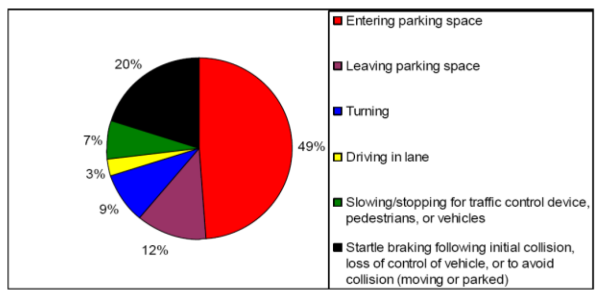


Fig 2. Breakdown of low speed sudden acceleration incidents by vehicle operations in progress[3]

4. A majority of drivers (62%) steadfastly maintain that sudden unintended acceleration occurred while their foot was on the brake. A small number of others have mentioned that it occurred when shifting out of PARK.
5. A disproportionate number of sudden unintended acceleration incidents involve drivers over age 60, including some in their seventies and even eighties.[4] (Fig 3).
   a. It has happened to policemen, chauffeurs, FBI agents trained in evasive car maneuvers, and even Toyota repairmen.
   b. It has happened to the same person in two different vehicles at least six times.
   c. It has been witnessed once by two NHTSA personnel, who verified that the accelerator was not involved

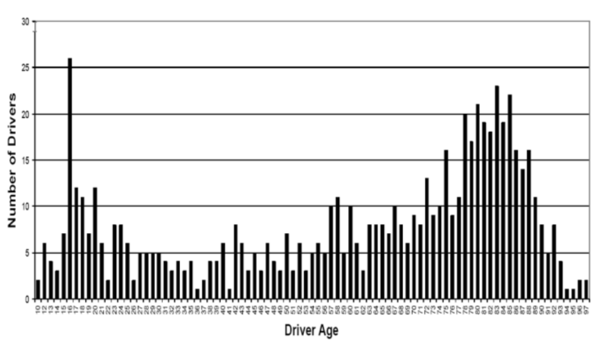


Fig 3. Number of sudden acceleration incidents versus driver's age[4]

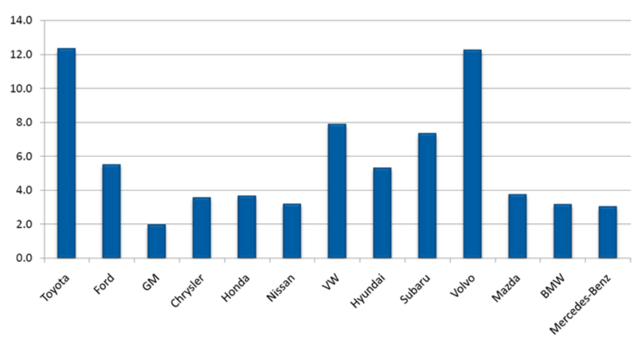


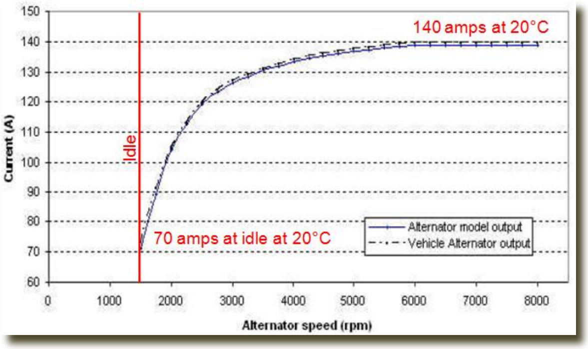
Fig 4. Alleged unintended acceleration complaints per 100K vehicles MY 1998-2010[5]

6. Sudden unintended acceleration incidents have occurred with all makes of automobiles. Toyota and Volvo have the highest incidence rates and General Motors has the lowest incidence rate.[5] (Fig 4.)
7. Sudden unintended acceleration occurs rarely. The incident rate is less than 12 incidents per 100K vehicles (<120 ppm).[5] (Fig 4).
8. Sudden unintended acceleration incidents have occurred in Toyota hybrid vehicles like the Prius.
9. Sudden unintended acceleration incidents occur rarely with police cars even though they are used a lot at low speeds.
10. When the ignition is turned on again after it has been turned off following a sudden unintended acceleration condition, the engine RPM's nearly always resume in a normal low state. That is, recycling the ignition nearly always removes the sudden unintended acceleration condition.
11. Sudden unintended acceleration occurs most often in autos having an automatic transmission and throttle by wire. But it has also occurred in autos having a stick shift or a conventional mechanical throttle.
12. Sudden unintended acceleration appears to have a higher rate of incidence in the USA than in Canada or Europe.
13. Drivers often complain that during sudden unintended acceleration the vehicle's brakes were ineffective, either partially or totally.
14. Some drivers have heard the ABS pump activate just before sudden unintended acceleration occurred.
15. If a crash occurs as a result of sudden unintended acceleration, sometimes the front airbags do not deploy even though damage to the vehicle is extensive.
16. Sudden unintended acceleration is a very intermittent condition. It has not been reproduced on demand.
17. If a vehicle has ever experienced sudden unintended acceleration, it has a higher probability of experiencing it again at some later time.
18. Sudden unintended acceleration can occur with the vehicle going either forward or backward.
19. In a few cases, voltage measurements taken after sudden unintended acceleration incidents have shown low voltages.

II. The Path Toward an Electronic Cause of Sudden Acceleration

Our search for an electronic cause of sudden acceleration starts with observation 2 above; i.e., that the majority of sudden unintended acceleration incidents (92%) occur at low vehicle speeds (<15 mph). These incidents usually occur in parking lots, driveways, or when approaching an intersection, stop sign, or traffic light.

Implications of Low Speed Operation. Let us examine what is happening to the vehicle during normal operation at low speeds, such as in parking lots, driveways, or when approaching a stop sign or traffic light. Certainly, one thing that is happening in these situations is that the engine is running a lot at idle. This is because the driver wants to operate the vehicle slowly to avoid pedestrians, maneuver in tight quarters, or obey traffic laws and avoid possible traffic accidents, and keeps his foot off the accelerator and usually on the brake. When the vehicle's engine is running at idle, we ask what is happening to the vehicle's electrical system. One thing that is certainly happening is that the vehicle's alternator is operating at its minimum efficiency because its current output depends upon its rotational speed and its rotational speed is tied directly to the engine speed (the ratio of alternator speed to engine speed is about 2.7:1). Therefore, at idle the alternator is supplying a minimum amount of output current to the vehicle's electrical system. Fig 1 shows how the alternator current output varies with alternator speed for a 140 amp alternator. One sees that a nominal 140 amp alternator puts out only about 50%, or 70 amps, at engine idle speed at 20°C. This amount decreases even further as the alternator temperature rises, as shown in Fig 2. At 100°C, which is a normal operating temperature for an engine compartment, the 140 amp alternator can put out only about 110 amps at high speeds, and only about 59 amps at idle. This is only about 40% of the 140 amp nominal rating. Considering that most Toyota vehicles have only 80 amp or 100 amp alternators instead of the 140 amp alternator shown in Figs 5 and 6, one can conclude that the alternators of Toyota vehicles are putting out only about 32 to 40 amps at idle.



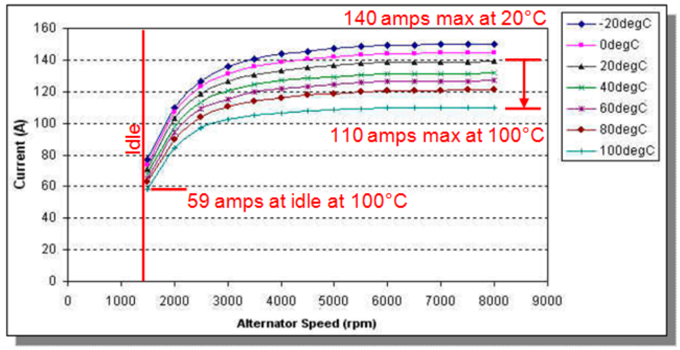


Fig 5. Alternator output current versus rotational speed for a 140 amp alternator.[6]

Fig 6. Alternator output current decreases as the operating temperature increases.[7]

How does this compare with the demand for current by the vehicle's electrical system? Table 1 lists the components (i.e., current loads) in a typical vehicle's electrical system. The current loads are organized into two major columns: a) the left hand major column contains current loads which are active at any vehicle speed, and b) the right hand major column contains current loads which are active mostly at low vehicle speeds. The current loads in each major column are further divided into DC current loads (i.e., direct current or steady current loads) and PWM current loads (i.e., pulse width modulated loads or loads that are supplied with a pulsed battery current having a variable pulse width). The left hand major column also contains aftermarket accessory loads which some drivers may add to their vehicle, and which are all DC current loads. In each major column, the individual current loads are listed along with an estimate of their steady state current (which is the time-averaged current in the case of PWM loads), their inrush current, and their fuse size (which is usually about 1.5x to 2x higher than the current load to allow for normal current variation). These estimates may vary from one auto manufacturer to another due to design details, but usually are similar across the manufacturer's various models. In this table the values correspond to Toyota Camry and Lexus ES350 vehicles. While the author has attempted to be as accurate as possible, some of the estimates may have a slight error because of design differences between Toyota models and the variety of sources from which the estimates have been taken (no auto manufacturer provides this information to the public). However, the estimates are believed to be accurate to within about 20%. We will have more to say about the inrush currents later in this paper.

Not all of these current loads are active at the same time. If we add up the current loads that are usually active at one time, we find that the vehicle requires between 57 and 87 amps at any speed (depending upon whether the air conditioning system is being used), with another 10 to 76 amps required at low speeds (depending upon whether the cooling fans and ABS brakes are being used). This gives a total of 67 to 163 amps required at low speeds, which is a much higher current than the alternator can supply at idle speed (32 to 40 amps for a Toyota 80 to 100 amp alternator). This is not an error in our estimates. It merely means that at idle, the battery is supplying the additional current that the electrical system requires. When this happens, the system voltage changes from the alternator voltage used to charge the battery (14.3V) to the battery voltage itself (12.6V for a fully charged battery). This has very little effect on the operation of the electrical system loads because the voltages are so similar. When this happens, the battery also discharges slightly. But as soon as the vehicle resumes operation at higher speeds, the alternator current output increases, the battery stops supplying current, the system voltage jumps back up to the alternator voltage of 14.3V, and the battery begins to charge up again. This is the way the battery and alternator are supposed to operate. However, if vehicle remains at idle for a long time, and the battery must supply this additional current for a long time, the battery will discharge even further. This can cause the battery voltage to drop below 12.6V or even much lower. If the battery voltage drops significantly below 12.6V, then its effect on electrical system operation will be noticeable by the driver as a dimming of the headlights and/or a dimming of the dashboard lights. The following changes also occur at lower system voltages:

1. Electric motors rotate slower, and may not start at all (e.g., HVAC blower motor, or ABS pump motor)
2. Electric motor starting current increases
3. Relays and solenoids may chatter, and at a low enough voltage may revert to their non-actuated state
4. Voltage regulators can go out of regulation
5. Sensors can start making errors, or may stop sensing completely.

Table 1. Current loads in a typical vehicle's electrical system

Current Loads Potentially Active at All Speeds	Fuse Size (amps)	Each Load Inrush Current (amps)	Each Load Steady Current (amps)	Total Load Inrush Current (amps)	Total Load Steady Current (amps)
DC Current Loads					
fuel injectors	20	50	10	50	10
PCM ECU (5V)		1	1		1
ABS ECU (5V)		1	1		1
headlights, std halogen (2)					
low beam (55W) (2)	2(15)	20	4.8	40	10
high beam (65W) (2)	2(10)	20	5.5		
headlights, HID xenon (2)		25	5.8		
fog lights (2)	15	20	5		
tail lights (2)	10	10	2.1		
side marker lights (4)	5	10	4	10	4
license plate light		1	0.5		
instrument panel lights					
turn indicator lights (2)		40	10		
audio system w/6 speakers	5		12		12
rear window defroster	40	25	25		
A/C clutch	10		4		4
transmission shift solenoids		20	2	20	2
seat heaters (2)	25	5	5		
PWM Loads					
fuel pump	25	18	8	18	8
throttle motor	10	28	7	28	7
front wiper motor	25	6	2		
rear wiper motor		6	2		
windshield washer motor	15				
power window motor		25	6		
power seat motors					
door lock motor		23			
A/C blower[2] (max)	50		14		14
A/C door motors (3)	25		14		14
rear A/C blower[2] (optional)			14		
Total DC Current					87
Aftermarket Accessory DC Loads					
radar detector			0.5		
GPS receiver			0.5		2
On-Star			0.5		
DVD with 2 LCD monitors			2		
boom box speakers (2)			40		
off road headlights (2)		100	25		
satellite radio tuner			1		
i-Pod adapter			0.5		
Total DC Current Including Aftermarket Accessories					89

Current Loads Active Mostly at Low Speeds	Fuse Size (amps)	Each Load Inrush Current (amps)	Each Load Steady Current (amps)	Total Load Inrush Current (amps)	Total Load Steady Current (amps)
DC Loads					
brake lights (3)	15	11	2	33	6
backup lights (2)		11	2		
ABS brake solenoids[4]	40	20	2	40	4
fan relay control	10				
starter motor		850	150		
PWM Loads					
radiator cooling fan[2,6]	30	85	18	85	18
A/C condenser fan[2,6]	30	85	18	85	18
ABS brake pump motor[4,5,7,8]	50	200	30	200	30
electric power steering motor			60		
brake booster vacuum pump[3]					
Total DC Current					76

Notes:
1. Current waveforms for many of these loads are shown in Appendix A.
2. Cooling fans and blowers vary considerably in current load. The Lincoln Mk VIII fan draws 36A continuously and has an inrush current over 100A.
3. Electric vacuum pumps for brake boosters are used in hybrid vehicles only.
4. When brakes are applied, brake lights, ABS solenoids, and ABS brake pump can all activate at the same time.
5. ABS pump motor is PWM modulated, but operates in DC mode until the motor begins turning to allow the turn-on transient to help in starting. See patent
6. When the A/C condenser fan turns on, the radiator cooling fan is designed to turn on simultaneously.
7. The Prius ABS pump motor has a 30A inrush current.
8. The Toyota Tahoe ABS pump draws 60 amps steady current.

Back in 1997, so many GM customers complained about this variation in light intensity at idle, that GM was forced to publish technical bulletin #43-64-07A, issued in January, 1997, to put its customers at ease[8]. It reads:

> **Subject:** Low Voltage Reading or Dim Lights at Idle
> **Models:** 1990-97 Passenger Cars and Trucks
> **Discussion**:
>
> Any vehicle may have a low voltage reading (if equipped with gauges) or lights that dim, when electrical loads are heavy at idle, or under very slow driving conditions. This condition may be worse with owner added electrical accessories, or with a discharged battery. THIS CONDITION IS A NORMAL OPERATING CHARACTERISTIC OF THE VEHICLE, AND NO REPAIRS SHOULD BE ATTEMPTED UNLESS A PROVEN FAULT HAS BEEN FOUND.
>
> At idle, vehicle electrical loads may exceed the low speed output of the generator, but the battery can make up for this shortfall from its reserve capacity for short periods. During normal driving conditions, the generator is designed to do two things: supply the necessary vehicle loads, and recharge the battery. Long periods of battery discharge due to high accessory loads at idle will cause the electrical system voltage to drop as the battery continues to deliver the electrical power. Increased generator temperatures from extended idling can also contribute to lower electrical

system voltage. As temperatures rise, the voltage set point is reduced to avoid battery overcharge, and the generator's output capability is reduced due to increased electrical resistance.

Depending on the vehicle application, normal generator output at idle can be as low as 35% of the full rated output. With enough electrical loads, it is easy to exceed the low speed generator output at idle. This is a NORMAL condition that the battery can compensate for during short periods. Items that affect the vehicle system voltage at idle are driving conditions, the number of electrical loads being used, add-on accessories, and extended idle times. Normal driving conditions will recharge the battery and restore the charging system to its normal state.

GM issued another technical bulletin in 2002 that elaborated on this condition. Here is GM technical bulletin #02-06-03-008, dated August 2002, in its entirety[9]:

Title: Charging System - Low Voltage Display ON/Dim Lights

File In Section: 06 - Engine/Propulsion System

Subject: Low Voltage Display on IP Gauge, Lights Dim at Stop Lights, Battery Discharged, No Start, Slow Cranking, Dim Lights at Idle, Low Generator Output

Models: 1990-2003 Passenger Cars and Light Duty Trucks
2003 HUMMER H2

Discussion:

This bulletin is being revised to update the model years and to update text. Please discard Corporate Bulletin Number 43-64-07A (Section 06 - Engine).

Any vehicle may have a low voltage display (if equipped with gauges), lights that dim at stop lights, slow cranking, no start, low generator output at idle or dim lights at idle when electrical loads are heavy at idle or under slow driving or infrequent usage conditions. These characteristics may be more noticeable with customer added electrical accessories, or with a discharged battery. These are normal operating characteristics of a vehicle electrical system and no repairs should be attempted unless a proven fault has been diagnosed.

During normal driving conditions, when engine speed is above 1000 RPM, the generator is designed to do two things:

1) Supply the current necessary to operate the vehicle's originally equipped electrical devices (loads).

2) Recharge/ maintain the battery's state of charge.

The following factors may affect generator and battery performance:

a) Non-usage of the vehicle for extended periods of time. The vehicle's computers, clocks and the like will cause the battery state of charge to drop (For example; 30 days in a parking lot and the vehicle may not start because of a dead battery or a vehicle which is driven to church only on Sunday may end up with a discharged battery to the point where the vehicle may not start). This would be considered abnormal usage of the vehicle and the normally expected result for the vehicle battery, generator and electrical systems.

b) At idle, vehicle electrical loads may exceed the low speed current (amperage) output of the generator and when this happens the shortfall comes from the battery. This will result in a drop in the electrical system voltage as the battery delivers the additional electrical current to meet the demand. This is equivalent to the brown outs experienced by homes and businesses when the electrical demand is more than the supply. See Figure 1.

c) Extended periods of engine idling, with high electrical loads, may result in a discharged battery. Attempting to recharge a battery by letting the engine run at idle may not be beneficial unless all electrical loads are turned "OFF".

d) Increased internal generator temperatures from extended idling can also contribute to lower electrical system voltage. As the generator's internal temperature rises, the generator's output capability is reduced due to increased electrical resistance.

Table X shows some typical examples of electrical loads.

Table X. Some typical electrical loads

LOAD	AMPS
Rear window defogger	25
Headlamps (low)	15
Headlamps (high)	20
High blower	20
Windshield wipers	6
Ignition	6
Brake lights	5

Depending on the vehicle application, generator current (amperage) output at engine idle speeds of 600-700 RPM can be as low as 35 percent of the full rated output. With enough electrical loads "ON" it is easy to exceed the generator current (amperage) output when the engine is at an idle of 600-700 RPM. This is a normal condition. The battery supplements for short periods of time. Items that affect the vehicle's electrical system current and voltage at idle are the number of electrical loads being used, including add-on accessories, and extended idle times. When the vehicle speed is above approximately 24 km/h (15 mph), the engine/generator RPM is high enough and the generator current (amperage) output is sufficient to supply the current (amperage) requirements of the vehicle as originally equipped and recharge the battery.

Dimming lights at idle may be considered normal for two reasons:

1. As the engine/generator speed changes, so will the current (amperage) output of the generator. As a vehicle slows, engine/generator RPM slows, and the current (amperage) output of the generator may not be sufficient to supply the loads, the vehicle system voltage will drop and the lights will dim. Dimming of the lights is an indication that current is being pulled from the battery. If the battery is in a low state-of-charge (discharged condition), the driver will notice a more pronounced dimming than a vehicle with a fully charged battery.

2. When high current loads (blower, rear defogger, headlamps, cooling fan, heated seats, power seats, electric "AIR" pump, or power windows) are operating or cycled "ON", the generator's voltage regulator can delay the rise in output. This effect, usually at lower engine speeds, can take up to ten seconds to ramp up the generator output. This is done to avoid loading the engine severely. To increase current (amperage) output, additional torque is consumed by the generator. The engine computer (PCM) will ramp up engine/generator speed in small steps so engine speed variations are not noticeable to the driver.

For diagnosis of the battery and or the generator, refer to the appropriate Service Information or Corporate Bulletin Number 02-06-03-006.

GM's technical bulletins have become even more relevant in recent years as the electrical content of automobiles has increased. Figure 7 shows how the average electrical load has increased and Figure 8 shows how the nominal current of the fuses and the installed alternator power has increased. It is expected that these trends will continue as the introduction of electronic power steering, electronic stability control, adaptive cruise control, electronically tuned suspension, and electronic brake by wire becomes more widespread.

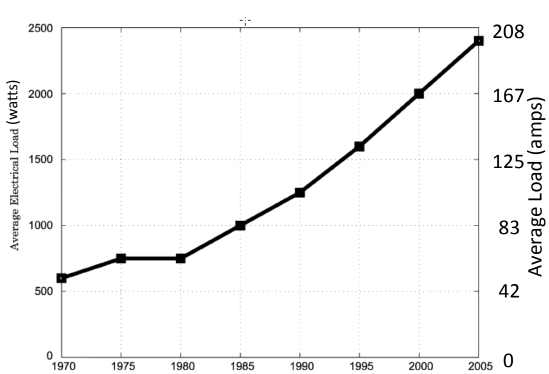


Fig 7. Increase of the average electrical load

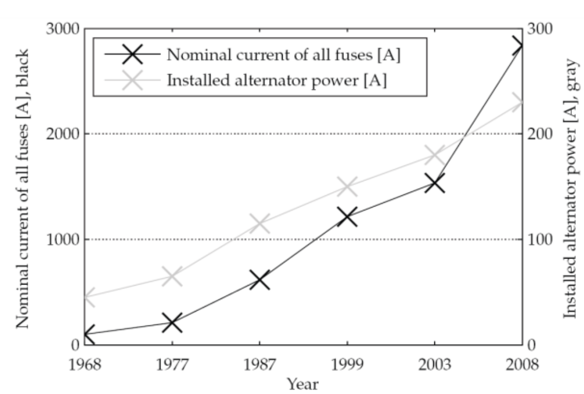


Fig 8. Increase of the total nominal current of the fuses

of an automobile versus model year.[10] (left scale) and the installed alternator power (right scale) in the latest decades.[11]

DC Battery Voltage. Having seen that idle operation can result in low battery voltage, we now ask how low a battery voltage is possible. If one draws a constant current from a lead acid battery and measures the voltage versus time, one gets a curve like that shown in Fig 9 for a constant current of about 18 amps. After about 10 hours, the battery becomes fully discharged and a voltage of 10.5V is measured. When the current is turned off, the battery voltage bounces back up to about 11.5 volts due to surface charge in the battery. Fig 10 shows a similar curve for a Delco Legend 50Ah battery discharged by about a 5.5 amp constant current. Fig 11 shows how the shape of this curve explains how the battery's ability to absorb (i.e., filter) voltage fluctuations decreases with decreasing state of charge (SOC). Fig 12 shows how these curves vary with increasing discharge rates.

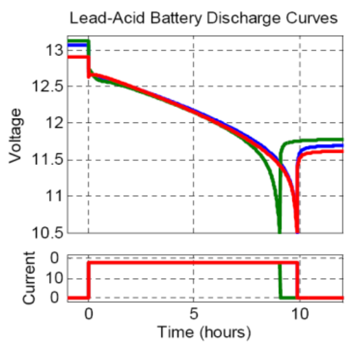


Fig 9. How battery discharge curves are measured at constant current[12]

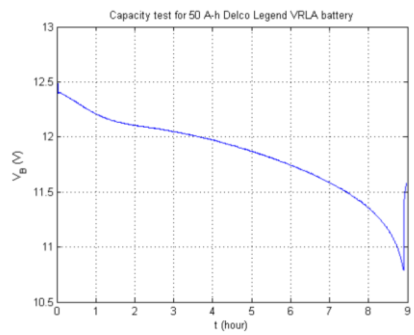


Fig 10. Measured constant current discharge curve for a 50Ah Delco Legend battery[13]

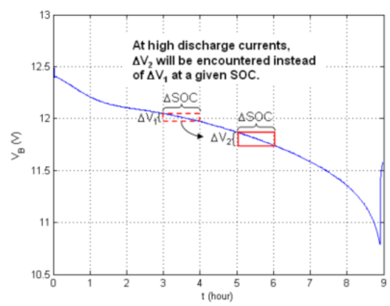


Fig 11. Discharge curve showing how the battery absorbs voltage variations at different SOC's[14]

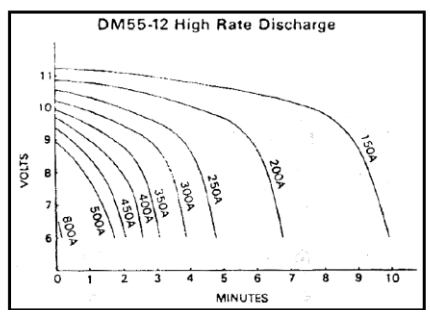


Fig 12. Manufacturer's discharge curves for the Yuasa DM55-12, 55Ah, 12V battery[15]

The shape of the above discharge curves is determined by the battery's internal construction. Figure 13 shows a simplified model of a lead-acid cell. It consists of a capacitor, which represents the battery's charge storage capability, a series resistance $R_{metallic}$ which has several components, and a parallel resistance $R_{electrochemical}$ which has several components. When measuring the constant current discharge curves, the voltage drops across the series and parallel resistances are included in the voltage measurement. However, if we measure the battery voltage using a high impedance voltmeter while no current is flowing, then we obtain a different voltage, called the battery open circuit voltage, which is the voltage drop across the capacitor when these internal resistances are absent. This voltage is plotted in Fig 14 as a function of the battery state of charge (SOC). From these two measurements, the battery internal series resistance can be derived, as shown in Figs 15 and 16. Figs 15 and 16 show that the battery internal series resistance varies with the battery state of charge (SOC) by about a factor of 3 to 10, from a fully charged battery (100% SOC) to a fully discharged battery (0% SOC), depending on the actual battery construction. Table 2 summarizes these two battery model parameters for the two extremes of battery operating condition (SOC).

Conversely, knowing the battery's open circuit voltage and its series resistance, one can now calculate the battery's terminal voltage. This makes it easy to calculate the voltage across any electrical load we add to the battery, because we only need to calculate the voltage drop across the battery's internal resistance that is caused by the imposed electrical load current and subtract it from the battery's open circuit voltage.

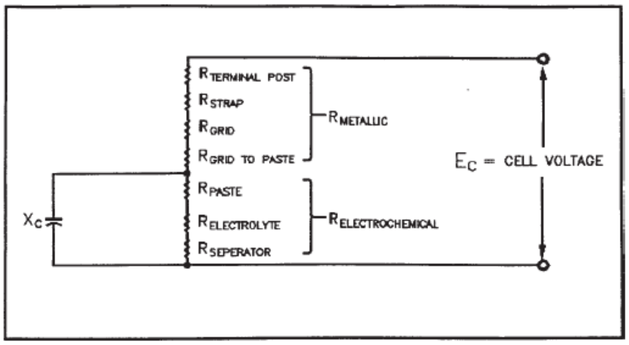


Fig 13. Simplified model of a lead-acid cell[16,17]

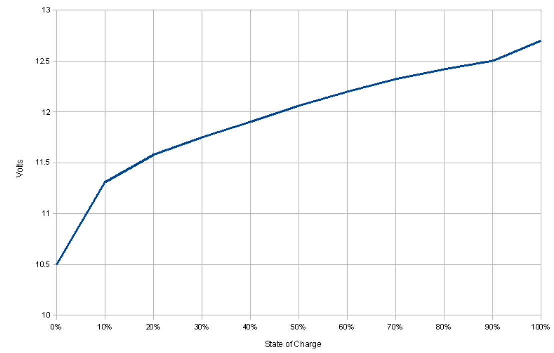


Fig 14. Open circuit voltage versus state of charge (SOC) for a lead acid battery[18]

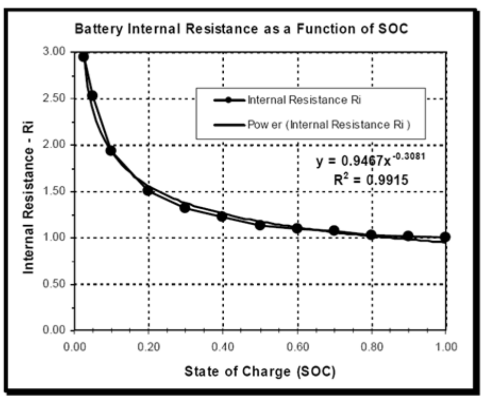


Fig 15. Internal resistance as a function of SOC for a typical lead acid battery[19]

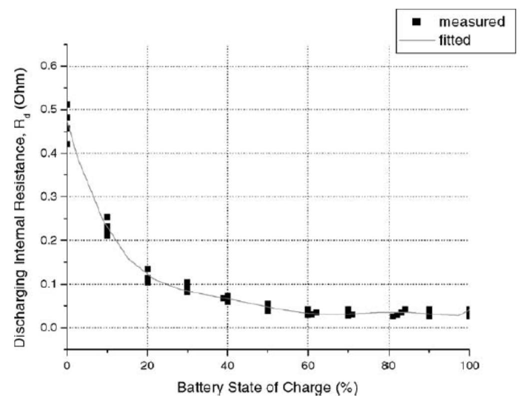


Fig 16. Internal resistance as a function of SOC for a different lead acid battery[20]

Table 2. Battery model parameters for the two extremes of battery state of charge (SOC).

Battery Model Parameters	Fully Charged (SOC = 100%)	Completely Discharged (SOC = 0%)
open circuit voltage (volts)	12.6 V	10.5V
internal series resistance (mohms)	10 mohms	100 mohms

Calculating the DC Voltage at the ECM. We can now calculate the DC voltage applied to an ECM by using our knowledge of the battery's internal series resistance, along with a circuit diagram of the automobile's electrical system, and a knowledge of the load currents listed in Table 1. Fig 17 shows a simplified circuit diagram of the electrical system in a 2005 Camry. Fig 18 shows the locations of each of the electrical components in the vehicle. In Fig 17, if we follow the current path in red, we can see that the current to the ECM flows from the battery's positive terminal, through a fusible link, through a red battery cable, through relay block No. 1, through junction block No. 1, through an instrument panel junction block, and through a harness splice point under the dash. The current back to the battery flows from the ECM, through two ground bolts on the engine cylinder head, through the engine, through a braided connector to a ground bolt on the passenger side fender, through the chassis to a ground bolt on the driver side of the radiator, through a black battery cable, to the battery's negative terminal. Fig 17 includes the "big three" battery cables that are important to electrical system operation, and which are usually not included in manufacturer's circuit diagrams (the two ground cables are usually replaced by a triangular ground symbol). Fig 17 also includes the current path through the skid control ECU. It is interesting to note that Toyota uses two different ABS brake systems in the 2005 Camry, one for vehicles made in the USA (TMMK – where K stands for Kentucky), and the other for vehicles made in Japan (TMC). The USA-made ABS system (believed to be a Bosch ABS unit) uses mechanical relays outside of the ECU whereas the Japanese-made ABS (believed to be a Denso ABS unit) uses electronic relays inside the ECU.

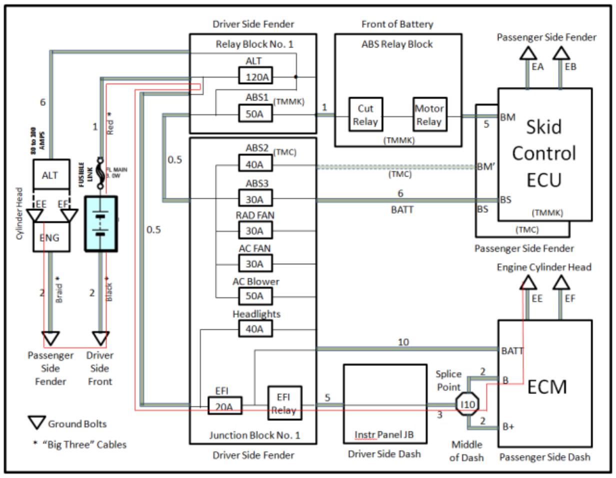


Fig 17. Simplified wiring diagram of a 2005 Camry showing the power train ECM current path[21]

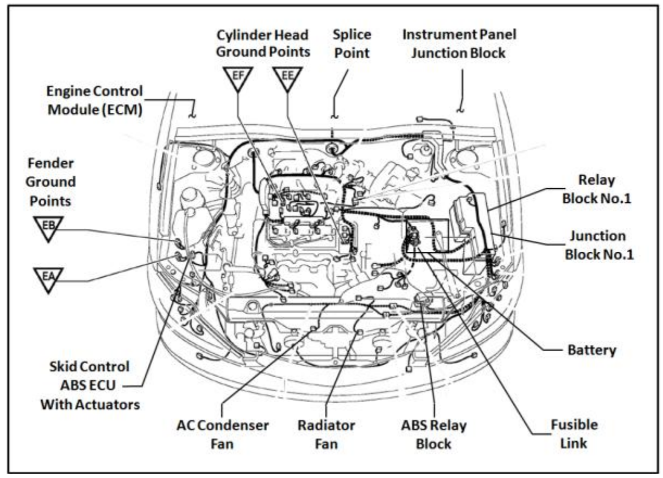


Fig 18. Locations of the electrical components in a 2005 Camry[22]

In making our calculation of the DC voltage applied to the power train ECM, we must include the voltage drops not only in the supply side to the ECM, but also in the ground side from the ECM back to the battery. Figure 19 shows how both of these voltage drops contribute to the voltage across the ECM. Fig 20 shows more clearly how the voltage at a component like an ECM depends upon the current path to that component. In calculating the individual voltage drop for each component, we must also use the total current through the component if the component also lies in a current path for other electronic functions as well as the power train ECM current path.

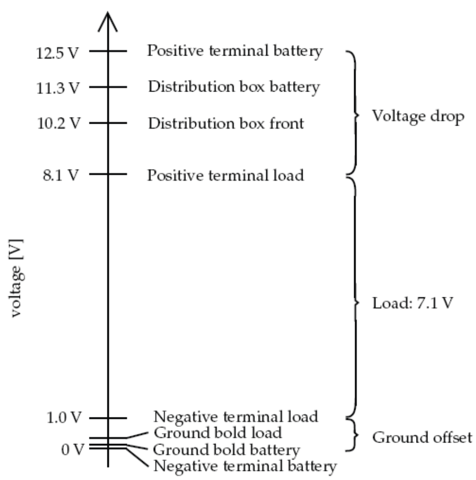


Fig 19. Voltage at different measurement points between the battery and an ECM.[23]

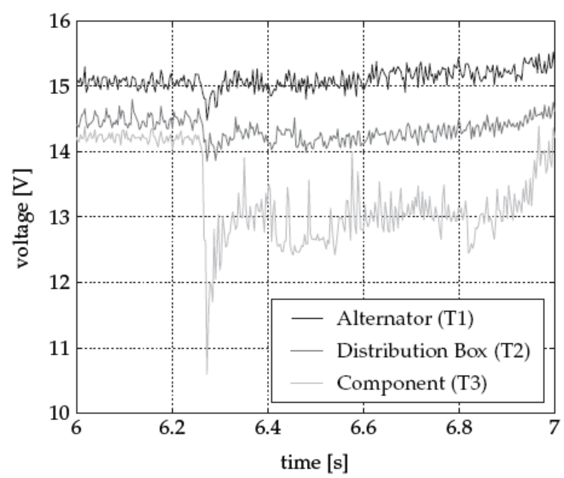


Fig 20. Voltages measured at the alternator (T1), a distribution box (T2), and terminals of an ECM (T3).[24]

Table 3 shows the results of our calculation of the ECM voltage. The calculation is more of an estimate than a detailed calculation because all connector drops have been approximated by the same one milliohm resistance and all cables have been approximated by the same 0.5 milliohm resistance. Also, the voltage drops across the fusible link, relays, and fuses have been neglected. Nevertheless, the table shows how such a calculation is done. The results are affected little by these approximations. The results show that the voltage drop at the power train ECM varies from 11.1 volts to 8.3 volts as the battery SOC decreases from 100% to 0%. Even the lowest voltage, 8.3 volts, will not cause a problem in most vehicle electrical systems.

Table 3. Calculation of voltage across the power train ECM for two extremes of battery conditions

		Full Battery		Depleted Battery	
	Current (amps)	Resistance (mohm)	Voltage (mV)	Resistance (mohm)	Voltage (mV)
(+) battery post connector	11	1	11	1	11
fuse link connectors	11	2	22	2	22
red cable	11	0.5	5.5	0.5	5.5
relay block connectors	11	2	22	2	22
junction block connectors	128	2	256	2	256
EFI fuse connectors	128	2	256	2	256
EFI relay connectors	128	2	256	2	256
ECM connectors	128	2	256	2	256
ECM cable to engine	128	1	128	1	128
engine bolt	128	1	128	1	128
braided cable to fender	11	0.5	5.5	0.5	5.5
ground bolts on fender	11	2	22	2	22
black cable to (-) battery	11	0.5	5.5	0.5	5.5
(-) battery post connector	11	1	11	1	11
battery internal resistance	11	10	110	70	770
Total			1494.5		2154.5
battery open circuit voltage (volts)			12.6		10.5
voltage across ECM (volts)			11.1		8.3

Table 4. Derivation of currents used in Table 3

	Current (amps)
current load of ECM	
ECM electronics (Table 1)	1
throttle motor (Table 1)	10
Total	11
battery current loads sharing part of ECM loop	
current loads active at all speeds (Table 1)	87
current loads active mostly at low speeds (Table 1)	76
alternator current at idle	-35
Total	128

Fig 21 shows the results of a similar calculation for the battery voltage in a vehicle with electric power steering (EPS), which uses a lot of current (80 amps). When the brakes are actuated the battery voltage dips to 11.8 volts, and when the EPS is actuated the battery voltage dips to less than 9 volts. Fig 22 shows that the battery voltage drops continuously as the battery discharges from 96% to 87% SOC. Since larger vehicles require EPS motors with higher torque, and higher torque means higher load current, this is the main reason why EPS is used only on smaller vehicles at this time.

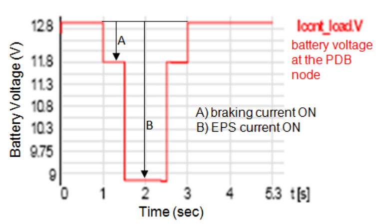


Fig 21. Battery voltage changes with braking current (A) and electric power steering current (B).[25]

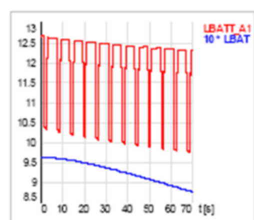


Fig 22. Battery voltage (top trace) and SOC variation (bottom trace) for repeated exercising of steering and braking.[26]

Figs 23, 24, and 25 show how the resistance of electrical connections can increase over time with corrosion. This type of corrosion is galvanic corrosion, which is enhanced by the current across the junction between the dissimilar metals. This corrosion can become so bad that the entire connector can be consumed, which creates an open in the current path. The corrosion can also form under the paint under a chassis ground bolt, making it appear as though corrosion is absent. This aging effect is present in all vehicles, but was not included in the voltage drop calculations above. Battery terminal corrosion directly adds to the battery's internal resistance. It is very important, therefore, to keep battery terminals clean and free of corrosion.

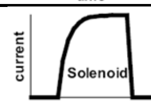
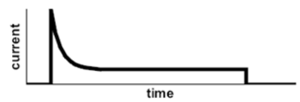
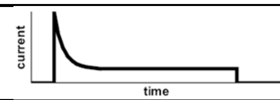
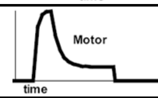
Fig 23. Corrosion on a battery terminal. Corrosion can also migrate 6 inches up the cable.[27]

Fig 24. Corrosion in a radiator fan motor connector.[28]

Fig 25. Connection of a ground strap to a chassis ground bolt.[29]

Inrush Currents. We will now discuss the inrush currents that we deferred while discussing Table 1. These inrush currents are of several types, as shown in Table 5. They all produce negative voltage spikes. Resistive loads, such as heating elements and rear window defrosters, have an inrush current equal to their steady state current value because their resistance does not change. Inductive loads, such as solenoids, relays, and clutches, have an inrush current that builds up slowly while energy is being stored in the magnetic field. After the magnetic field has reached its maximum value, the load behaves like a resistor until turn-off, when the energy in the magnetic field is released as the field collapses. This creates a huge voltage spike on turn-off which can be useful (as with ignition coils), or which must be suppressed using diodes or snubbers (as with relay coils). Capacitive loads, such as filter capacitors in ECU's, have a large inrush current at turn-on because the current initially sees the full voltage across the uncharged capacitor. As the capacitor charges with an exponential time constant (determined by the RC time constant of the capacitor and any series resistance), the current drops to nearly zero. The current then stays low while the voltage remains on. The ratio of the initial current spike to the steady state current value is about a factor of 5. An incandescent lamp, such as a headlamp, tail lamp, or flasher lamp, has a current waveform similar to a capacitor, but for a different reason. When the lamp is first turned on, the resistance of the filament is very low because it is a metal conductor like tungsten. As current continues to flow, the resistance of the filament increases, which reduces the current through the filament. After reaching a maximum temperature, the filament resistance ceases to increase, and the current reaches a steady state value. It then stays at its steady state value until it is turned off. The ratio of inrush current spike to the steady state current is about a factor of 5.

Table 5. Types of inrush currents. In a motor vehicle, these currents all draw current from the battery and produce negative voltage spikes

Load	Examples	Typical Current Waveform	Inrush Current (X = Steady State current)
Resistive	Heating elements, rear window defroster		1
Inductive	Solenoids, relays, clutches, ignition coils		1
Capacitive	Filter caps in ECU's (e.g., PWM, ABS, air bag ECU's)		~5X
Incandescent Lamp	Headlamps, tail lamps, flashers		~5X
Motor	Pumps, fans, blowers		5X to 10X

Electric motors behave in a more complicated fashion as shown in Fig 26. When a motor is first turned on, the windings in the motor behave like a very low value resistor, which creates almost a direct short to ground. Larger motors have smaller winding resistances, causing larger inrush currents. As the motor begins to spin, the spinning rotor interacts with the stationary stator coils to produce a voltage (called a counter-EMF) which opposes the initial voltage applied to the motor. This reduces the current through the motor, which reaches a steady state value as the motor speed becomes constant. The ratio of the inrush current to the steady state value is about a factor of 5 to 10 times, depending on motor size. A slower rotational speed means a smaller counter-EMF voltage, and a higher steady state current through the motor. A slower rotational speed may be the result of a heavy load on the motor, due to either a greater load imposed by the external accessory connected to the motor, or due to friction in the bearings inside the motor itself (due to wear or to dimensional changes imposed by high temperatures). A slower rotational speed also may be the result of a lower applied voltage, which makes the motor run slower. If the motor does not rotate at all, it is said to be seized or stalled, and the counter-EMF in this case is zero. This condition can happen for a variable length of time, called the stall duration, which can last many seconds or minutes (or even longer). During this time the motor current stays at its maximum value, called the stall current. After some arbitrary time, the motor can start rotating again to cause the current through the motor to decrease as normal.

Electric motors in an automobile can be powered either by a continuous battery DC current, as with most radiator fans and HVAC blowers, or by a pulse width modulated (PWM) battery voltage waveform, such as throttle motors, ABS brake pumps, windshield wipers, fuel pump, and nearly all remaining electric motors on the vehicle. In the case of PWM excitation, it is the time-averaged DC current that is relevant to the motor operation shown in Fig 26. This makes it difficult to add the inrush currents produced by two different PWM-controlled motors, because the motor currents are rarely in phase. However, there are two ways in which the inrush currents of two motors can add. In the first way, if one motor powered by a DC current (e.g., a radiator fan motor) is started and stalls temporarily, then a second motor (e.g., an ABS pump motor) started during the stall will add its inrush current to the first motor's stall current. The second way applies to some PWM-controlled motors used in applications requiring a high starting torque (e.g., an ABS pump). These PWM-controlled motors are designed to start in the direct current mode, which produces a higher starting torque. After a counter EMF voltage is detected, the controller switches the drive waveform to the PWM mode. In this case, if the motor is started and temporarily stalls, the PWM mode is never entered. During the stall duration, it is then possible for a second motor (e.g., a radiator fan motor) to add its inrush current to the inrush current of the stalled motor (e.g., ABS pump motor), as shown in Fig 27. These two cases can produce a giant current spike of approximately twice the magnitude of a single current spike.

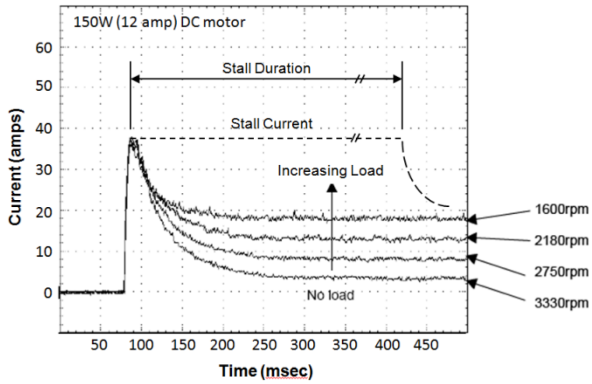


Fig 26. Current drawn by a 150W (12 amp) DC motor showing how the steady state current varies with rotational speed, reducing to the stall current when completely stopped or seized[30]

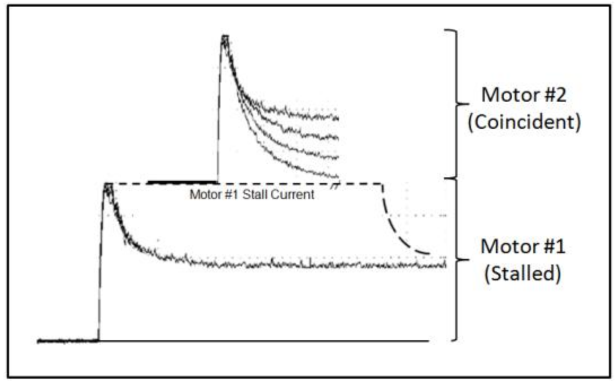


Fig 27. If a motor is stalled at start-up, the inrush current of a second motor may add to the inrush current of the stalled motor to produce a giant current spike of approximately twice the magnitude

Inrush current waveforms for all the current loads listed in Table 1 are shown in Appendix 1. The reader can view these to get a better understanding of their shapes and values. The inrush currents of these waveforms have been extracted and included in Table 1 as the inrush current values. These inrush current values can now be added to the steady state currents to determine the effect of a voltage spike caused by a particular inrush current or combination of inrush currents.

For example, we can calculate the effect of a radiator cooling fan start-up spike by including the radiator fan inrush current in the calculation of Tables 3 and 4 above. The result is shown in Tables 6 and 7 below. We see that the radiator fan inrush current (one of the largest), when added to the existing steady state current load, produces a voltage dip across the power train ECM of 10.4 volts with a fully charged (SOC = 100%) and 7.7 volts with a fully depleted battery (SOC = 0%). At battery charges between these two extremes, the voltage dip will be between 10.4 volts and 7.7 volts. Any voltage below 8 volts will cause a CPU reset to occur, as discussed below.

Table 6. Calculation of voltage across the power train ECM for two extremes of battery conditions assuming a radiator fan inrush current

		Full Battery		Depleted Battery	
	Current (amps)	Resistance (mohm)	Voltage (mV)	Resistance (mohm)	Voltage (mV)
(+) battery post connector	11	1	11	1	11
fuse link connectors	11	2	22	2	22
red cable	11	0.5	5.5	0.5	5.5
relay block connectors	11	2	22	2	22
junction block connectors	195	2	390	2	390
EFI fuse connectors	195	2	390	2	390
EFI relay connectors	195	2	390	2	390
ECM connectors	195	2	390	2	390
ECM cable to engine	195	1	195	1	195
engine bolt	195	1	195	1	195
braided cable to fender	11	0.5	5.5	0.5	5.5
ground bolts on fender	11	2	22	2	22
black cable to (-) battery	11	0.5	5.5	0.5	5.5
(-) battery connector	11	1	11	1	11
battery internal resistance	11	10	110	70	770
Total			2164.5		2824.5
battery open circuit voltage (volts)			12.6		10.5
voltage across ECM (volts)			10.4		7.7

Table 7. Derivation of currents used in Table 6

	Current (amps)
current load of ECM	
ECM electronics (Table 1)	1
throttle motor (Table 1)	10
Total	11
battery current loads sharing part of ECM loop	
current loads active at all speeds (Table 1)	87
current loads active mostly at low speeds (Table 1)	76
cooling fan inrush current (Table 1) less steady val	67
alternator current at idle	-35
Total	195

The important thing to remember is that all of these inrush currents are present in the electrical system at all times. Whether they can cause a voltage at the ECM below the 8 volt limit is determined by the state of charge (SOC) of the battery. If the battery is fully charged (SOC = 100%), the inrush currents will cause a voltage drop at the ECM of only 10.4 volts or above. However, if the battery is fully discharged (SOC = 0%), the voltage may drop as low as

7.7 volts. With intermediate levels of battery charge, or with any of the other (smaller) inrush currents, the voltage at the ECM will fall somewhere between 10.4 volts and 7.7 volts. One might say that a weak battery or low battery activates the existing inrush current spikes, causing the voltage at the ECM to drop momentarily to a value below 8 volts, at which a CPU reset will occur.

For example, Fig 28 shows that the inrush current of large radiator fan will cause the battery voltage to drop to only 10 volts if the battery is fully charged. As another example, Fig 29 shows that with a fully charged battery, ABS brake inrush currents of over 100 amps will cause the battery voltage to fall from 14.3V to only 14.1V and the voltage at the ABS ECU from 14.3V to only 11.5V.

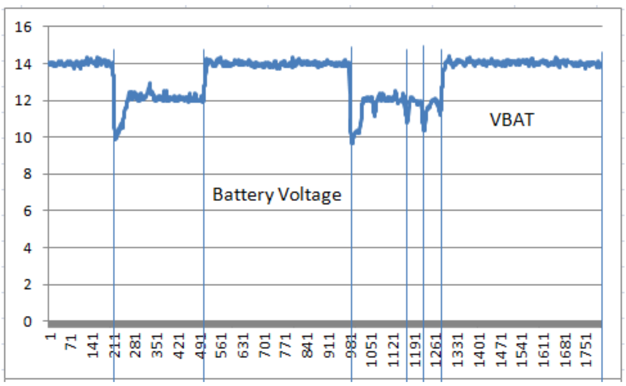


Fig 28. With a fully charged battery, a radiator fan with a large inrush current of 100 amps causes the battery voltage to drop to only about 10 volts.[31]

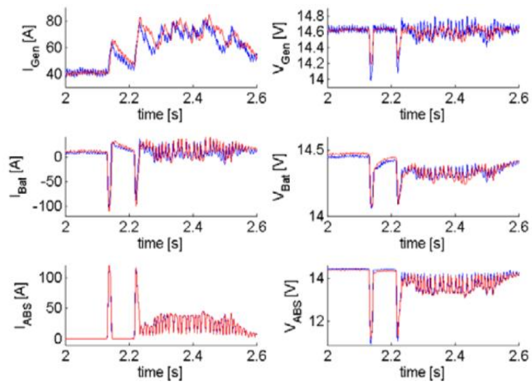


Fig 29. With a fully charged battery, ABS brake inrush currents of over 100 amps will cause the battery voltage to drop from 14.3V to only 14.1V and the voltage at the ABS ECU from 14.3V to only 11.5V.[32]

However, as the battery internal resistance increases due to a weak or low battery condition caused by internal corrosion or sulfation, the existing inrush current spikes cause the battery voltage to spike to lower and lower values. Fig 30, for example, shows that two inrush currents of constant size will produce larger voltage spikes as the battery state of charge (as indicated by the changing specific gravity) decreases. Fig 31 shows that the battery voltage drop during starter operation is greater as the battery internal resistance increases. Corrosion of the battery terminals, the "big three" battery cables, or the chassis ground bolts will add resistance in series with the battery's internal resistance and produce the same effects. A shorted battery cell, which drops the battery voltage from 12.6V to 10.5V, will also produce the same effects.

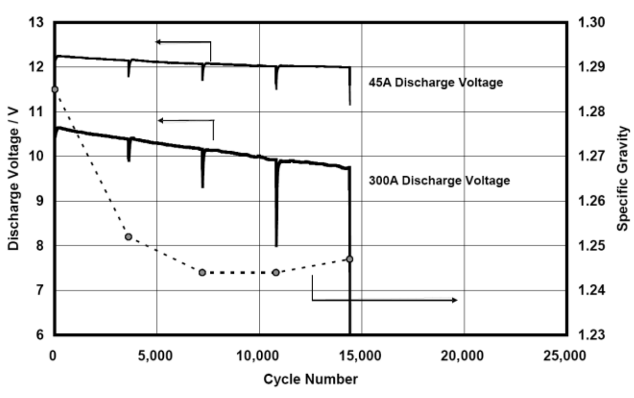


Fig 30. Two inrush currents of constant size produce larger voltage spikes as the battery state of charge (as indicated by the changing specific gravity) decreases[33]

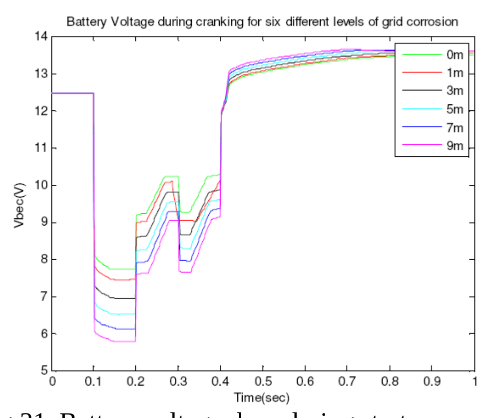


Fig 31. Battery voltage drop during starter operation varies from 7.7V to 5.8V as the battery internal resistance increases (simulation)[34]

Fig 32 shows a conceptual illustration of how the voltage spike associated with an inrush current has a noise margin above some critical voltage V_0 when sitting on the battery voltage of a fully charged battery. Fig 33 shows how this same voltage spike falls below the critical voltage V_0 when sitting on the battery voltage of a low or weak battery. The battery voltage has dropped due to a decreased open circuit voltage and the spike has grown larger due to a larger battery internal resistance.

Fig 34 shows a simulation of how the battery internal resistance increases with time due to normal aging by sulfation. This causes no problems until the internal resistance reaches a hazard zone, at which strange things start happening to the vehicle's electronics. We now know from the preceding discussion that as the battery internal resistance increases, the inrush currents produce battery voltage spikes that drop to lower and lower voltage values. The hazard zone is the point at which the negative voltage spikes drop down to some critical voltage V_0 at which a CPU reset may occur.

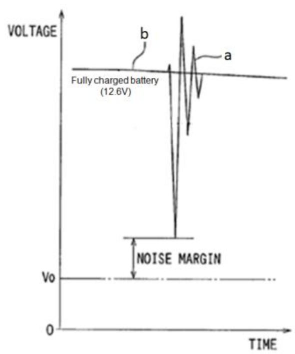


Fig 32. Inrush spike (a) on a fully charged battery voltage (b)

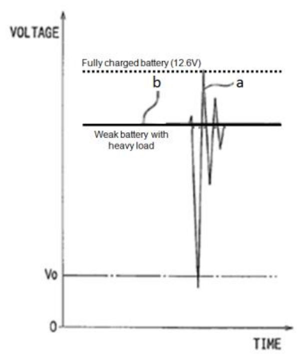


Fig 33. Inrush spike (a) on a weak battery voltage (b) pulled lower by a heavy load

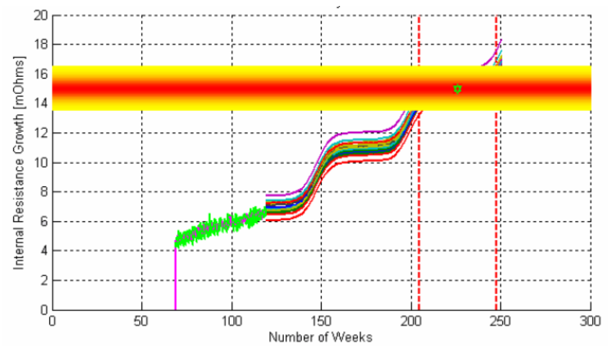


Fig 34. Long-term prediction for the change of battery internal resistance over time. The red/orange bar represents the hazard zone.[35]

What is so special about a battery voltage of V_0 = 8 volts? Why do strange things start happening to the electrical system at this battery voltage? We can answer these questions by taking a look inside the power train ECM.

Inside the power train ECM. If we follow the battery supply line into Toyota's power train electronic control module (ECM), the first thing we come to is a power supply ASIC. Fig 35 shows a block diagram of this ASIC as deduced from the NHTSA/NASA report on Unintended Acceleration. The ASIC contains a switching mode power supply regulator that drops the 12V battery voltage down to 6V. This voltage then feeds four linear regulators which drop the 6V down lower to 2.5V or 5V as required by the main CPU, the sub-CPU, and the CAN bus. The ASIC also supplies V_c = 5V power to all the vehicle's sensors that operate on a 5V supply. The ASIC contains a UVLO (under voltage lock out) voltage monitor which detects when the battery voltage drops below 8V and a second UVLO voltage monitor which detects when the 5V supply voltage drops below 4.7V. It also contains a watch-dog monitor which receives a pulse train from the main CPU. The ASIC contains a fifth linear regulator which operates directly off the raw battery voltage and which supplies power to the keep-alive memory in the CPU. This memory stores the learning information generated continuously by the engine control algorithms in the CPU as well as the diagnostic codes (OBD-II codes) that indicate faults found during engine operation. The most interesting thing is that the ASIC can issue reset commands to the main CPU and sub-CPU to cause them to shut down their operation based on the voltages detected by the UVLO voltage monitors and watchdog monitor.

Why does the power supply ASIC contain these CPU reset functions? The short answer is that the CPU's can make errors when their supply voltage temporarily drops below some arbitrary value. So when a voltage drop occurs, either on the battery supply input or the regulator supply outputs, and before it reaches the CPU's, the ASIC quickly tells the CPU's to shut down until the voltage drop goes away. Such a voltage drop is referred to in the semiconductor industry as a brown-out condition, as opposed to a black-out condition which indicates the complete loss of power supply voltage (see Fig 36).

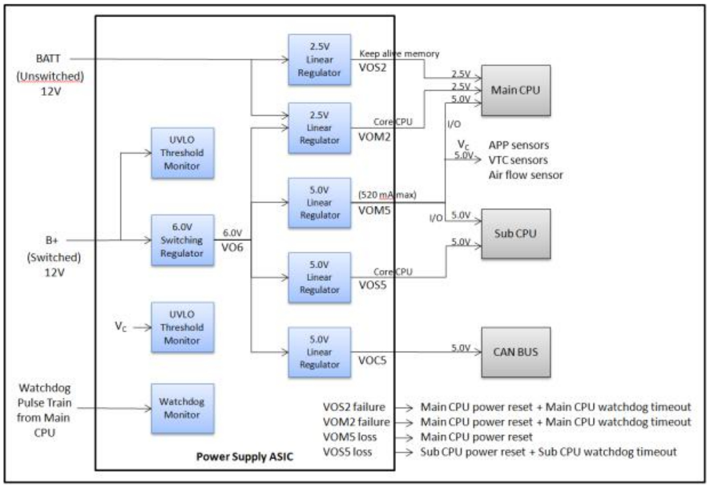


Fig 35. Block diagram of Toyota's power supply ASIC showing a switching regulator, linear regulators, voltage monitors, and reset functions[36]

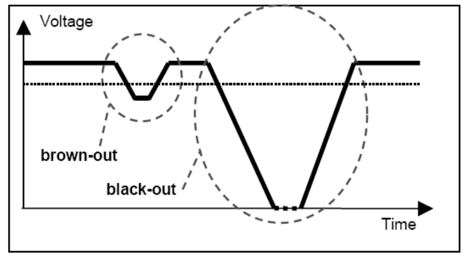


Fig 36. A brown-out is a temporary drop in the power supply voltage below the normal value as opposed to a black-out, which is a complete loss of the supply voltage.[37]

During a brownout condition, when the CPU supply voltage drops below some minimum voltage V_{min} that depends upon the clock rate, the following CPU errors can occur:

1) All registers in the CPU can have one or more bits changed in a random fashion, including:
    a. The program counter
    b. The memory address and data registers
    c. The data I/O register
    d. I/O control registers
2) All volatile on-chip memory (CMOS SRAM) can have one or more random errors in each word
3) Some or all non-volatile memory data can be corrupted including:
    a. All on-chip keep-alive memory (CMOS SRAM) can have one or more random errors in each word if the un-switched battery voltage drops below some minimum sustaining voltage V_{min2}
    b. External EEPROM can have all bytes in a page corrupted if an interrupt occurs during writing
4) The ALU can make random bit errors due to metastable states
5) The I/O pins can toggle randomly.

These errors can result in memory locations being unintentionally programmed and erased, runaway code, and port pins that can erratically change their states, potentially harming the actuators and motors being controlled by the CPU. The only way to avoid these CPU errors is to shut down CPU operation and wait out the low voltage brownout condition. This is what Toyota's power supply ASIC is designed to help achieve. There are also a host of software techniques to help detect and mitigate errors caused by brownouts.

The operation of Toyota's power supply ASIC is described in detail in Denso's US patent No. 7956587. Fig 37 shows a functional diagram of the ASIC's construction. Fig 38 shows a timing diagram of the ASIC's control functions. The patent describes how the ASIC monitors the 12V battery supply and the engine starter signal (STA). If the battery supply drops below 8V, or if the STA signal indicates that the starter is engaged, then the ASIC issues one of several commands to the CPU, depending on the magnitude of the switching regulator output (normally 6V). These commands can tell the two CPUs either to:

a) inhibit writing to their internal RAM memory (WI command),
b) store information quickly into the external EEPROM (PREINIT),
c) halt all CPU operation (HALT), or
d) reset their CPU registers (RESET) prior to power supply shutdown.

After the negative spike in the switching regulator has gone away, these CPU commands are withdrawn, and the CPUs are allowed to resume their normal function. While the 12V battery supply is above 8V and the STA signal indicates that the starter is not engaged, the ASIC monitors the 5V output of the linear regulator that produces the sensor bias voltages. If this voltage gets too low, then either a write inhibit (WI) command or a reset (RESET) command can be issued (but not the other two commands).

This patent clarifies several unknowns in our previous discussion of battery and inrush current operation:

1) What is significant about the 8V limit on the battery supply? (Answer: At this voltage the switching mode power supply output voltage gets so low that the linear regulators go out of regulation. This can cause an error in CPU operation).
2) What prevents the CPUs from being affected by the negative voltage spikes on the battery supply line caused by the inrush currents? (Answer: These spikes get passed through the switching regulator and the linear regulators just like the normal supply voltage. The CPUs are not affected because they are turned off by the ASIC commands just before the spikes arrive, and are turned back on later).
3) How do the CPUs withstand the huge negative voltage spike on the battery supply due to the starter inrush current? (Answer: The ASIC turns off the CPUs during engine starting, and turns them back on after the engine is running and the battery voltage becomes stable).
4) In what memory does the CPU store its information temporarily during a negative voltage spike? (Answer: It is stored in the keep-alive memory on the CPU chip, which is a part of the CMOS SRAM powered directly by the battery voltage. Also, when a negative voltage spike is detected a PREINIT command is issued by the power supply ASIC, causing the CPU to write some information to the external EEPROM. This information can then be retrieved after the negative spike has passed).
5) If both CPU's are turned off during reset, why does the engine continue to run? (Answer: Rotational inertia keeps the engine running during CPU reset. At 600 rpm the engine rotates one revolution in 100 msec. Reset durations are around 40 msec to 400 msec).

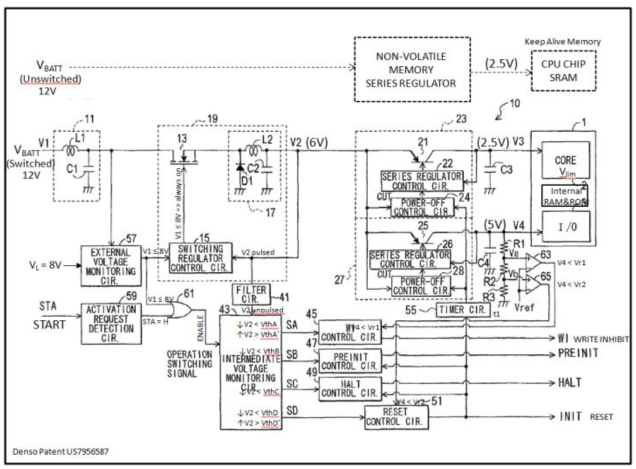


Fig 37. Functional diagram of Toyota's power supply ASIC as discussed in Denso's US patent 7956587[38]

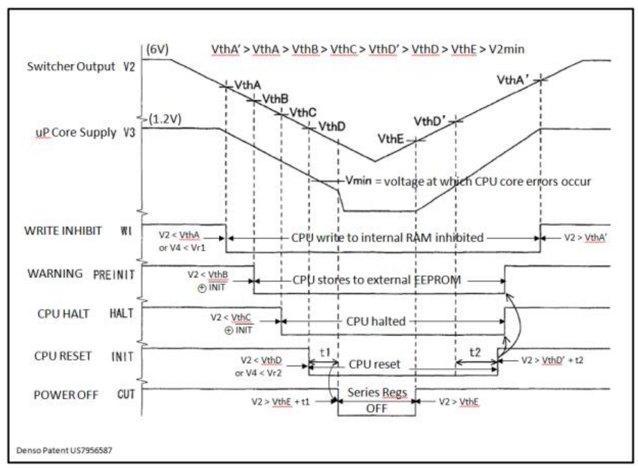


Fig 38. CPU control operations performed by Toyota's power supply ASIC[39]

Toyota's power supply ASIC is similar to Motorola's (now Freescale) 33394DH power supply ASIC that is used in some other automotive manufacturers' automobiles. Fig 39 shows a functional diagram of Motorola's 33394DH ASIC. Fig 40 shows a timing diagram of the 33394DH ASIC's control functions. Table 8 describes the operations performed during ASIC turn-on, brownout detection producing a regulator fault, brownout detection producing a keep-alive memory (KVAM) fault, and ASIC turn-off.

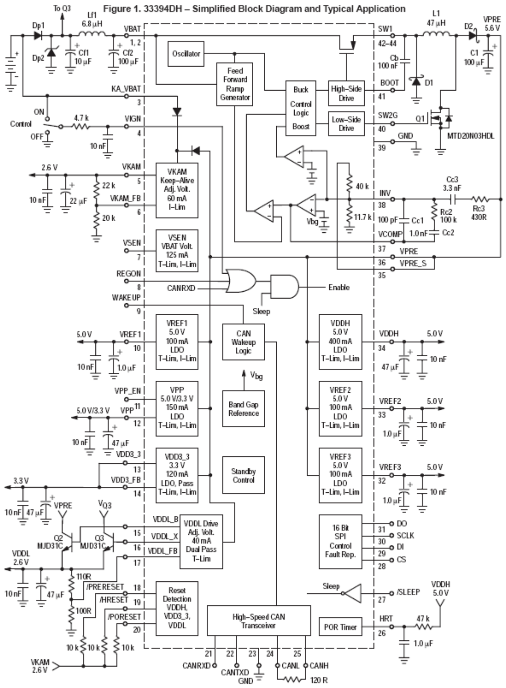


Fig 39. Functional diagram of Motorola's 33394DH power supply ASIC[40]

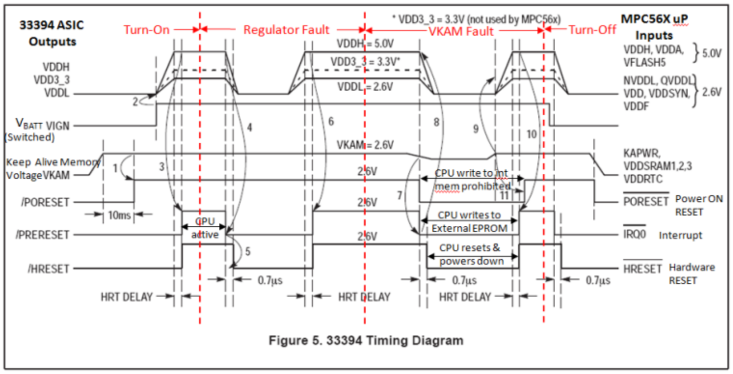


Fig 40. CPU control operations performed by Motorola's 33394DH power supply ASIC[41]

Table 8. Description of ASIC operation during ASIC turn-on, brownout detection, and ASIC turn-off as shown in Fig 40

1.	After ASIC is first connected to a battery, VKAM starts to regulate. After it stays in regulation for 10 msec, /PORSET is released.
2.	When VIGN is applied, a power start-up sequence is initiated.
3.	When all output voltages are stable and in regulation, /PRERESET and /HRESET are released after a programmable HRT delay.
4.	If any output voltage goes out of regulation, /PRERESET is asserted and a power down sequence is initiated.
5.	/HRESET is asserted 0.7 usec after /PRERESET.
6.	When all output voltages are again stable and in regulation, /PRERESET and /HRESET are released after a programmable HTR delay, and a power start-up sequence is initiated.
7.	If KVAM goes out of regulation (4% below its nominal value), /PORESET, /PRERESET, and /HRESET (after a 0.7 usec delay) are asserted .
8.	A power down sequence is initiated.
9.	When KVAM is back in regulation, a power start-up sequence is initiated.
10.	When all output voltages are again stable and in regulation, /PRERESET and /HRESET are released after a programmable HRT delay.
11.	After the fault on KVAM is removed, /PORESET is released after a 10 msec delay.

There are several similarities between Denso's ASIC and Motorola's ASIC:

1) Both consist of a single switching mode buck regulator that supplies power to multiple linear regulators. (This is an industry-wide technique that reduces power dissipation because the switching mode regulator is very efficient at reducing voltage without power dissipation).
2) Both have nearly the same switching regulator output voltage (6V vs 5.8V), and the same linear regulator output voltages (2.5V and 5V).
3) Both supply voltages to the main CPU, the sub-CPU, the keep-alive memory, and a CAN bus controller.
4) Both supply reset signals to the main CPU and sub-CPU to prevent their brownout due to negative spikes on the battery supply

The following differences exist between Denso's ASIC and Motorola's ASIC:

1) During normal operation, Motorola's ASIC monitors all output voltages directly. Denso's ASIC monitors them indirectly via the intermediate switching regulator output or the V_c = 5V output voltage only.
2) Motorola's ASIC has power up/down output voltage sequencing. This is not discussed for the Denso ASIC.
3) Motorola's ASIC has no CPU HALT function (without reset) while Denso's ASIC does.

4) Motorola's ASIC /PORSET (Power On Reset) signal combines the functions of Denso's WI (Write Inhibit) and PREINIT (Warning) functions.
5) Motorola's ASIC monitors the keep-alive memory supply voltage and issues a reset when it is out of regulation to prevent a CPU write operation. Denso's ASIC does not.

Can anything go wrong with the reset function in these ASICs to allow a brownout voltage to get to the CPUs without causing a reset? Yes, the following things can go wrong with both ASICs:

1) The power ASIC trigger voltages that produce a reset may not match the vulnerability threshold voltages of the CPU because:
   a. the vulnerability voltages of the CPU depend upon the CPU clock speed. Therefore, if a higher clock speed is being used in the ECM than was tested for by the CPU semiconductor manufacturer, arithmetic errors may result.
   b. both the CPU vulnerability voltages and the supply ASIC trigger voltages have a spread due to manufacturing tolerances in the semiconductor process. Therefore, some outliers may cause errors by failing to have the proper voltage match. This can be mitigated by:
      i. tightening the spread on the CPU vulnerability voltages, which raises the cost of the CPUs,
      ii. by raising the ASIC trigger voltages, which may cause CPU resets when not really necessary, or
      iii. by using trigger voltages with hysteresis.
   c. the CPUs may not be supplied according to the original design specification because either:
      i. the CPU test is faulty by design, or
      ii. to save cost, a test is not done on each CPU, allowing outliers that cause errors to get delivered to the ECM manufacturer.

   There is a constant battle between the ECM manufacturer and the CPU chip supplier to lower the CPU chip cost while maintaining the specs on vulnerability levels.
2) The power ASIC reset durations may not match the actual times that the negative voltage spikes spend below the ASIC trigger voltages:
   a. At the beginning of a brownout, if the supply voltage drops too slowly, then the CPU can execute some instructions while the supply voltage is below the minimum CPU voltage before the supply voltage drop can be detected. Another way to say this is: Reset can occur too late.
   b. During CPU recovery after a brownout condition, the supply voltage may rise so slowly so that the CPU begins executing while the supply voltage is still below the minimum CPU voltage. Another way to say this is: The CPU start-up after reset may occur too soon, or the reset time is not long enough.

We conclude this section by mentioning several things that can happen to a CPU when it is affected by a brownout condition. The first of these is latch-up, which can be caused by improper sequencing of the multiple bias voltages of the CMOS CPU during start up/power down. This possibility is well known in the semiconductor community, as evidenced by Motorola discussing how its 33394 power supply ASIC includes a provision for power up/down voltage sequencing. If Toyota's power supply ASIC lacks this provision, as Denso's failure to include it in their patent discussion seems to imply, then it is difficult to understand how latch-up can be avoided in a Denso ECM during reset recovery after the CPU power has been removed. This is particularly true when considering that the CPU may have a 5V bias applied to the STP digital input during power-up if the driver has his foot on the brake pedal during a brownout event, as shown by the Toyota wiring diagram in Fig 41. However, it appears that both CPU's continue to operate during a sudden acceleration incident based on Toyota's design of the ETCS-i system. So this seems to rule out latch-up as a cause of sudden acceleration.

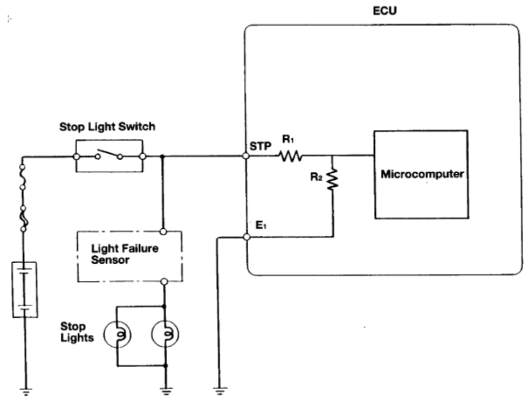


Fig 41. Toyota wiring diagram showing that a ratio of the battery supply voltage gets applied to the ECM microcomputer when the brake pedal is applied[42]

Another thing that can happen during brown-out is that data stored to memory can have bits changed in a random fashion. It is well known that error correcting codes exist which can detect and even repair the contents of a memory cell. However, these codes require time to execute which may not allow them to be used in time-critical control loops. Therefore, these codes may not be used all the time, or even not at all. It is not known whether Toyota's CPU software uses these error correcting codes for every memory access. And even if they are used, these codes fail for more than one bit error in a data word.

Another thing that can happen during brown-out is that a floating point datum in memory can be changed to a non-numerical datum. Once a non-numerical datum appears, a computation result using the non-numerical datum also becomes non-numerical. The same thing can occur with an infinity datum. Either type of error can cause a throttle control algorithm to suddenly change its output, resulting in unpredictable engine behavior. This is discussed further in Denso patent number US6816777. The way this works is shown in Figs 42 and 43. It is possible to detect such a non-numerical datum or infinity datum and prevent the error from spreading through a calculation by substituting a more normal data value. However, the code to do this requires more time to execute, which may not be available in a time-critical control loop. Therefore, the error may go undetected and the CPU will continue to execute but will issue an incorrect control output. It is not known whether Toyota's ECM software tests for this type of error in all its control algorithms.

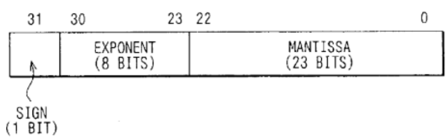


Fig 42. A 32-bit floating point number is represented by a sign bit, an 8-bit exponent, and a 23-bit mantissa[43]

EXPONENT	MANTISSA	MEANING
255	OTHER THAN 0	NON-NUMERAL
	0	+∞, −∞

Fig 43. If the exponent of a floating point datum gets changed to 255 (hex FF) then the datum becomes either an illegal non-numerical datum or an infinity datum[44]

Finally, an error can occur while writing to the EEPROM. The EEPROM in this case is a bit-serial EEPROM included in the ECM to satisfy 2004 CARB regulations for storing OBD-II DTC's[45]. This same EEPROM is used to store learning information for calibrating the accelerator position sensors, the throttle position sensors, computing the throttle position in response to the APP sensors or cruise control, calculating the fuel injection amount required, and calculating the ignition timing duration required.[46,47,48] If an error, such as a CPU interrupt generated by the reset command, occurs during the write operation, then the memory segment being written into will be left in an all "ones" (hex FF) state. This state occurs because an erase operation, which generates all "ones", must precede any EEPROM write operation. A serial EEPROM will have a single page (a page is usually eight bytes) set to all "ones" before writing. The EEPROM memory stores not only the learning information used by Toyota's unique engine control learning algorithms, but also the fault diagnostic codes detected during engine operation and read out using an OBD-II scanner. Therefore, it is possible that the OBD-II codes can also be incorrect or absent if a brownout event has caused an EEPROM memory error. Besides the possibility of data errors occurring during the EEPROM write operation, there are several other EEPROM fault modes that can result in data corruption. This makes the serial EEPROM a particularly vulnerable component for data corruption during reset.

Electronic Cause of Sudden Unintended Acceleration. We have now reached the point where we can combine the results of the previous sections and provide an explanation for an electronic cause of sudden acceleration. Our explanation is as follows:

> At idle, when the alternator cannot supply all the current required by the vehicle's electrical system, and the battery must supply the additional current, the system voltage is determined by the battery voltage. In this case, if the battery charge is weak (i.e., the battery becomes "run down"), then the battery voltage will be low, and the inrush current caused by one of the vehicle's electrical functions (e.g., an electric motor) starting up will cause a large negative voltage spike on the battery supply line that passes through the ECM voltage regulators and leads to a brownout error in the CPUs, if the CPUs are not properly held in reset by the ECM voltage supply. The brownout error can cause faulty operation of the CPUs, keep-alive memory, and/or EEPROM memory, leading to a software error that causes unpredictable engine behavior, such as sudden acceleration.

Supporting evidence for this explanation is provided in the following sections of this paper. The supporting evidence includes testimonials describing how battery replacement cured sudden acceleration in several vehicles, and discussions of how the above explanation explains many driver observations associated with sudden acceleration.

At this point someone might say. "This explanation is just pure speculation which combines normal electrical system operation with an unsupported assertion that the power supply ASIC reset function is faulty, causing the CPU's to produce erroneous outputs leading to sudden acceleration by some unspecified means".

The answer to this criticism is that the explanation, indeed, fails to explain how "a brownout condition can cause faulty operation of the CPU hardware and/or software, leading to unpredictable engine behavior, such as sudden acceleration". However, it is not speculation that a brownout condition can result from vehicle operation at idle when the battery is discharged and the battery voltage is low. These conditions follow directly from driver's observations of low speed at the time of sudden acceleration. The only logical conclusion is that this brownout condition is the cause of sudden acceleration. We shall see in the following sections that this mechanism can explain many other observations associated with sudden acceleration, including why all vehicle makes and models with electronic throttle control similar to Toyota's ETCS-i design are susceptible to sudden acceleration to some extent. Therefore, there is more than enough evidence to indict faulty reset operation during a brownout as a cause of sudden acceleration. This explanation clearly focuses attention on a weak point in the electrical system design of all automobiles with electronic throttle control.

III. Supporting Testimonials

Testimonials describing drivers' experiences with sudden acceleration being cured by battery replacement and related automobile electrical problems also being cured by battery replacement are given in Appendix 2. Appendix 2 also contains descriptions of electrical problems in some non-automotive control systems and how they were cured by battery replacement, including:

1) runaway pacemakers,
2) runaway wheel chairs,
3) runaway golf carts,
4) runaway robots in robot competitions,
5) loss of control in amateur radio-controlled airplanes, and
6) loss of engine control in a non-commercial aircraft.

These non-automotive applications were included because they imply that battery state of charge is an important condition that can have a dramatic impact on the operation of many types of electrical systems controlled by digital microcontrollers.

IV. Application to Remaining Observations of Sudden Acceleration

We now apply our findings to explain the remaining observations of sudden acceleration as listed in Section I.

Observation 3 - Sudden unintended acceleration incidents occur four times more often when entering a parking space than when leaving a parking space.

We can explain Observation 3 by the fact that the alternator is hotter when entering a parking space (because the vehicle has been running a long time) than when leaving a parking space (because the vehicle has likely just been started prior to leaving). Since alternator current output decreases as the alternator temperature increases, as shown in Fig 6, the difference in incident rates can be attributed to the difference in alternator temperature, which produces a higher alternator current when leaving the parking space than when entering a parking space. This higher alternator current makes it less likely that the battery is setting the system voltage when leaving the parking space than when entering it, which raises the system voltage to the alternator voltage level of 14.3V, which increases the voltage margin for inrush spikes to reach down to the critical 8V level.

Observation 5 – Sudden unintended acceleration incidents occur more often with elderly people.

We can explain Observation 5 by the fact that elderly people are frequently retired, and make shorter trips closer to home than younger people, who are usually working and must commute a longer distance. Also, elderly people may not use the vehicle every day while younger people must do so to go to work. These shorter and less frequent trips mean that with elderly people the battery is more likely to run down (i.e., have a lower state of charge), which lowers the battery voltage and increases the probability for a brownout event.

Observation 6a – Sudden unintended acceleration incidents occur with all makes of automobiles.

We can explain Observation 6a by the fact that all automobiles have the same basic electrical system design, consisting of a battery, an alternator that has a lower current output at idle, accessories that have similar inrush currents, an ECM containing a power supply ASIC having a switching mode power supply and multiple linear regulators, and two CPU's in control of the electronic throttle system.

Observation 6b – GM has a lower sudden unintended acceleration incident rate than Toyota and Ford.

We can explain observation 6b by the fact that GM Delco alternators have a delta winding configuration while Toyota and Ford alternators have a Wye winding configuration. The delta winding allows GM alternators to produce a higher current output at idle than Toyota or Ford alternators of the same nominal output (which is specified at 6000 RPM), as shown in Fig 44. GM vehicles may also use alternators having a slightly higher specified current output than Toyota or Ford, who tend to use alternators that are undersized for the number of accessories on the vehicle.

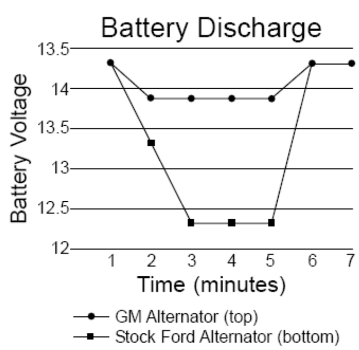


Fig 44. The same discharge current produces a higher battery voltage at idle with all accessories on for a GM alternator than for a stock Ford alternator[49]

Observation 12 – Sudden unintended acceleration incidence rates are higher in the USA than in Canada or Europe.

We can explain this observation by the fact that the USA requires daytime running lights (i.e., headlights on) while Canada and Europe do not. Headlights, because they are on for long time, can discharge a battery quickly when the vehicle spends a lot of time at idle. Also, European automobiles have a higher percentage of stick shift transmissions than US models because of the high price of fuel in Europe. Therefore, Europeans may not be as sensitive to sudden high speed engine operation.

Observation 13 – Drivers often complain that during sudden unintended acceleration the vehicle's brakes were ineffective, either partially or totally.

This observation has become a major stumbling block for drivers trying to convince the NHTSA that the vehicle was at fault for sudden acceleration. Many drivers have contended that during sudden acceleration the brake pedal was ineffective, sometimes even going all the way down to the floor, and still the vehicle did not stop. NHTSA responds by saying that they have examined the brakes after the incident and that they are fully functional. They then note that the only way the brakes could have appeared to fail is if the power brake booster operation was diminished or lost. This can occur because the power brake booster operates on engine vacuum, which is much less at high engine speeds. This might cause the loss of power brake assist during an incident when the engine is running at high speed, but the unpowered brakes are designed to allow the driver to stop in a reasonable distance from any speed, even if the engine is running at its highest speed. Therefore, it is likely that the driver just did not apply the brakes. If the driver still insists that he did, and that the brakes were "mushy", or went all the way to the floor, then the NHTA will say that this can't happen because the loss of power brake assist causes a "hard pedal" feel due to the remaining unpowered brakes still functioning, and the driver is describing a "soft pedal" feel. NHTSA then says that if the driver indeed felt a "soft pedal", then he must have been pressing on the accelerator, because this is the only pedal that feels "soft" and goes to the floor. And this, they maintain, can also explain the high engine speed in the first place. If the driver still maintains that he was pressing on the brake pedal, and not the accelerator pedal, then NHTSA responds that the only way the unassisted brakes can fail is to have a mechanical problem in the brake system, which would create a physical change that can be observed. They then challenge the driver to produce evidence of this physical change. This is why the NHTSA has included "apparent loss of braking effectiveness" in its 1989 definition of sudden acceleration. It forces the driver into the dilemma of proving either: a) that his foot was on the brake and not on the accelerator (which is nearly impossible to prove), or b) providing evidence that the brake system was mechanically defective (which rarely happens and is also nearly impossible to prove).

Consider, now, that many automobiles have ABS brakes. ABS brakes have become more popular since the late 1990's, starting as an option on higher-end models, then after 2000 as an option on lower-end models, until in the mid 2000's is a standard item on most models. ABS brakes operate by using solenoid valves that open to release brake fluid from the brake lines temporarily, which reduces hydraulic pressure in the brake cylinders. Then the valves close again to resume normal braking operation. This is like taking one's foot off the brake and then re-applying it again, but it occurs at a higher repetition rate of about eight times per second. "Wait a minute", one might say. "That can't be correct because it would mean that ABS brakes are less effective at stopping the vehicle than normal brakes. Isn't it the goal of ABS brakes to stop the car faster?" The answer is that it is not the goal of ABS brakes to stop the car faster. It is the goal of ABS brakes to maintain control of the car during stopping, which is believed to prevent accidents. ABS brakes maintain control of the car by detecting when a tire starts slipping on the road surface. They then relieve pressure on the brake for that specific tire to keep the tire rolling, which prevents slipping. By preventing slipping of the tires on the road surface, the car can continue on its intended path, allowing the driver to maintain control of the vehicle. This improved control is obtained at the expense of a longer stopping distance. As far as brake "effectiveness" is concerned, we have subtly changed the definition of "brake effectiveness" from "stopping the car faster" to "improved control during stopping".

Continuing the description of ABS brake operation, when the ABS solenoid valves open to release brake fluid, the released brake fluid is captured and pumped back into an accumulator by an electric ABS pump. When the pressure in the accumulator gets too low, the electric pump is activated to increase the pressure. The solenoid valves are controlled by an electronic control unit (called the Skid Control Unit by Toyota) that contains two CPU's just like the engine control unit (called the ECM by Toyota). The CPU's get information from speed sensors on each wheel, and make a decision on whether a wheel is beginning to slip or not. If slip is detected, then the CPU's activate the solenoid valves for that wheel. One can imagine that the design of the ABS brake electronic control unit is much like the design of the engine control unit. In fact, its CPU's, memory, keep-alive memory, EPROM's, and power supply ASIC are usually exactly the same devices as used in the engine control module. Therefore, its CPU's are susceptible to brownout caused by voltage spikes on the power lines from inrush currents just like the CPU's in the engine control module. This means that the same voltage spike, which causes an upset in the engine control module to produce a sudden increase in engine speed, can also cause an upset in the ABS control module to cause the solenoid valves to open, reducing pressure on the brakes. This can produce a reduction in brake pressure or even a total failure of the brakes, which creates a "soft pedal" that can go all the way down to the floor.

So here we have identified a single fault that can produce both "acceleration from a stationary or very low initial speed position" and "loss of braking effectiveness", which is required by NHTSA's 1989 definition of "sudden acceleration incident". Both NHTSA's 1989 report and NHTSA's 2011 NASA report state that no connection was found between brake operation and ECM or cruise control operation. This is akin to observing one's TV and refrigerator turning off in one's home during a storm, and saying that a connection cannot be found between these totally different events, one of which is electronic and the other mechanical. The connection, of course, is a disruption of the electric power. The authors of these reports apparently did not look hard enough for such a connection.

One might challenge this conclusion by saying that the ABS brake system does not operate below 35 mph, so it can't be the cause of brake failure at low vehicle speeds such as in parking lots and at traffic intersections. This statement is not true because, if the ABS brakes would stop functioning below 35 mph, then the tires could slip below 35 mph, and much of the effectiveness of ABS brakes would be lost. Also, many drivers have reported that the ABS brakes can be felt operating through the brake pedal, or that the ABS pump can be heard operating at low vehicle speeds, while in a parking lot. What is really meant by this statement is that the <u>initiation</u> of ABS braking cannot begin below 35 mph, but that once initiated, the ABS braking functions can continue until the vehicle is stopped. Therefore, the ABS brakes can remain operable even in low speed situations, such as pulling into a parking lot or approaching an intersection, as long as one's foot remains on the brake. If this doesn't happen by design, then it does happen by faulty ABS operation wherein a wheel speed sensor (usually a front wheel sensor) detects slipping erroneously because of magnetic debris on the sensor or because it is misaligned on its mount due to corrosion. And this keeping one's foot on the brake is what many drivers contend was happening during sudden acceleration. While the ABS brakes remain activated in these situations, it may happen that the inrush current of a radiator fan turning on or the ABS pump turning on creates a brownout-producing event that freezes the solenoid valves in an open state. Or it may also happen that, if the brake fluid (pressure) gets too low as a result of the continued operation of the ABS brakes, the ABS pump cannot turn on to restore fluid (pressure) in the accumulator. These, and possibly other modes of faulty operation, should be examined further.

Finally, one might say that this explanation fails to account for sudden acceleration incidents while leaving a parking lot because the vehicle speed started low and remains low. Therefore, the ABS brakes cannot activate. The answer to this is that when the engine is first turned on, the ABS electronic control module in all automobiles is designed to initiate a diagnostic routine which tests all the components of the ABS system. It turns on and off the ABS pump motor and turns on and off each solenoid valve to check for proper operation. It also runs the pump for about 14 seconds to increase the pressure in the accumulator. If a brownout event occurs during this diagnostic routine, then a solenoid valve can be left open or the accumulator may not be at full pressure. The result of either condition would be a "soft pedal".

This explanation of ABS brake operation during sudden acceleration leads to a verifiable prediction that most drivers' claims of braking ineffectiveness during sudden acceleration occur in vehicles having ABS brakes. This can be checked by the VIN number.

It is interesting that the ABS electronic control unit contains a keep-alive memory just like the engine control module does. Therefore, the contents of this memory can be examined after a sudden acceleration incident just like the contents of the engine control module keep-alive memory. This might provide further information that can be of value in determining the exact cause of CPU upset.

<u>Observation 9</u>. Sudden unintended acceleration incidents occur rarely with police cars even though they are used a lot at low speeds.

Police cars do operate a lot at idle, and do have a lot of high current loads at idle. However, they also have high-output alternators which can produce over 200 amps at idle. Also, they have an idle-up feature which senses when the battery voltage is getting low, and increases the engine idle speed to increase the alternator current output. It is interesting that for over two decades the Ford Crown Victoria has been the only police car for every police force across the USA. This changed in 2011, when Ford decided to get out of the special police car market. In the future, police cars will be adaptations of stock motor vehicles, including Ford's Taurus, Chevrolet's Caprice and Dodge's Charger. It will be interesting to see if this increases the incident rate of sudden acceleration in police cars.

Observation 10. When the ignition is turned on again after it has been turned off following a sudden unintended acceleration condition, the engine RPM's nearly always resume in a normal low state. That is, recycling the ignition nearly always removes the sudden unintended acceleration condition.

We can explain this observation if we assume that after a brownout reset, the CPU reads an adaptively learned value, such as the accelerator pedal position (APP) sensor idle position or the throttle position sensor (TPS) idle position, from the keep-alive memory and uses it in succeeding calculations. This learned value is usually stored in the kep-alive memory, but may have been temporarily parked in the EEPROM after being warned of an arriving brownout condition by the power supply ASIC. If this adaptively learned value has been corrupted while in the keep-alive memory or the EEPROM, then reading it from the keep-alive memory or EEPROM will cause the succeeding throttle control calculations to be in error, and unpredictable engine operation may result.

On the other hand, after an engine start-up, it is known that the CPU performs a calibration of the APP and TPS sensors, and then stores the learned idle position values in the keep-alive memory. Therefore, these values are the correct learned values, and the succeeding throttle control calculations will be correct, causing no unpredictable engine operation, such as sudden acceleration.

Observation 15. If a crash occurs as a result of sudden unintended acceleration, sometimes the front airbags do not deploy even though damage to the vehicle is extensive.

The explanation of this observation is similar to that for Observation 13 on ABS brakes. The air bags operate using an electronic control module which contains a CPU (which may be a simpler one than the ones used in the engine control module and the ABS control module). The CPU is powered by a power supply ASIC with reset capability. The CPU can be upset by a brownout event. This can be the same brownout event that disrupts the engine control module and the ABS control module.

Observation 8. Sudden unintended acceleration incidents have occurred in Toyota hybrid vehicles like the Prius.

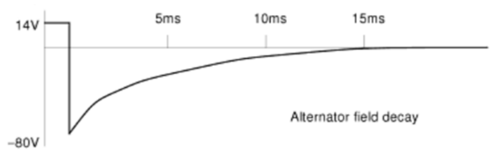
The Prius does not have an alternator. Instead, it has a DC/DC converter which charges the 12V battery. The 12V battery is used for the engine control module, brake control module, headlights, power steering, electric water pump, and radiator cooling fans. (The air conditioner compressor runs off the traction battery). The engine control module has two CPUs and a power supply ASIC, and controls engine sensors and actuators just like other Toyota vehicles. Therefore, the electrical system is very similar to the electrical system used in most other Toyota models. This means that the 12V battery can run down and activate inrush currents that can cause brownout of the CPU's, leading to sudden acceleration, just like in other Toyota models.

It is interesting that the new 2012 Prius has LED headlights instead of the incandescent headlights used in other Toyota models. Since LED headlights operate at lower currents than standard incandescent headlights, this shows that Toyota wanted to reduce the current load on the 12V battery. Evidently, they saw a need to manage this current load.

Observation 2. 8% of sudden unintended acceleration incidents occur at high speeds.

At high speeds the voltage of the electrical system is set by the alternator and not the battery. Therefore, the explanation that a low battery condition activates inrush currents leading to brownout of the CPU's does not apply at high speeds. However, this explanation for low speed incidents appeared so convincing to the author that he was led to look at the alternator for a source of negative voltage spikes that might explain the high speed incidents. And he soon found two such sources. Worn or bouncing brushes inside the alternator can interrupt the field current and produce a huge negative voltage spike on the alternator output as shown in Fig 45. This spike is known as an alternator field decay waveform. It is produced when the alternator field current is disconnected or interrupted, and the alternator field decays, such as when the engine is shut off. It has been discussed and modeled in ANSI/ASAE Standard 455, entitled “Environmental Considerations in Development of Mobile Agricultural Electrical/Electronic Components”, published by the American Society of Agricultural Engineers (ASAE) in 2000.

Another possibility is shown in Fig 46. Fig 46 shows an oscilloscope trace of the “12V” system voltage of a 1995-96 Ford van under a low load condition when the alternator is setting the system voltage. Notice that the baseline DC voltage is 14.3V, which is the alternator voltage. When these negative spikes appeared on the generator output the engine would miss-fire, lose power, and backfire through the exhaust. Changing the generator repaired the vehicle. On internal inspection of the disassembled generator it was found to have an intermittent broken wire connection in the diode bridge. Spikes occurred when the connection was open. These spikes will certainly generate a brownout condition in the CPUs if they are not held in reset during the pulse.



ASAE Standard EPP 455 model:
$-90e^{-t/0.038}$ from + 14 V for 60 cycles

Fig 45. Alternator field decay pulse produced when the alternator field current is interrupted[50,51]

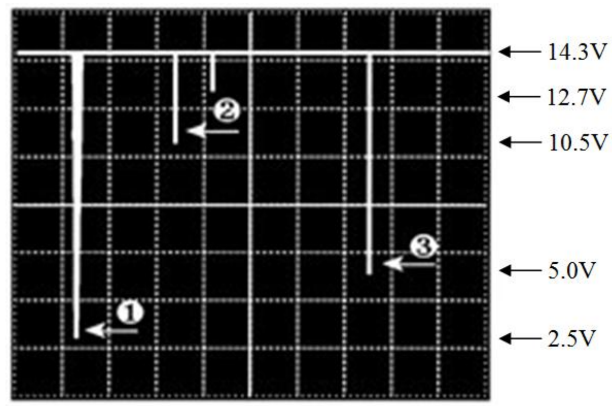


Fig 46. Oscilloscope trace of the “12V” system voltage in an automobile under a low load condition when the alternator is setting the system voltage[52,53]

Worn or bouncing brushes in the alternator, or an open in the diode bridge, provide an explanation for high-speed incidents like the Pepski and Haggerty incidents. This explanation makes a prediction that can be verified or negated by experiment. All one needs to do is disassemble the alternator after a high speed incident and inspect it to look for signs of worn or bouncing brushes or an intermittent broken wire in the diode bridge.

Observation 16. Sudden unintended acceleration is a very intermittent condition. It has not been reproduced on demand.

We can explain this observation by the fact that the battery state of charge can change. Immediately after a sudden acceleration incident, the battery will still be in a low state of charge, and sudden acceleration may reoccur. However, several hours after a sudden acceleration incident, after driving the vehicle for a half hour or more at highway speed, the vehicle’s battery will recharge, and sudden acceleration may not reoccur. That is, it may not reoccur until the battery runs down again, which can happen with a weak battery.

This also explains why sudden acceleration has not been observed during testing of vehicles by manufacturers or the NHTSA. Prior to normal electrical testing, the battery condition is usually inspected and, if the state of charge is low, the battery is brought up to a full charge. This removes the condition which leads to sudden acceleration in the first place. Another testing detail that must be considered is how conductive spikes are injected into the 12V system. If they are voltage spikes, the source impedance of the voltage supply must be low (less than the battery internal resistance) or else the currents injected will be attenuated and there will be little effect on the battery voltage. If the “12V” system voltage, as seen on a high-speed oscilloscope, does not go below 8V during spike injection, this would not be a valid test of sudden acceleration caused by negative voltage spikes producing CPU brownout.

V. Mitigation Techniques

Several measures may be considered by automobile manufacturers to lessen the probability of a low battery condition causing a reset that leads to sudden acceleration. These are:

1) Connect the engine ECM (i.e., PCM) power and ground inputs directly to the battery terminals instead of to the alternator and the engine block, respectively. This will eliminate all voltage drops across battery cables and connectors that are shared by other high-current loads, leaving only the voltage drop across the battery internal resistance. Use shielded wires, if necessary, to avoid EMI and use large enough diameter wire to keep the wire resistance small.
2) Power the engine ECM (i.e., PCM) using a second 12V battery independent of the main 12V battery that powers all the high-current loads. Charge the second battery with the alternator only at high vehicle speeds, and isolate the second battery from being discharged by all other electrical loads.
3) Use an alternator with a higher output current at idle.
    a. Use a high-output (HO) alternator that can provide between 100 and 200 amps at idle, which is more than adequate for keeping the existing battery charged up. Several suitable HO alternators already exist, however they are more expensive and have a larger size, which reduces the design options for a small vehicle with a low profile hood design.
    b. Add an alternator clutch pulley that allows the alternator to spin faster at low engine speeds, thereby producing a higher output current. Such clutch pulleys are already used in some European vehicles such as BMW and Audi, but have not been widely adopted because of problems with bearing noise at high speeds and short pulley life. However, some manufacturers claim to have solved these problems with improved materials and a better clutch design.
4) Use a 12V battery with a higher current capacity that does not run down as fast. Larger batteries also have lower internal resistances, which reduce voltage drops to the ECM. The obvious drawback to larger batteries is that they can still run down if not maintained well or kept fully charged. They also deteriorate with age, just like existing batteries.
5) Use ferroelectric RAM (FRAM or FERAM) instead of EEPROM in the ECUs. This measure will only apply if the cause of sudden acceleration can be further traced to faults in the EEPROM during reset. Serial ferroelectric RAMs having the same package, pin-outs, and functions as EEPROMs already exist from several manufacturers, and have faster erase/write times and fewer data corruption mechanisms than existing serial EEPROMs.

None of these measures will completely eliminate the possibility of sudden acceleration due to low battery voltage causing a reset. Also, the first two measures apply only to mitigating engine ECM faults, and not to reducing the associated incidents of ABS brakes being lost or air bag sensors failing to be deployed unless the ECUs for these functions have the same measures applied to them as well. The remaining three measures apply to resets in all ECUs, but their effectiveness is difficult to quantify. All of these measures except the last would increase the vehicle cost.

There is one simple measure that the owner/driver can take to mitigate sudden acceleration incidents. The driver can purchase a battery voltage monitor similar to the ones shown in Figs 48 to 50 that plugs into the cigarette lighter and that displays the battery voltage. When the monitor displays a low battery voltage, the driver can either turn off some electrical accessories until the voltage rises again, or can avoid driving the vehicle all together. Some of these voltage monitors even produce an aural alarm when the voltage drops below a given voltage. One should exercise caution in using such a voltage monitor, however, since it draws current from the battery and can run down the battery if left plugged in while the vehicle is unattended. Therefore, it is best to unplug the monitor when exiting the vehicle, which can become a burden for some users.

Fig. 48. BatteryMole voltage monitor by 4Peaks-Tech.com

Fig 49. Equus 3721 voltage monitor from Equus.com

Fig 50. 12 Volt Minder UPG 71730 from BatteryStuff.com

VI. Conclusion

Drivers' observations of sudden acceleration were presented, and one of them – a high incident rate during low speed vehicle operation – was used to deduce an electronic cause of sudden acceleration. This cause was then able to explain many of the remaining observations of sudden acceleration, including sudden acceleration at high vehicle speeds. The role of the battery state of charge in causing sudden acceleration was discussed, and how it varies with the vehicle's total electrical current demand and its alternator output capacity at idle. It was shown that the total electrical current demand will continue to grow in the future as more electronic functions, such as electronic power steering, electronic stability control, adaptive cruise control, electronically tuned suspension, and electronic brake by wire, are added to vehicle. Without a major improvement in the alternator capacity at idle, these new electronic functions will only increase the incident rate for sudden acceleration in the future.

Finally, it was shown that the inrush currents from electrical loads turning on create negative voltage spikes that are present at all times in all vehicle systems. These negative voltage spikes can be activated by a low battery voltage associated with a weakly charged battery. It was concluded that the present designs of CPU reset supervisors, such as Toyota's power supply ASIC, still allow some of these negative voltage spikes to produce a brownout event in the CPU, or to affect keep-alive memory or EEPROM operation, despite elaborate reset strategies. It is hoped that this paper will initiate a widespread investigation into inrush current waveforms and brownout reset operation in battery-operated vehicle control systems and how CPU errors or keep-alive memory errors can lead to sudden acceleration. In this way a permanent solution to sudden acceleration can be achieved.

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