A More Detailed Electronic Mechanism
for Sudden Unintended Acceleration

by

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Abstract: Long term unintended acceleration events with engine speeds approaching 5000 to 6000 RPM are explained in terms of the author's previous theory of sudden unintended acceleration. It is shown that these events have a common origin with vehicle surging events at low speeds and that both can happen while the driver's foot is off the accelerator. This means that brake override systems are completely ineffective in preventing sudden unintended acceleration in vehicles having electronic throttles. It is shown that unintended acceleration is a problem inherent to the electronic throttle systems of all automobile manufacturers. The root cause of unintended acceleration in vehicles having electronic throttles is identified, and a solution is presented.

I. Introduction

Thousands of drivers over the past ten years have stated that their automobiles have accelerated suddenly on their own, sometimes going to full wide open throttle, before the driver could regain control or before the vehicle crashed. The problem has occurred in nearly all makes and models of automobiles, although it seems to predominate in vehicles having electronic throttles (i.e., drive by wire). Yet, all auto manufacturers have stated that their vehicles cannot accelerate on their own, and that the problem is caused by the driver – either as a result of the driver confusing the accelerator for the brake, or the driver pressing on the accelerator and the brake at the same time, or the driver allowing a floor mat to capture and hold down the accelerator, or the accelerator sticking down because of a manufacturing defect. This problem continues to occur in 2013 even on some MY2010 vehicles having brake-throttle override and even after NHTSA has required all manufacturers to include brake-throttle override on all their vehicles starting in 2012.

Sudden unintended acceleration is characterized by the following summary of driver's observations:
1. Sudden unintended acceleration happens at a low rate in vehicles from all manufacturers.
2. Sudden unintended acceleration incidents increased with the introduction of electronic throttles (i.e., drive by wire).
3. Sudden unintended acceleration occurs while the driver's foot is off the accelerator. Usually the driver insists that his foot is on the brake.
4. Sudden unintended acceleration never starts while the vehicle is in PARK or NEUTRAL.
5. The sudden increase in engine speed often coincides with shifting out of PARK into either DRIVE or REVERSE.
6. After experiencing high engine speed in either DRIVE or REVERSE, shifting into NEUTRAL or PARK causes the engine speed to increase further.
7. In sudden unintended acceleration the engine speed increases rapidly. It increases much faster than re-creations of incidents in which people floor the accelerator pedal and keep it held down.
8. The engine speed stays high for varying amounts of time from incident to incident. Sometimes incidents consist of temporary surges lasting only a few seconds. Other incidents can last for minutes or even hours.
9. Engine speed can vary from one incident to another. Engine speeds from 2000 RPM to 6000 RPM have been reported.
10. Some drivers have observed the coincidence of RPM increase with the air conditioner turning on.
11. Sudden unintended acceleration has occurred in vehicles having brake override.
12. Some drivers have stated that applying the brakes caused the vehicle to speed up.
13. High RPM's usually do not recur when ignition is turned off and then back on again.
14. DTC's are rarely found after an incident by service personnel.

This paper discusses a detailed mechanism that explains these driver observations. To preserve the reader's interest and to avoid getting bogged down in a myriad of design and operational details, the next section will quickly get to the point of explaining the mechanism involved, leaving it to appendices to supply additional design and operational details.

II. Detailed Mechanism for Unintended Acceleration

In two previous papers[1,2] the author proposed that negative voltage spikes on the 12 volt power bus are the cause of unintended acceleration in vehicles having electronic throttles. Specifically, it was proposed in the second paper that if a negative voltage spike of relatively short duration (e.g., 10 to 100 microseconds) occurs on the power bus while the analog-to-digital converter (A/D) in the ECU is sampling the battery voltage, then the A/D senses the battery voltage as being a low value (e.g., 0 to 12.6 volts) even though the DC value of the battery voltage remains at its normal value of 12.6 volts. Ordinarily, the A/D value is used to compensate for variations of the DC voltage which cause a reduction in the performance of electric motors and solenoids in the vehicle when the DC supply voltage to these functions decreases. Therefore, the A/D value is used to increase the input to the electric motor or solenoid just enough to compensate for the reduced DC supply voltage, bringing the output back to its normal value. But when the A/D value is sensed during a negative voltage spike, it causes the motor input to increase even though the DC voltage to the function remains unchanged. This causes the outputs of the electric motors or solenoids to increase above their normal values. This results in the following four changes in engine operation:
1) The throttle motor duty cycle is increased, opening the throttle more and increasing the amount of air into the engine,
2) The variable valve timing oil control valve duty cycle is increased, advancing the intake valve timing, and increasing the torque produced by the engine,
3) The injector opening time is lengthened, increasing the amount of fuel injected into the engine,
4) The ignition dwell time is increased, causing a larger spark to be produced.

This means that all of the inputs to the engine are changed, which will have an effect on the engine output. We now discuss each of these in turn.

A. <u>Throttle motor duty cycle is increased</u>. Figure 1 shows the throttle motor control loop with the PID controller and the battery voltage correction operation. The key things to know about this loop are that the loop sets the throttle opening in response to a target value determined by the maximum of either the accelerator position sensor (APS) or the cruise control (CC), with the idle setting added in all cases. The loop is updated every 2 msec (i.e., at a 500 Hz rate). The PID controller gain is adjusted by setting its coefficients, and the output of the PID controller is
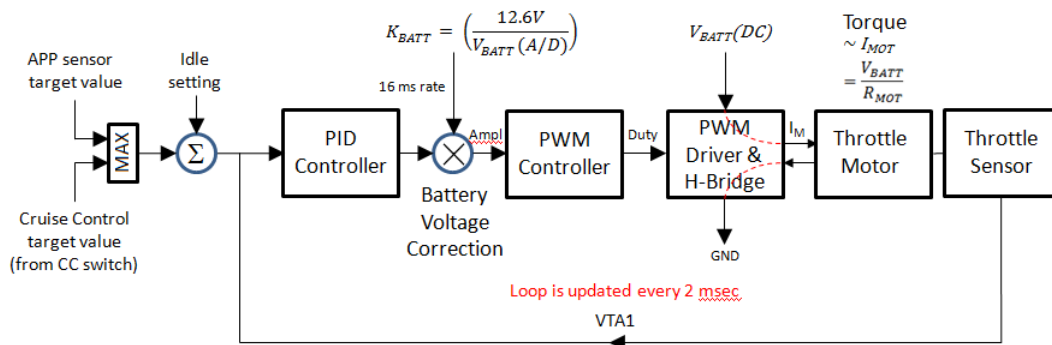

$$K_{BATT} = \left(\frac{12.6V}{V_{BATT}(A/D)} \right)$$

Figure 1. Throttle motor control loop with PID controller and battery voltage correction shown[3]

multiplied by a battery voltage compensation coefficient which adjusts for the variation of throttle motor torque with throttle motor supply voltage. The throttle motor torque is proportional to the motor current, which is just the battery supply voltage divided by the motor resistance, so when DC value of the battery voltage drops slightly, the throttle motor has less torque and can't push as hard against the spring that pulls the throttle valve back to the limp home position, causing a smaller throttle opening. The battery voltage correction operation is included to multiply the PID controller output by the inverse coefficient K_{BATT}, which brings the throttle motor torque back to its normal value. If the battery voltage $V_{BATT}(A/D)$ measured by the A/D converter equals the battery voltage $V_{BATT}(DC)$ supplied to the throttle motor, then everything works as intended and the throttle motor torque does not change with variations of battery voltage. However, if the battery voltage $V_{BATT}(A/D)$ measured by the A/D converter is smaller

than the battery voltage $V_{BATT}(DC)$ supplied to the throttle motor as a result of the A/D converter sampling the battery voltage during a negative voltage pulse, then the throttle motor gets a <u>larger</u> input than its normal value.

    1. <u>PID Gain Scheduling</u>. The PID coefficients in Figure 1 are not the same at all times. The coefficients are changed according to the mode of operation of the vehicle as shown in Table 1.[4] This is called "gain scheduling" by the automotive community. The coefficients are changed because one set of coefficients does not provide the performance desired in all operating modes. For example, in NORMAL mode when the vehicle is operated in DRIVE or REVERSE the driver wants responsiveness to the throttle, meaning that the throttle opening should change quickly with changes in the accelerator input. This requires larger PID coefficients, or higher PID gains. However, in the ISC mode when the engine is idling in PARK or NEUTRAL, the engine speed is so low (~800 RPM) that changes due to cylinder variations might cause the engine to stall. Therefore, the PID coefficients are made smaller in the ISC mode than in the NORMAL mode to make the engine less sensitive to changes in engine speed and other disturbances, such as accessories turning on.

Table 1. PID coefficients are changed according to the different modes of vehicle operation[4]

$$G = Kp \{1 + 1/(Ti \times S) + Td \times S\}$$

PID Coefficients
Kpt = proportional coefficient (target)
Tit = integral coefficient (target)
Tdt = differential coefficient (target)

	ISC	TRC	C/C	NORMAL
Kpt	1	10	5	7
Tdt	10	1	5	3
Tit	3	3	3	3

Vehicle Operating Modes
ISC = Idle Speed Control mode (PARK / NEUTRAL)
TRC = Traction Control mode
C/C = Cruise Control mode
NORMAL = Normal mode (DRIVE / REVERSE)

This changing of the PID coefficients has important consequences with regard to throttle operation. It explains why sudden acceleration never begins while in PARK or NEUTRAL (driver observation number 4), because the PID coefficients are so much smaller in the ISC mode (1/7x) that the additional gain provided by an incorrect battery voltage compensation operation (1 to 3x) does not bring them up to the normal PID values found in the NORMAL mode. It also explains why sudden acceleration begins only when shifting out of PARK into either DRIVE or REVERSE (driver observation number 5), because shifting out of PARK suddenly changes the PID coefficients to their larger values, making the throttle more sensitive to the additional gain provided by an incorrect battery voltage compensation operation. This means that when testing a vehicle for sudden acceleration, one should always test with the vehicle in the NORMAL mode; i.e., with the transmission in either DRIVE or REVERSE. This was not done during the NASA/NHTSA study, in which all vehicles were tested while idling in PARK[5]. Despite this, some sensitivities were still found. Clearly, these sensitivities would have been much greater if the vehicles had been tested in either DRIVE or REVERSE.

    2. <u>Effects of PID Loop Gain Changes on Throttle Operation</u>. Figure 2 shows how the throttle operation is affected by PID loop gain changes. Concentrate first on the green curve, which shows the normal throttle operation. The PID output is first adjusted with the throttle completely closed (-100% PWM duty cycle), to position the PID output zero point at the limp home position. Then the PID output is adjusted to be maximum (+100% duty cycle) when the throttle is hitting the throttle stop at 90° open. The maximum PID output is then re-adjusted to be 88% when the throttle opening is 2° less than the maximum throttle opening, or 88°. This means that in normal operation the throttle never hits the maximum throttle stop. Notice that on the x-axis during normal operation the PWM duty cycle is the same as the PID output in percent when the battery voltage is being compensated correctly.

Now look at the red curve, which shows what happens when an incorrect battery voltage compensation value is applied to the duty cycle. The gain from PID output to throttle opening angle is increased by the ratio $12.6V/V_{BATT}(A/D)$, which for $V_{BATT}(A/D) = 9.0V$ (for example) implies an increase of 1.3x. This means that when the PID controller is outputting a value x in the throttle opening, the throttle motor is really receiving the command 1.3x. The effect is to make the throttle open 30% more than the PID output would indicate, which applies to all PID inputs, including the accelerator position sensor. In the positive PWM direction, or opening direction, this means that the driver will notice an <u>increase</u> in the engine response, making it seem more "jittery" if the incorrect battery voltage compensation value is large enough. It also means that the throttle will now reach 100% open with less

accelerator pedal effort than before, and may even hit the mechanical throttle stop, because the duty cycle change allows the throttle to open more than the electrical limit set by the PID controller output. This may have consequences on the integrity of the throttle gears, because something must give if the throttle motor rams the throttle valve into the mechanical throttle stop. The most likely place in the gear train to suffer shock damage is the teeth of the smallest diameter gear.
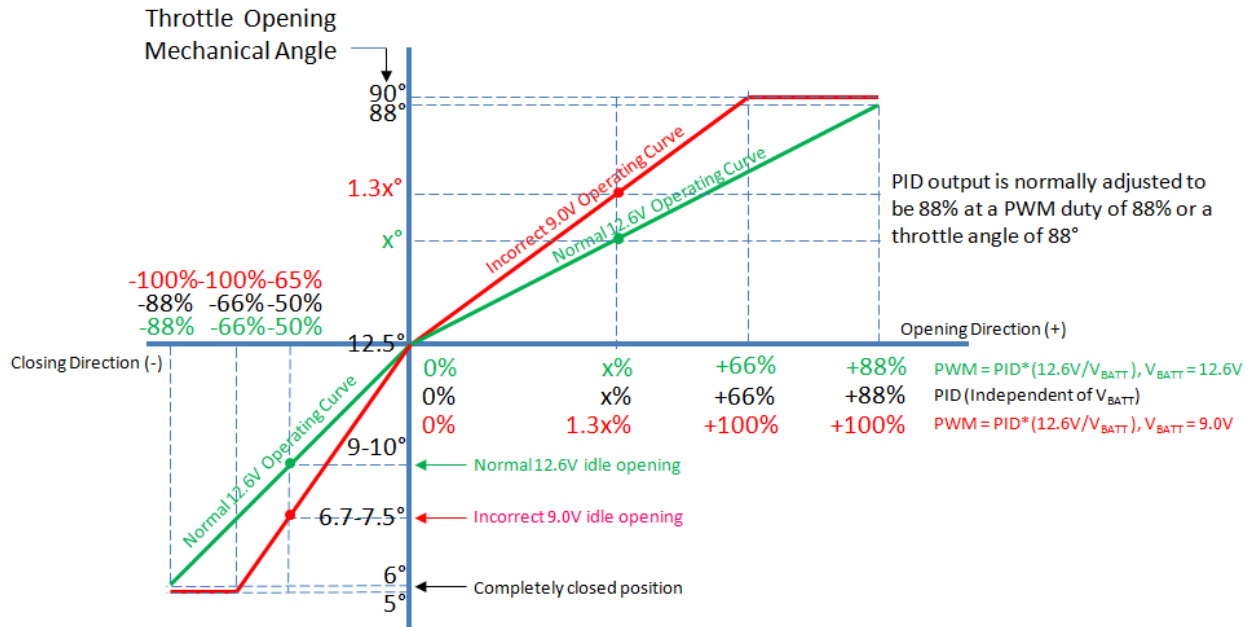

Figure 2. Incorrect battery voltage duty cycle compensation causes throttle opening angles above the limp home discontinuity to increase above their normal values while the idle opening below the discontinuity decreases.

In the negative PWM direction, or closing direction, an increase of 1.3x in the duty cycle means that the idle speed is <u>reduced</u> by about 30%, making the engine idle at a lower RPM. This makes the engine more susceptible to fluctuations and disturbances, and may even cause the engine to stall if an incorrectly compensated duty cycle causes the throttle valve go to its fully closed position.

It is possible, of course, that the incorrect battery voltage may be any value between 12.6 volts and 0 volts, with the resulting compensation coefficient K_{BATT} varying between 1 and some arbitrarily large number, while the DC battery voltage remains at 12.6 volts. This means that there will be a continuous spectrum of throttle behaviors corresponding to the overall gain of the throttle loop, which may vary from its normal value below 1 to a value greater than 1, where the loop becomes unstable. This means that one may see small overshoots in throttle position corresponding to small temporary surges in engine speed. Or one might even see larger hunting oscillations in throttle position, corresponding to unstable throttle loop behavior. One driver even measured such oscillating behavior, but had no explanation for it[6].

It is interesting to see what happens to the throttle opening when the vehicle's head lights or air conditioner are turned on. Figures 3 and 4 show what the load on the engine and the electrical current load look like in these two cases[7]. If these loads are not accompanied by an increase in engine torque output, then the vehicle's idle speed will decrease, which might cause the engine to stall. Therefore, the ECU opens the electronic throttle slightly to increase the engine torque output to offset any load that has been turned on. Figure 5 shows that when the headlights are turned on, the throttle opens about 9 degrees initially, and stays open about one degree as long as the lights stay on. Figure 6 shows when the air conditioner is turned on, the throttle opens with two peaks of about 10 degrees and 8 degrees, and stays open about two degrees as long as the air conditioner continues to run. The driver never notices these changes, however, because the throttle opening amounts are carefully adjusted by the automobile manufacturer to produce an increase in engine torque output that exactly cancels the load placed on the engine from these events. The only change that the driver sees is shown in Figure 7, which shows a small drop in idle RPM, followed by a

long term increase in idle RPM that may vary from 50 RPM to 200 RPM. The actual drop and long term increase vary somewhat with load and engine design. This process of canceling a sudden load on the engine by an increase in the throttle opening is called an "idle-up" in the auto industry.
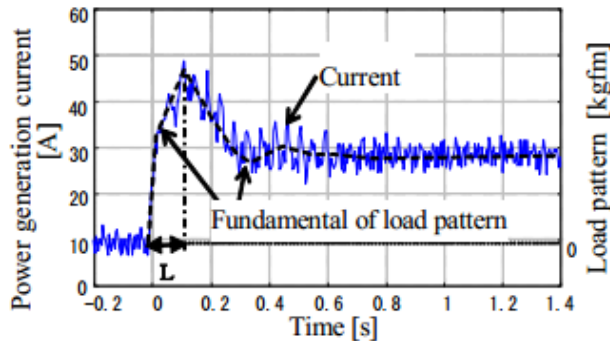

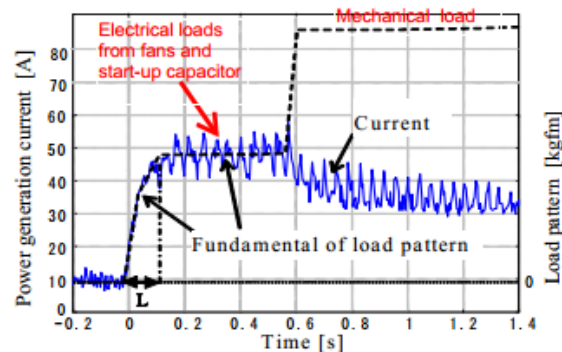Figure 3. Load current and load torque generated by turning on four high beam headlights at t=0[7]

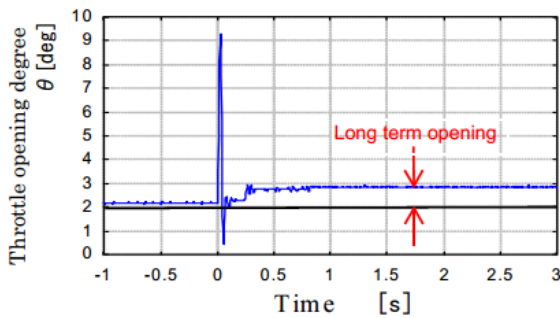Figure 4. Load current and load torque generated by turning on the air conditioner at t=0[7]

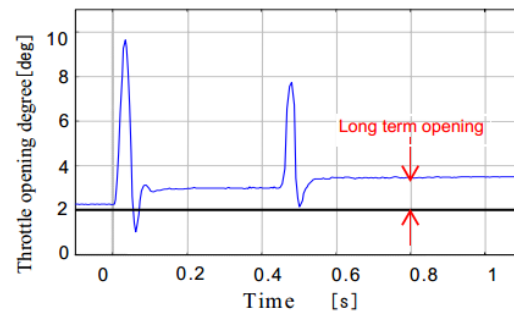Figure 5. Throttle angle upon turning on four high beam headlights at t=0[7]

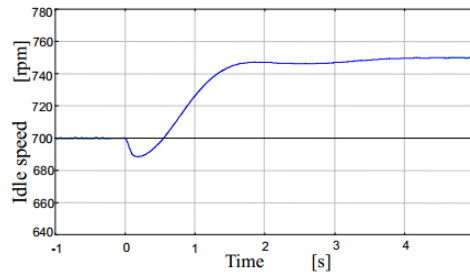Figure 6. Throttle angle upon turning on the air conditioner at t=0[7]

Figure 7. Effect of either event on idle speed (RPM)[7]

One should know that these "idle-up" throttle opening responses are fixed in the ECM's memory, having been measured on a prototype engine during the design phase of the automobile. The automobile manufacturers refer to this as a "feed-forward" compensation process. Therefore, if the air conditioner load increases as the unit ages, the "idle-up" response is still the same, and may not be enough to exactly cancel the added load any more. Therefore, the idle speed may decrease a little more when the air conditioner is turned on as the unit ages. Also, the "idle-up" response assumes that the throttle is operating normally; i.e., with the normal PID coefficients and the throttle motor duty cycle being properly compensated for changes in DC battery voltage by the correct battery voltage compensation coefficient. If this is not the case, and if the compensation coefficient is, say N times larger because the battery voltage has been sampled during a negative voltage spike, then the throttle openings for these "idle-ups" will become N times larger. In this case, the "idle-up" response will exceed the load that has been added to the engine when the load is turned on, and the driver will notice a temporary surge in engine RPM followed by a larger long-term increase in engine RPM. The magnitude of the surge will be proportional to the incorrect throttle motor

duty cycle battery voltage compensation coefficient. This explains part of driver observation number 8, which notes that surges can vary in magnitude from incident to incident.

     3. <u>Cause of Long Duration Events at High Engine RPM's</u>. Long duration events with high engine speeds are the most difficult unintended acceleration incidents to explain. This is where the author's first two papers fell short and failed to convince perceptive readers that the proposed solution was indeed correct. We will now explain how long duration events can happen and how high engine speeds approaching 6000 RPM can occur.

First, assume that the A/D converter samples the battery voltage during a negative voltage pulse on the 12V power bus, and assume that this sampling occurs after the engine is started, but before the unintended acceleration event occurs. The throttle is therefore in a state of higher sensitivity than normal. Assume, now, that the air conditioner cycles on, producing an "idle-up" throttle opening response as shown in Figure 6. Note that the air conditioner may cycle on at any time as long as the air conditioner switch is turned on and the air temperature is above a certain value. This "idle-up" event will produce a short-term surge in the throttle opening along with a long-term throttle opening that persists as long as the air conditioner remains turned on. The long-term throttle opening will cause the throttle to open above the limp-home position if the incorrect battery voltage compensation coefficient causes a sufficient increase in the PID loop gain.

Now, the throttle opening is controlled by means of maps (i.e., look-up tables) in the ECU which translate the accelerator position sensor and the idle speed controller command into a throttle opening command. Two maps are used between each resource having the ability to open the throttle and the PID controller, which means that the accelerator position sensor (APS), the cruise control, the idle speed control, and the TRAC system all have unique first maps. But the second map is the same in all cases and translates a requested torque (or a requested cylinder air charge) into a target throttle opening. An example of this last map is shown in Table 1. This map comes from a 2006 Impreza 2.5i 5MT[8], but is considered to be typical of the final map used in all makes of vehicles having electronic throttles. If the current engine speed or requested torque (or requested cylinder air charge for earlier non-torque-based control systems) happen to lie in between the values in this table, then the ECU interpolates between the table values to find the target throttle opening.

Table 1. Throttle opening angle is controlled by having the driver's requested torque value access a table containing the throttle opening angle as a function of engine speed (RPM)[8]

	Requested Torque (raw ecu value)																									
	0.0	25.0	50.0	75.0	100.0	120.0	130.0	135.0	140.0	145.0	147.5	155.0	157.5	165.0	167.5	170.0	175.0	180.0	185.0	193.0	197.5	200.0	205.0	212.0	225.0	250.0
400	0.0	2.0	4.1	6.2	9.3	11.9	26.2	52.8	79.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
600	0.0	2.0	4.1	6.2	9.3	11.9	26.2	52.8	79.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
800	0.0	2.0	4.1	6.2	9.3	11.9	26.2	52.8	79.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1000	0.0	2.6	5.2	7.6	9.8	11.6	15.6	19.0	23.5	39.6	82.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1200	0.0	3.5	6.5	8.5	10.4	12.2	14.5	15.7	16.8	18.5	21.4	33.5	74.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1400	0.0	4.5	7.2	9.1	11.0	13.3	15.0	15.8	16.6	17.4	17.8	24.7	27.0	34.2	57.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1600	0.0	6.0	8.1	10.1	12.2	14.8	16.1	16.8	17.4	18.4	19.4	22.3	23.2	46.6	56.1	65.7	84.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1800	0.0	6.7	8.8	10.9	13.4	15.7	16.8	17.4	18.2	19.8	20.5	22.9	23.6	31.7	41.3	50.9	70.2	89.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2000	0.0	7.3	9.5	11.8	14.3	16.4	17.4	18.1	19.4	20.6	21.2	23.1	23.8	27.5	28.7	30.9	47.0	63.1	79.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2400	0.0	8.5	11.0	13.5	15.9	17.8	19.3	20.1	20.8	21.6	22.0	23.2	23.5	26.1	27.1	28.1	32.5	47.5	62.6	86.6	100.0	100.0	100.0	100.0	100.0	100.0
2800	0.0	9.3	12.4	14.9	17.5	20.0	21.4	22.1	22.7	23.4	23.7	25.7	26.3	28.3	29.0	29.7	32.6	35.6	39.4	45.4	60.4	81.9	100.0	100.0	100.0	100.0
3200	0.0	10.4	13.7	16.4	19.2	21.7	23.0	23.6	24.6	25.7	26.3	27.9	28.5	30.5	31.6	32.8	35.0	37.9	41.1	46.3	59.7	72.3	97.2	100.0	100.0	100.0
3600	0.0	12.1	15.0	17.8	20.7	23.1	24.5	25.4	26.3	27.2	27.7	29.0	29.5	31.7	32.5	33.3	34.8	36.6	38.7	44.1	56.7	63.7	77.8	97.3	100.0	100.0
4000	0.0	13.3	16.3	19.2	22.1	24.6	26.2	26.9	27.7	28.5	28.9	30.3	30.9	32.8	33.5	34.1	35.4	37.2	39.2	43.9	49.3	52.3	58.2	91.7	100.0	100.0
4400	0.0	14.1	17.4	20.3	23.2	25.8	27.1	27.7	28.4	29.1	29.4	30.8	31.4	33.1	33.6	34.2	35.3	36.9	38.8	41.8	44.6	46.1	56.3	81.7	100.0	100.0
4800	0.0	15.4	18.7	21.6	24.7	27.3	28.6	29.2	29.9	31.0	31.6	33.2	33.8	35.4	36.2	37.1	38.9	40.7	43.4	50.9	58.4	66.5	85.6	100.0	100.0	100.0
5200	0.0	16.3	19.9	23.0	26.2	28.8	30.3	31.3	32.4	33.4	33.9	35.5	36.2	38.5	39.3	40.0	41.6	44.4	47.4	58.4	73.9	83.7	100.0	100.0	100.0	100.0
5600	0.0	18.0	21.2	24.5	27.8	30.8	32.9	33.9	35.0	36.2	36.9	39.2	39.9	42.6	44.0	45.3	48.5	54.6	62.9	92.7	100.0	100.0	100.0	100.0	100.0	100.0
6000	0.0	19.2	22.7	26.1	29.6	33.6	35.7	37.3	38.9	40.5	41.3	44.9	46.2	52.9	55.7	58.5	76.9	98.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6400	0.0	20.6	24.3	28.0	32.4	36.8	40.2	42.1	44.5	46.9	48.8	56.7	59.3	95.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6800	0.0	22.2	26.2	30.2	35.1	41.8	46.5	50.1	55.1	62.6	77.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
7200	0.0	24.2	28.3	32.9	39.7	49.0	58.3	86.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Target Throttle Plate Opening Angle (%)																									

Now, assume that vehicle's "idle-up" response causes a long-term request for an additional torque of 100.0 units, which corresponds to the column shown in red in Table 1. When the engine is at idle (800 RPM), the requested torque of 100.0 units will produce a target throttle opening angle of 9.3%, as shown in Table 1. This means that the PID controller will output a duty cycle to cause the throttle motor to open the throttle to an angle of 9.3%. If the battery voltage duty cycle compensation coefficient is now 1.3 for example, because the battery voltage was measured incorrectly to be 9 volts when the DC value of the supply voltage remains at 12.6 volts, then the duty cycle seen by the throttle motor will be 1.3 times 9.3% = 12.2% instead of just 9.3% as the PID controller is

providing[9]. But this table was constructed by measuring the response of a prototype engine on a dynamometer when the engine was running with a normal battery voltage duty cycle compensation coefficient of 1. This means that table values are equilibrium values. Therefore, the engine speed will increase to the value associated with a throttle opening of 12.2%, or about 1600 RPM, even though the requested torque (or requested air charge) remains the same at 100.0 units. Now, every 2 milliseconds a new value of the throttle opening is calculated. In the second iteration, the engine is now at a 1600 RPM. So the same requested torque of 100.0 units produces a PID controller output of 12.2%. But the duty cycle seen by the throttle motor will be 1.3 times 12.2% = 15.9% instead of just 12.2% as the PID controller is providing. Therefore, the engine speed will increase to the value associated with a throttle opening of 15.9%, or about 2400 RPM. Every 2 milliseconds this process is continued, with the engine speed increasing each iteration as fast as the engine speed can ramp up. One can easily see that the engine speed can increase quite rapidly, even for modest increases in the battery voltage duty cycle compensation coefficient. Within less than one second, or 500 iterations, the engine speed will end up at the highest speed that the table provides (in this table 7200 RPM), or else at some maximum engine RPM limit that is built in for safety reasons. Of course, the incorrect battery voltage duty cycle compensation coefficient may be any number between 1 and some arbitrarily large number, so this will have an influence on the rate of increase also.

This example provides an interesting insight; namely, that turning off the air conditioner should cancel the "idle-up" torque request to the engine, which should stop the increase of engine RPM's causing the unintended acceleration. The example also shows that there might be some sort of threshold on the size of the negative voltage spike below which no long term unintended acceleration can take place. This follows because the throttle opening angles in Table 1 all correspond to positive duty cycles, while the throttle opening duty cycle at idle is negative. During a normal "idle-up" the engine speed is incremented by only 100 to 200 RPM, as shown in Figure 7, causing the idle speed to be raised from 800 RPM to about 1000 RPM, leaving the engine still at idle with a negative duty cycle. This increment is increased, as previously discussed, by multiplying the duty cycle by the incorrect battery voltage duty cycle compensation coefficient. But to get the duty cycle to change sign, the engine speed must be raised above the speed associated with the limp home condition, which is approximately 1200 to 1500 RPM. Therefore, the increase in the duty cycle must be enough to cause the engine speed to go from 1000 RPM (where it is negative) to 1200 to 1500 RPM (where it is positive) to cause the duty cycle to change sign. Above this threshold duty cycle increase, the duty cycles are all positive. Therefore, there is a threshold duty cycle increase, which means there is a threshold duty cycle compensation coefficient, which implies that there is a threshold battery voltage value and a threshold negative voltage spike magnitude.

    4. <u>Comparison with Driver's Observations</u>. Let's now compare this theory to driver's observations during unintended acceleration incidents.
        1. <u>Sudden unintended acceleration happens at a low rate in vehicles from all manufacturers</u>. This is explained by the theory because all automobile manufacturers use a similar design for the electronic throttle, with a battery voltage duty cycle compensation coefficient and a look-up table for the throttle control.
        2. <u>Sudden unintended acceleration incidents increased with the introduction of electronic throttles (i.e., drive by wire)</u>. This is explained by the theory because it describes a specific fault in the electronic throttle control system. Therefore, sudden acceleration incidents would begin with the introduction of an electronic throttle.
        3. <u>Sudden unintended acceleration occurs while the driver's foot is off the accelerator</u>. This is explained by the theory because the theory shows that the increase in engine speed during a sudden acceleration incident is caused by an accessory, such as an air conditioner, increasing the idle speed while the throttle motor duty cycle battery voltage compensation coefficient is incorrect, increasing the gain of the PID controller in the throttle control loop. In this operation the accelerator pedal remains released, and the idle speed control system has the authority over the throttle. The idle speed control system is used during all modes of vehicle operation, including idle mode, normal mode (DRIVE and REVERSE), cruise control mode, and TRAC mode.
        4. <u>Sudden unintended acceleration never starts while the vehicle is in PARK or NEUTRAL</u>. This is explained by the theory because in PARK and NEUTRAL the PID controller uses PID coefficients that are seven times smaller than the PID coefficients used in DRIVE and REVERSE. When these PID coefficients are effectively increased by an incorrect throttle motor duty cycle battery voltage compensation coefficient, they are still less than the PID coefficients used in DRIVE and REVERSE. In other words, the idle control system is so insensitive to disturbances by design that the disturbance created by an incorrect throttle motor duty cycle battery voltage compensation coefficient is not noticed.
        5. <u>The sudden increase in engine speed often coincides with shifting out of PARK into either DRIVE or REVERSE</u>. This is explained by the theory by the fact that the PID coefficients are changed to higher gain

coefficients when the transmission is shifted out of PARK into either DRIVE or REVERSE, making the control system more sensitive to disturbances. Effectively, there are two idle states, one in PARK and NEUTRAL with low PID coefficients, and one in DRIVE and REVERSE with high PID coefficients. The latter one gets affected more easily by an incorrect throttle motor duty cycle battery voltage compensation coefficient.

6. After experiencing high engine speed in either DRIVE or REVERSE, shifting into NEUTRAL or PARK causes the engine speed to increase further. This is explained by the theory by the fact that the load on the engine is decreased while in NEUTRAL or PARK, while the requested torque to the engine from the idle speed controller remains the same. Therefore, the engine speed increases because the engine has less load on it.

7. In sudden unintended acceleration the engine speed increases rapidly. It increases much faster than re-creations of incidents in which people floor the accelerator pedal and keep it held down. This is explained by the theory by how an incorrect throttle motor duty cycle battery voltage compensation coefficient causes the throttle controller to step through the throttle control map while the requested torque stays constant. This process makes the engine go to full throttle in less than one second because it is limited only by the 500 Hz update rate of the electronic throttle control system. Normal engine speed increases in which the throttle is held down while the engine accelerates with the vehicle in gear are limited by the torque available from the engine that can offset the load imposed by the transmission and the road conditions. This takes several seconds in most cases.

8. The engine speed stays high for varying amounts of time from incident to incident. Sometimes incidents consist of temporary surges lasting only a few seconds. Other incidents can last for minutes or even hours. This is explained by the theory by the fact that the size of the incorrect throttle motor duty cycle battery voltage compensation coefficient can vary with the size of the negative voltage spike during A/D conversion of the battery voltage. Larger compensation coefficients cause larger surges in acceleration. Long duration incidents can vary in time mostly because of some external intervention, such as a crash or because the engine is turned off. But some long duration incidents may end before such intervention takes place because the incorrect compensation coefficient may be replaced in memory by a newly sampled battery voltage, which creates a new compensation coefficient.

9. Engine speed can vary from one incident to another. Engine speeds from 2000 RPM to 6000 RPM have been reported. This is explained by the theory by the fact that that the size of the incorrect throttle motor duty cycle battery voltage compensation coefficient can vary with the size of the negative voltage spike during A/D conversion of the battery voltage. Larger compensation coefficients cause higher engine RPM's during an engine surge. High engine RPM's during long duration events, or when the engine speed remains high after the vehicle is put in PARK or NEUTRAL, are explained by the throttle control system stepping through the map of Table 2 while the requested torque remains constant.   The maximum speed encountered after stepping through Table 2 will vary from engine to engine, and therefore from manufacturer to manufacturer, because the table entries are tailored to the specific engine used. Different auto manufacturers and different engines may also use different safety limits for the maximum engine speed.

10. Some drivers have observed the coincidence of RPM increase with the air conditioner turning on. This is explained by the theory by how an incorrect throttle motor duty cycle battery voltage compensation coefficient modifies the air conditioner long-term "idle-up" response. The same mechanism can explain both short-term lunges, lurches, and surging, as well as long-term accelerations lasting several seconds to several minutes. This is illustrated in Figures 8 and 9 below.

Figure 8 illustrates a typical air conditioner idle-up response (previously shown in Figure 6) that has been modified by an incorrect throttle motor duty cycle battery voltage compensation coefficient that is small enough to keep the long-term idle-up response below the limp-home position. In this case one will experience lunging, lurching, and surging from the two peak throttle openings, but will not experience long-term unintended acceleration. Figure 9 illustrates the same air conditioner idle-up response modified by a larger incorrect throttle motor duty cycle battery voltage compensation coefficient that is large enough to raise the long-term throttle response above the limp-home position. In this case one will experience long-term unintended acceleration in addition to the two lunges, lurches, or surges. When the long-term throttle response remains above the limp-home position, the incorrect throttle motor duty cycle battery voltage compensation coefficient then causes the throttle opening to increase to its maximum value by mapping the air conditioner long-term load to a target throttle opening that is always larger than the equilibrium value associated with the current engine speed (illustrated by the dashed line in Figure 9). This causes the engine speed to increase each time the throttle controller traverses the throttle control loop, which takes only 2 milliseconds. The result is that the engine goes to full throttle within less than one second.
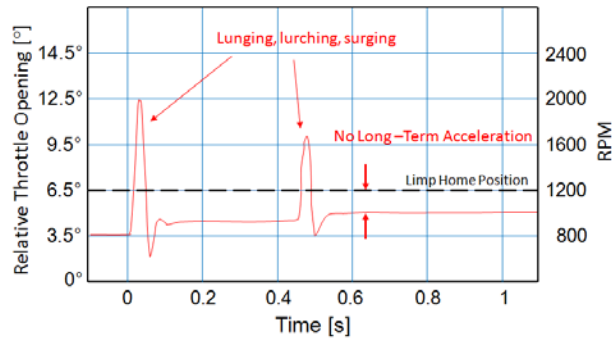
Figure 8. Lunging, lurching and surging result when the incorrectly compensated throttle motor duty cycle produces a throttle opening that exceeds the limp home position for only a short duration.
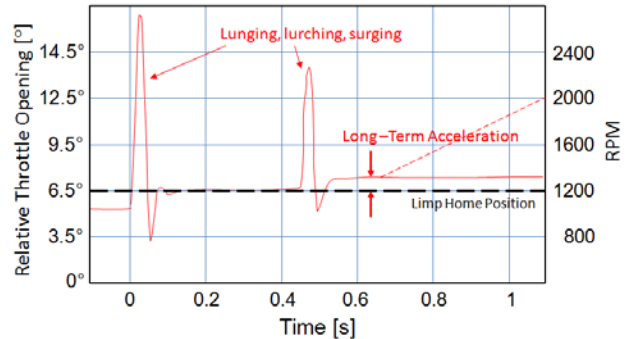
Figure 9. Long-term unintended acceleration results when the incorrectly compensated throttle motor duty cycle produces a throttle opening that stays above the limp home position. The incorrect compensation coefficient then causes the throttle map to further increase the throttle opening each time the control loop is traversed (dashed line).

There is evidence to support this explanation of short-term and long-term unintended acceleration. The evidence is that NHTSA has been investigating 238 reports of sudden "lunging" in 2005-2007 Ford Freestyles which seems to be made worse during air conditioner operation.[10] There have also been over 20 reports of Toyota Tacoma "lurching" incidents in which the drivers have noted that it seems to be related to the air conditioner turning on.[11] Finally, in 2008, Volkswagen announced a recall of 4,079 MY 2008 Passat and 2,500 MY 2009 Tiguan passenger vehicles because: *"These vehicles have an engine control module (ECM) containing software that may not properly control engine idle with the air conditioning turned on. In rare cases, the ECM may unexpectedly increase engine rpm. An engine surge caused by an unexpected increase in engine rpm may surprise the vehicle operator and can result in a crash without warning"*.[12]

Although the air conditioner idle-up is the most likely idle-up to cause an unintended acceleration because it is the largest, it may also be possible that some other engine idle-up disturbance, such as an ABS brake pump turning on, rear window defroster turning on, engine cooling fan turning on, headlights turning on, or an after-market accessory turning on, can cause a similar "idle-up" response that gets magnified by an incorrect throttle motor duty cycle battery voltage compensation coefficient. This is particularly true for short-term peaks in the idle-up response which cause short-term unintended acceleration events. If the disturbance is created by the driver himself by turning on some accessory switch, such as a rear window defroster switch, then the driver will easily recognize that the increase in engine speed is caused by turning on the switch. But if the accessory cycles on and off by itself, such as an air conditioner compressor turning on, or ABS brake pump turning on, then the driver is not forewarned and will not recognize the cause of the higher engine speed.

      11. <u>Sudden unintended acceleration has occurred in vehicles having brake override</u>. This is explained by the theory by the fact that the high engine speeds are not caused by the driver pressing on the accelerator pedal, but are caused instead by the idle speed control system reacting to an incorrect throttle motor duty cycle battery voltage compensation coefficient. The driver's foot can be off the accelerator pedal and on the brake at all times and the engine speed will still increase according to the theory. The brake override system assumes that the engine speed increase during unintended acceleration is caused by the driver pressing on the throttle, and therefore nullifies the throttle input if the driver's foot is simultaneously pressing on the brake. This assumption is incorrect, as explained by the proposed theory, and thus the brake override system is completely useless in preventing unintended acceleration.

      12. <u>Some drivers have stated that applying the brakes caused the vehicle to speed up</u>. This is an interesting observation that the theory presented thus far does not explain. However, we are not finished yet explaining the theory. Please see the next section for how this is explained.

      13. <u>High RPM's usually do not recur when ignition is turned off and then back on again</u>. This is explained by the theory by the fact that an incorrect throttle motor duty cycle battery voltage compensation coefficient is caused by the A/D converter in the ECU sampling the battery voltage during a negative voltage spike. The theory assumes that this sampling takes place soon after the engine is turned on because it is then that the battery is usually at its lowest state of charge after having been used to start the engine. Therefore, it makes sense

that the battery voltage is sampled at this time. However, it is possible that the battery voltage is also sampled at regular intervals during engine operation, perhaps in response to a timer in the ECU. The sampling would then take place at a next convenient time when the vehicle is at idle with the accelerator released, since this is the time when the battery is determining the system supply voltage, and not by the vehicle's alternator. If these assumptions are correct, then the observation that the high RPM's do not recur when ignition is turned off and then back on again is explained by the fact that the battery voltage is re-sampled when the ignition is turned back on, and a new throttle motor duty cycle battery voltage compensation coefficient replaces the incorrect one.

       14. <u>DTC's are rarely found after an incident by service personnel</u>. This is explained by the theory because the theory requires no faults in either hardware or software operation other than the occurrence of a negative voltage spike during A/D conversion of the battery voltage causing an incorrect throttle motor duty cycle battery voltage compensation coefficient. And this fault is not detected because there is no diagnostic test to test the result nor any diagnostic maintenance routine to apply a mitigation response. Essentially, this is a design flaw that all auto manufacturers have overlooked. One effectively has a sensor (voltage sensor) with no diagnostic routine to assess a fault in the sensor. Therefore, the sensor is susceptible to faults produced by negative voltage spikes which are always present in a vehicle's power supply system. There is no need to assume hardware faults, software faults, EMI, cosmic rays, tin whiskers, or any other cause of throttle system malfunction because the throttle system is performing exactly as designed except for the incorrect throttle motor duty cycle battery voltage compensation coefficient. The only diagnostic that might apply in this case is a comparison of the throttle sensor output with the accelerator pedal sensor output or the idle speed controller output. This diagnostic should detect that the throttle is open with no matching input from either the accelerator pedal or the idle speed control system. It is possible that a pending DTC is set by this diagnostic, but that the pending DTC is removed (i.e., not made permanent) after the ignition is turned off and then back on again, when a new throttle motor duty cycle battery voltage compensation coefficient is created and the engine resumes its normal operation. This means that if one does not re-start the engine after an unintended acceleration incident, and instead checks for DTC's while the engine is off, then one might find this pending DTC. The author has never encountered a case where this strategy has been tried. In all cases that the author has read about, the engine was restarted again after an unintended acceleration incident, either at the location of the incident, or at a service shop afterward, before the DTC's were queried.

In summary, the proposed theory explains all the driver observations about unintended acceleration but one; namely, observation 12: Applying the brakes caused the vehicle to speed up. We now turn our attention to this observation.

B. <u>Variable Valve Timing</u>. Variable valve timing is used in all engines having electronic throttles. Variable valve timing and electronic throttles were introduced together starting in 1997 by some manufacturers, and finally by all manufacturers in 2005. They were introduced together because manufacturers wanted higher engine performance with smaller displacement engines to achieve the higher gas mileage demanded by the new CAFÉ rules, but an electronic throttle was needed to correct for temporary drops in engine speed while the valve timing was adjusted. Ford Motor Company, in fact, has stated that: *"The torque-based ETC strategy was developed to improve fuel economy and to accommodate variable camshaft timing (VCT). This is possible by not coupling the throttle angle to the driver pedal position. Uncoupling the throttle angle (produce engine torque) from the pedal position (driver demand) allows the powertrain control strategy to optimize fuel control and transmission shift schedules while delivering the requested wheel torque"*[13,14,15].

The reader is referred to Appendix B for an explanation of how variable valve timing works. We need only to know here that variable valve timing can change the amount of torque that the engine supplies, increasing it when the engine accelerates, and decreasing it when the engine is at idle or at high RPM. Since engine torque is also increased by pressing on the accelerator to open the throttle valve, variable valve timing acts in a way like another accelerator, although one which is usually slaved to the true accelerator.

Variable valve timing (VVT) is controlled by a map as described in Figure 10. In this map the intake opening advance angle command is provided as a function of the engine load and engine speed. The engine load is represented by the output of the MAF sensor, which measures the amount of air that the engine is consuming as a result of the throttle being opened. This map is unlike the throttle opening map, in that the engine load (or MAF sensor) is used in place of the driver-requested torque (or cylinder air charge). The engine load is a dependent variable that depends on the engine torque. The latter is an independent variable controlled by the driver or the ECU.

1. <u>Normal VVT-i Operation During an Unintended Acceleration Event</u>. Recall, now, how an incorrect throttle motor duty cycle battery voltage compensation coefficient caused the engine speed to increase in Table 1 and the throttle valve to open. Let's see how this affects the operation of the VVT-i system shown in Figure 10[16]. In Figure 10 as the throttle valve opens up, the engine load increases as measured by the MAF sensor on the Y-axis. The engine speed in Figure 10 is the same engine speed as in Table 1. This means that while the engine speed is increasing, the path shown by the red line in Figure 10 is being traversed. Therefore, the engine torque starts out small in the idle range 1, gets larger while traversing the medium load range 2, and ends up smaller again in the high load, high speed range 5. This means that for most of the engine speed transition, the engine is providing the maximum torque available. It also means that if the driver applies the brakes to reduce the vehicle speed, then the load on the engine increases because the brakes create a slowing torque that gets transferred back to the engine through the torque converter.[1a] This causes the engine speed to decrease, changing the VVT-i operating point from range 5 to range 2. According to the table, this causes the VVT-i map to increase the intake cam advance, which creates a higher output torque. The net effect of applying the brakes, then, is to increase the engine torque, which is exactly what happens when an active cruise control system encounters a hill. The driver perceives this as the engine accelerating against the brakes just like the accelerator gets pulled down more by the active cruise control system when it encounters a hill (in an older vehicle with a mechanical throttle). This explains driver observation number 12, which says that some drivers have observed that applying the brake caused the engine to accelerate. This occurs when the VVT-i system is operating normally.
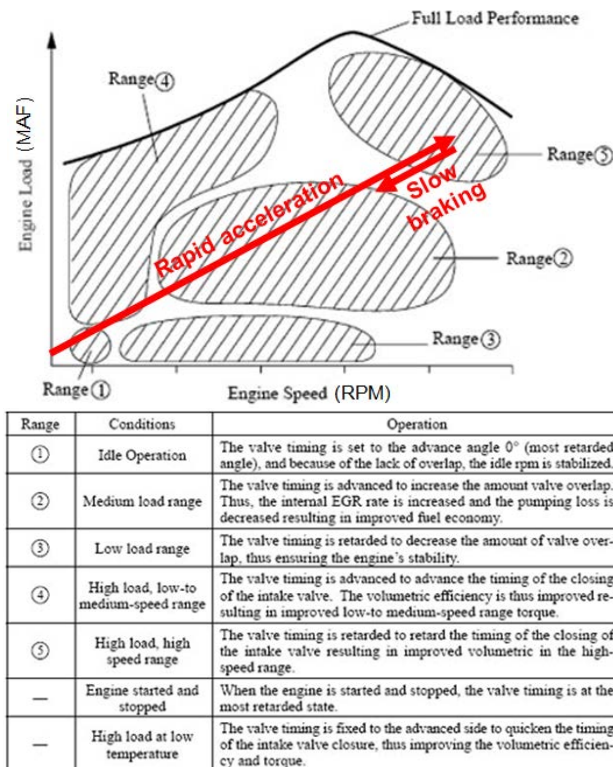

| Range	Conditions	Operation
①	Idle Operation	The valve timing is set to the advance angle 0° (most retarded angle), and because of the lack of overlap, the idle rpm is stabilized.
②	Medium load range	The valve timing is advanced to increase the amount valve overlap. Thus, the internal EGR rate is increased and the pumping loss is decreased resulting in improved fuel economy.
③	Low load range	The valve timing is retarded to decrease the amount of valve overlap, thus ensuring the engine's stability.
④	High load, low-to medium-speed range	The valve timing is advanced to advance the timing of the closing of the intake valve. The volumetric efficiency is thus improved resulting in improved low-to medium-speed range torque.
⑤	High load, high speed range	The valve timing is retarded to retard the timing of the closing of the intake valve resulting in improved volumetric in the high-speed range.
—	Engine started and stopped	When the engine is started and stopped, the valve timing is at the most retarded state.
—	High load at low temperature	The valve timing is fixed to the advanced side to quicken the timing of the intake valve closure, thus improving the volumetric efficiency and torque.

Figure 10. Variable valve timing map showing changes made during unintended acceleration
and braking when the VVT-i system is operating normally[16]

2. <u>Incorrect VVT-i Operation During an Unintended Acceleration Event</u>. In some cases, the VVT-i controller may not operate exactly as designed. Some VVT-i controllers use a battery voltage compensation coefficient that

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[1a] The term "load" used here means a torque applied <u>to</u> the engine, which slows the engine down like when the air conditioner is turned on. The term "load" shown on the x-axis of Figure 10 is the output of the MAF sensor, which measures the air flow through the throttle valve, and is therefore a measure of the torque produced <u>by</u> the engine. The two loads are related by a minus sign.

modifies the PWM duty cycle of the oil control valve that changes the valve timing. This battery voltage compensation coefficient can increase the oil control valve output when the coefficient is incorrect as a result of sampling the battery voltage during a negative voltage spike. In this case, as the engine speed increases, the oil control valve sees a larger opening command than the PID controller is sending out, just like with the throttle valve in Table 1. This causes the intake valve opening to advance with increasing engine speed. However, this time the intake valve opening advances to a maximum value in range 2 and then stays at the maximum value instead of decreasing again in range 5, as shown in Figure 11. This means that the intake valve timing does not increase when the brakes are applied because the intake valve opening stays at its maximum value. Therefore, the driver does not observe the engine accelerating as the brakes are being applied.
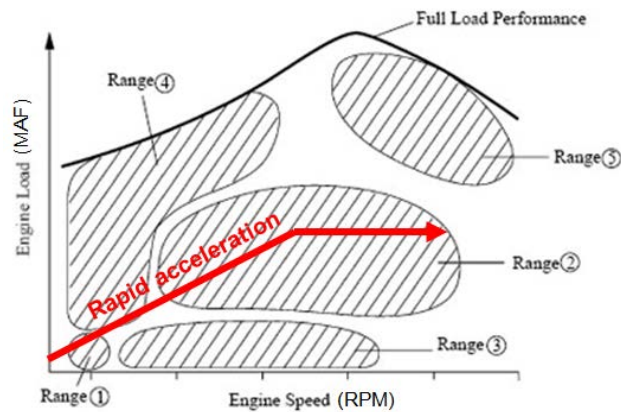
Figure 11. Variable valve timing map showing changes made during unintended acceleration and braking when the VVT-i system is operating with an incorrect battery voltage compensation coefficient

It is interesting that in some videos of sudden unintended acceleration incidents, one can actually hear the VVT-i intake cam oil control valve hitting the mechanical stop at the end of its travel as the vehicle begins to accelerate. This is indicated by a tell-tale "tick-tock" or "click-clack" sound heard on the video at the start of sudden acceleration. The "tick-tock" sound is the result of two oil control valves used for the two intake cams in a V-6 or V-8 engine, with one for each side of the "V". This is opposed to hearing only one "click" on an in-line 4-cylinder engine having only one oil control valve for one intake cam. The slightly different sound for each valve on a V-6 or V-8 engine is the result of the engine being transversely mounted, with one bank closer to the driver than the other bank. The oil control valve closer to the driver produces a higher pitched sound than the farther oil control valve, which has its higher pitches attenuated while passing through the intervening engine.

C. Injector Opening Time. The injector opening time is normally adjusted according to a map of injector base opening times as a function of engine speed (RPM) and engine load (i.e., MAF sensor output, which senses the amount of air being used by the engine). The map is designed to keep the air-to-fuel ratio as close as possible to the stoichiometric value of 14.7:1, which produces the lowest emissions. Since the injector solenoid opens slower at lower battery voltages than at the normal battery voltage of 12.6 volts, a battery voltage compensation coefficient is applied to the base injector value to increase the injector opening time as the battery voltage decreases. If the compensation coefficient is correct, then the final injector opening time is independent of the battery voltage, and everything works as designed. If the battery voltage compensation coefficient is incorrect, however, as a result of the battery voltage being sampled during a negative voltage spike, then the injector opening time is made longer even when the injector opening time is normal as a result of the DC battery voltage to the injector being normal. In this case, more fuel is injected into the engine than is required for stoichiometry, and the engine will run rich. This applies even during a sudden acceleration incident when the throttle is being opened more than designed due to an incorrect throttle motor battery voltage compensation coefficient because the MAF sensor is still measuring the amount of air through the throttle, including the increased amount during a sudden acceleration incident. When this happens, however, the additional fuel causes no additional acceleration effect other than a decrease in the air-to-fuel ratio. And this decrease gets reset when the injector battery voltage compensation coefficient gets reset when the engine is restarted.

A scan of the engine parameters taken during a sudden acceleration incident should reveal that the injector dwell time has increased and that the air-to-fuel ratio has gone rich. Such a scan has not been done, however, because the scanner must be attached ahead of time and must be logging these values during a sudden acceleration incident. Due to the indeterminacy of a sudden acceleration event, this has not been possible. However, if one were to use a data logger like the CarChip Pro[17] that attaches to the vehicle's OBDII connector, then one might be able to record these parameters during a sudden acceleration incident.

D. Ignition Dwell Time. The ignition dwell time is modified by a battery voltage compensation coefficient which increases the ignition dwell time in response to the ignition coil putting out a lower voltage as the battery voltage decreases. Therefore, the ignition voltage will increase above the normal amount when an incorrect ignition voltage battery voltage compensation coefficient is used. This will have little effect on acceleration, however, because the ignition dwell time does not directly affect the engine torque or engine speed. The ignition dwell time relates to the charging of the ignition coil, which determines the voltage that the coil puts out. The ignition advance relates to the timing of the coil discharge, and therefore the spark timing, and strongly affects the engine torque and engine speed. But the ignition coil compensation coefficient has no effect on the ignition advance.

III. Root Cause and Solution for Unintended Acceleration

Unintended acceleration in vehicles having electronic throttles has been found to be associated with the improper battery voltage compensation of the throttle motor PWM duty cycle and the variable valve timing actuator oil control valve PWM duty cycle because of the wrong battery voltage being sensed by the ECU. Essentially, if the analog to digital converter (A/D) in the ECU samples the battery voltage during a negative voltage spike of relatively short duration (e.g., 1 to 500 microseconds), then the A/D senses the battery voltage V_{BATT} as being a low value (e.g., 0 to 12.6 volts) even though the DC value of the battery voltage remains at its normal value of 12.6 volts. This causes the throttle motor PWM duty cycle and the variable valve timing actuator oil control valve PWM duty cycle to be multiplied by the ratio $(12.6V/V_{BATT})^N$ where N is an exponent associated with the electric motor or solenoid that produces less torque as its supply voltage is lowered (e.g., N = 1 for a permanent magnet DC throttle motor). This means that the throttle motor PWM duty cycle or the variable valve timing actuator oil control valve PWM duty cycle are multiplied by a number between 1 and 10 (or more) even though the DC value of the battery voltage which is being used to supply the throttle motor or the oil control valve remains at its normal value of 12.6 volts. The result is that the throttle motor torque and the variable valve timing actuator oil control valve solenoid torque are increased above their normal values, causing an increase in the throttle opening angle and an increase in the intake valve opening timing advance, both of which increase the torque that the engine provides.

The root cause of this behavior lies in the battery voltage sensing circuit shown in Figure 12. Figure 12 shows that the battery voltage is translated from the normal 12.6 volts down to 5 volts by a simple resistor divider. (The ratio is actually greater than this, to allow battery voltages of up to 18 volts to be mapped down to the 5 volt range of the A/D converter). The problem is caused by the battery supply voltage being suddenly pulled down for a short duration when an accessory such as an air conditioner (A/C) turns on. Because the accessory has such a low impedance to ground (a few tens of ohms or less), the battery supply voltage is effectively shorted to ground temporarily. This is exacerbated by a partially discharged battery. The temporarily shorted battery node immediately discharges any capacitance that may be present, either parasitically or by design, with the intent of holding up the node during a short voltage pulse. The effect is similar to shorting the two terminals of the capacitor together with a wire conductor. If the A/D converter samples the battery supply while the supply voltage is being pulled down temporarily, then the ECU will conclude incorrectly that the DC value of the battery supply is low even though the DC value remains unchanged after the short turn-on event has passed. This incorrect DC voltage value remains in memory until another A/D sample is taken, which may happen many minutes or hours later. In the meantime, the incorrect DC value is used for compensation of the throttle motor PWM duty cycle and the variable valve timing actuator oil control valve PWM duty cycle while these functions are operating at a normal 12.6V supply voltage.
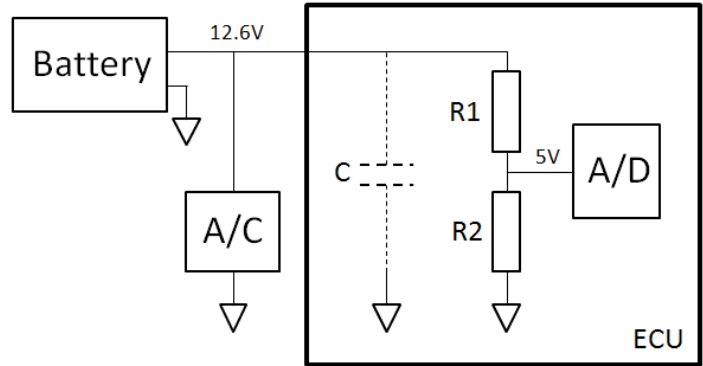
Figure 12. Battery voltage sensing circuit

One possible solution to the problem is to use the improved battery voltage sensing circuit shown in Figure 13. In this circuit diode D has been added to isolate the A/D from the battery supply voltage while the supply voltage is being pulled low by the A/C (or other accessory) turning ON. The isolation occurs because the diode is operating in its reverse-biased state while the supply voltage is temporarily low. While this happens, capacitor C is used to hold the A/D node at its prior DC value. When the battery supply voltage is restored to its normal DC value of 12.6V, then the diode conducts in the forward direction and the circuit works normally. In this circuit R1 and R2 are changed slightly from the values used in Figure 12 to allow for the diode voltage drop in the forward direction. Also, the diode must have a suitable reverse breakdown voltage to allow it to withstand the voltages encountered on the 12V battery supply in an actual vehicle.
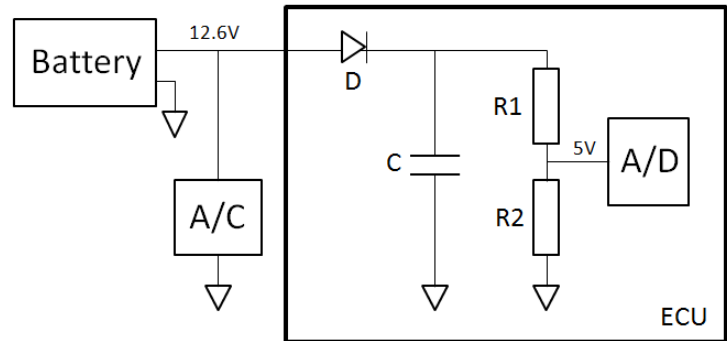
Figure 13. Improved battery voltage sensing circuit

Another possible solution is to take multiple samples of the battery voltage a short time apart. Then one can look at the samples and make a judgment as to which one is most likely to not have been taken during a negative voltage spike. This may be as simple as taking two (or more) samples a few seconds apart and then selecting the one having the higher (or highest) voltage as the preferred sample. One can also take two samples a few seconds apart and test them to see if they have the same voltage value within a fixed error limit. If they do not, then one can take a new sample and repeat the test on the last two samples until a common voltage is reached, which can then be used as the desired DC voltage. An advantage of using two or more samples to decide on a preferred DC voltage sample is that the method can be implemented in a software program which can be used in addition to the hardware fix above to achieve an even greater insensitivity to a negative voltage spike. A software program also allows being downloaded into the ECU of a user-owned vehicle as a service upgrade to improve its insensitivity to a negative voltage spike. Another solution is to take multiple samples and then to average them or filter them in some way. The problem with averaging or filtering is that a very low voltage sample can still draw down the ensemble average or the filter result below a value that is safe for compensation.

IV. Testing the Proposed Theory

A straightforward way to test the proposed theory is to inject a negative voltage spike on the battery supply line at exactly the same time that the voltage is being sampled by the CPU. This is difficult to do, however, because the A/D sampling time is unknown without information from the manufacturer. This means that one is left with injecting the negative voltage spike asynchronously, and hoping that by doing it often enough one of the spikes will occur by chance during the A/D sampling time. The chances of this happening are very slim, however, because this same stochastic process determines the unintended acceleration incident rate of the vehicle, which is about 10 to 100 events per 100,000 vehicles. Therefore, one needs to repeat this test thousands of times or more before one gets a single chance coincidence that changes the A/D sample of the supply voltage.   This is probably why the problem was not found during EMI testing by the auto manufacturers, if their test departments were unaware of the need to synchronize the negative voltage test pulse with A/D converter operation[18].

A better way to test the theory is to disconnect the normal battery supply voltage from the ECM input going to the H-bridge[19], and to substitute the output of a variable DC voltage supply adjusted to a DC voltage of around 8 to 9 volts (i.e., the same voltage as a voltage spike that is slightly above the voltage level able to cause a CPU reset)[20]. One can then start the vehicle and run it while monitoring the battery voltage seen by the ECM via the OBDII connector using a scan tool in the data logging mode. When it has been confirmed that the 8 to 9 volt DC voltage has been sampled and stored in the ECM, one merely needs to raise the applied voltage to the H-bridge to 12.6V or 14.4V, which will cause the motor control loop to assume a condition exactly like the one produced by a voltage correction coefficient resulting from a negative voltage spike[21]. Turning on the air conditioner will then cause an idle-up which will lead to an increase in engine speed without having a foot on the accelerator. For this test the vehicle's drive wheels must be off the ground (or alternatively, the vehicle must be on a dynamometer), and the engine must be running with the transmission in DRIVE or REVERSE, and not in PARK or NEUTRAL.

V.   Conclusion

Unintended acceleration in vehicles having electronic throttles has been found to be associated with the improper battery voltage compensation of the throttle motor PWM duty cycle and the variable valve timing actuator oil control valve PWM duty cycle because the wrong DC battery voltage has been sensed by the ECU. The root cause of the unintended acceleration is the battery voltage sensing circuit, which detects an improper value of the DC battery voltage when the battery supply voltage is being sampled in the presence of a negative voltage spike. Such negative voltage spikes are always present on the power bus of every vehicle, and are increased in magnitude as the battery becomes more discharged[1]. This explains the stochastic nature of unintended acceleration, and the low probability of its occurrence. It also explains why many sudden acceleration incidents occur in parking lots and at stop lights because this is when the engine is at idle, causing the vehicle's supply voltage to be determined by the vehicle's battery and not by the vehicle's alternator[1]. It also explains why older people have a higher incident rate, because they tend to drive shorter distances and to make fewer trips, so their batteries have a higher likelihood of being not fully charged, which allows larger negative voltage spikes on the power bus[1].

When this incorrect DC battery voltage is used to compensate the throttle motor PWM duty cycle and the variable valve timing actuator oil control valve PWM duty cycle while the throttle motor and oil control valve are operating with a normal DC battery supply voltage, then the outputs of these functions increase above their normal values, causing the throttle opening to increase and the intake cam timing to advance. Both of these increase the engine torque, which causes vehicle acceleration. This all happens while the driver's foot is off the accelerator. There is no need to assume hardware faults, software faults, EMI, cosmic rays, tin whiskers, or any other cause of throttle system malfunction because the throttle system is performing exactly as designed in every way except for the incorrect throttle motor duty cycle battery voltage compensation coefficient. This is why no diagnostic trouble code is ever found. Essentially, this is a design flaw that occurs in all vehicles having electronic throttles. It is not just a problem with Toyota vehicles or Ford vehicles, but is a problem with the vehicles of all auto manufacturers. Since the driver's foot can be off the accelerator while it is happening, a brake override system is completely ineffective in preventing unintended acceleration. A more effective design solution which cures the true root cause has been proposed.

VI. Acknowledgements

VII.   References

[1] R. Belt, *"An Electronic Cause for Sudden Unintended Acceleration"*, April 2012, http://www.antony-anderson.com/Cruise/belt-hypo/sum.html. Also available at: http://www.autosafety.org/dr-ronald-belt%E2%80%99s-sudden-acceleration-papers-2012.

[2] R. Belt, *"A Detailed Electronic Mechanism for Sudden Unintended Acceleration"*, August 2012, http://www.antony-anderson.com/Cruise/belt-hypo/sum.html. Also available at: http://www.autosafety.org/dr-ronald-belt%E2%80%99s-sudden-acceleration-papers-2012.

[3] This figure has been changed from the one found in the author's second paper, reference 2, to correct the compensation coefficient from a quadratic dependence on voltage to a linear dependence on voltage.

[4] K. Shirai, H. Miyano, S. Kamio, and Y. Nakaya, *"Engine Throttle Control with Variable Control Constants"*, U.S. patent number US5669351, awarded to Denso, 23 Sept, 1977. Same as European patent number EP0735256B1, awarded to Denso, 1996.

[5] NASA NESC Technical Assessment Report, *"NHTSA Toyota Unintended Acceleration Investigation – UA Report"*, January 18, 2011, (revised April 15, 2011), p. 162 of 177.

[6] http://carproblemzoo.com/subaru/forester/vehicle-speed-control-problems.php, #17 - Vehicle Speed Control problem of the 2006 Subaru Forester. "When I came home for lunch and pulled into our drive and put in the clutch, the rpms shot up to around 3000. Turning the vehicle off and restarting will "reset" the rpms to around 1500 until it is put in gear once again and the clutch depressed. A couple of times this happened: after the rpms shot up to 3000+, I kept the clutch pressed to see how long the rpms would stay around 3000. The rpms did a decaying sinusoidal oscillation of about 6 cycles over a period of about 30-45 seconds, finally leveling out around 1500 rpm." This vehicle had an electronic throttle.

[7] Teruji Sekozawa,*"Model-based Control and Learning Control Method for Automobile Idle Speed Control using Electric Throttle"*, WSEAS Transactions on Systems and Control, Issue 2, Volume 3, February 2008, http://www.wseas.us/e-library/transactions/control/2008/25-682.pdf

[8] Williaty,*"Subaru Drive By Wire and How to Improve It"*, 14 June 2008. http://forums.nasioc.com/forums/show-thread.php?t=1537010,

[9] This argument does not depend on the assumed value of 30%. The argument applies to any increase which does not exactly compensate the decrease seen in the supply voltage by the throttle motor. The value of 30% was chosen merely to avoid the complication of interpolation, which the ECU uses routinely in all its maps.

[10] NHTSA Investigation PE11-018 entitled *"Throttle body malfunction in 2005-2007 Ford Freestyles, 2005-2007 Ford Five Hundreds, and 2005-2007 Mercury Montegos"*, opened 5/11/2011, closed 2/7/2013. See ODI opening resume INOA-PE11018-6504.pdf obtainable at http://www-odi.nhtsa.dot.gov/owners/SearchNHTSAID by inserting PE1101 in the search box.

[11] See the following web sites for driver reports on Tacoma incidents related to air conditioners:
http://www.customtacos.com/forum/archive/index.php/t-88560.html,
http://www.ttora.com/forum/archive/index.php/t-84645.html,
http://archive.columbiatribune.com/2008/Apr/20080418Busi013.asp,
http://townhall-talk.edmunds.com/direct/view/.f20003b/419,
http://www.tundrasolutions.com/forums/sitemap/t-90542.html,
http://www.topix.com/forum/autos/TIUVQT6QDCKMIOCDK,
http://www.autospies.com/news/NHTSA-Sides-With-Toyota-On-Unintended-Acceleration-Issues-Claiming-400-Owners-Had-No-Case-34348/,

http://www.toyotanation.com/forum/79-1st-generation-1995-5-2004/304441-2003-tacoma-stumbling-local-wrench-perplexed.html

[12] Volkswagen recall 24M9/R7, entitled *"Volkswagen is recalling 4,079 MY 2008 Passat and 2,500 MY 2009 Tiguan passenger vehicles equipped with 2.0t FSI ULEV II engines. These vehicles have an engine control module (ECM) containing software that may not properly control engine idle with the air conditioning turned on. In rare cases, the ECM may unexpectedly increase engine RPM"*, announced 28 May 2008. See NHTSA recall campaign number 08V235000, obtainable at http://www-odi.nhtsa.dot.gov/cars/problems/recalls/results.cfm?SearchType=Quick-Search&rcl_ID=08V235000&summary=true

[13] Ford Motor Company, *"Torque Based Electronic Throttle Control (ETC)"*, in 2007 PCED On Board Diagnostics, SECTION 1: Description and Operation, Procedure revision date: 03/29/2006, p3, "Electronic Throttle Control (ETC) System Strategy", http://www.allfordmustangs.com/forums/attachments/2005-2010-mustang-talk/103576d1278091673-someone-please-explain-why-my-car-maybe-all-cars-do-torque-based-electronic-throttle-control-etc.pdf.

[14] Ford Motor Company, *"Torque Based Electronic Throttle Control (ETC)"*, in Gen II Torque-Based ETC, 2008, http://www.justanswer.com/uploads/asemaster327/2008-10-01_141304_ANSWER.pdf,

[15] Ford Motor Company, *"Torque Based Electronic Throttle Control (ETC)"*, in 2009 PCED On Board Diagnostics, SECTION 1: Description and Operation, Procedure revision date: 05/27/2010, p2, "Electronic Throttle Control (ETC) System Strategy", http://mygtcs.com/mustang/documents/ford/PCED/1-DescriptionAndOperation//Torque-Based%20Electronic%20Throttle%20Control%20(ETC).pdf

[16] Toysrme, *"How VVT-i Works in General"*, 4/27/07, http://www.toyotanation.com/forum/10-hardcore-tech-competition/184335-vvt-i-head.html, Taken from the Lexus LS400 repair manual for the 1UZ-FE engine, 1997, p.90. This engine had an ETCS-i throttle with the APS sensor on the throttle body connected to the accelerator by a cable. The throttle motor was coupled to the throttle valve through a clutch as a fail-safe measure.

[17] Carchip Pro Data Logger, Davis Instruments, 3465 Diablo Avenue, Hayward, CA 94545-2778 U.S.A. • 510-732-9229 • www.davisnet.com, http://www.davisnet.com/product_documents/drive/spec_sheets/8226_SS.pdf

[18] Test standards ISO 7637-2, SAE J1113-11, and ISO 16750-2 specify test waveforms, methods, and procedures for evaluating electronic devices and equipment for immunity to conducted electrical transients along the battery feed or switched ignition inputs of passenger cars and commercial vehicles, but do not specify the need to synchronize the waveforms to equipment operation.

[19] The H-bridge is supplied by the BM input on a Toyota.

[20] Between the ignition switch and the ECM input there is usually a fuse and a harness connector, either of which provides a convenient point for removing the battery voltage and substituting an adjustable power supply.

[21] This follows from the following reasoning. A normal PID loop state is when the battery voltage sampled by the A/D is the same as the DC battery voltage seen by the throttle motor from the H-bridge; i.e., $V_{BATT}(A/D) = V_{BATT}(Throttle\ Motor)$. Normally, this is 12.6 volts, but it can be as low as 8-9 volts as long as both voltages are the same. An abnormal PID loop state associated with unintended acceleration is when $V_{BATT}(A/D) < V_{BATT}(Throttle\ Motor)$. Therefore, one can achieve an unequal state either by lowering $V_{BATT}(A/D)$ from 12.6V to 8-9 volts (or lower) or by raising $V_{BATT}(Throttle\ Motor)$ from 8-9 volts to 12.6 volts (or higher).