Answers to Some Remaining Questions On Belt's Theory of Sudden Acceleration

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Abstract: An explanation is given for how the electronic throttle gain can change even when the throttle PID controller remains stable and converges to the driver-commanded throttle opening. This gain change can then produce sudden acceleration by causing a runaway engine speed condition in the higher-level open loop throttle controller. It is further explained why one cannot prevent long duration sudden acceleration incidents by merely updating more frequently the battery voltage duty cycle compensation coefficient for the electronic throttle. Finally, it is explained where the battery voltage is sampled, and how the same voltage sample is used to correct all the actuators that are sensitive to battery voltage variations. This leads to a convenient way to test the proposed theory of sudden acceleration.

I. Introduction

Previous papers by this author[1] have discussed how sudden unintended acceleration is caused in vehicles having electronic throttles or idle air control valves. The explanation is as follows. The amount of air injected into the engine by the electronic throttles or idle air control valves in all these vehicles is sensitive to the supply voltage of the air actuator. So to make the engine operation insensitive to changes in the supply voltage, the air actuator opening command (in the form of a duty cycle) must be corrected by a compensation coefficient that is the inverse of the air actuator supply voltage. The air actuator supply voltage is measured by an A/D converter sampling the supply voltage shortly after the engine is started. Normally, this 50 microsecond A/D sample turns out to read 12.6 volts, which is the DC voltage of a healthy battery. In this case, the compensation coefficient becomes unity, which results in no change being made to the gain of the air control actuator. When the driver shifts the vehicle into DRIVE or REVERSE with his foot on the brake, nothing happens besides feeling the normal creep of the vehicle while idling in gear.

Once in a blue moon, however, a negative voltage spike can occur during the 50 microsecond A/D sampling time. The negative voltage spike is caused by an electric motor or solenoid turning on, like the air conditioner compressor or a radiator fan, which causes practically a dead short to appear across the battery for a very short time on the order of 100 microseconds. The chance of this negative voltage spike occurring during the 50 microsecond A/D sampling time is about 1 in 10,000, and determines the sudden acceleration incident rate in all types of vehicles. The magnitude of the negative voltage spike may be anywhere between one half a volt to several volts, depending on the state of charge of the battery after starting the engine. Therefore, the negative voltage spike makes the voltage of the A/D sample read lower than 12.6 volts, say 11.0 volts, instead of the normal battery voltage of 12.6 volts. In this case, the compensation coefficient that results is larger than unity. Normally, if this compensation coefficient results from a low DC voltage without a spike, and is applied to the idle actuator valve when the DC battery voltage is at the same low voltage, then the gain of the IAC valve, which decreases with a lower DC battery voltage, is brought back up to the normal gain once more. However, in this case, when the lower A/D sample voltage is caused by a negative voltage spike, then the larger-than-unity compensation coefficient is applied to the normal idle actuator gain associated with the normal DC battery voltage of 12.6 volts. This causes the gain of the electronic throttle or IAC valve to become higher than normal. While the engine continues to idle in PARK or NEUTRAL, this causes no observable change in the engine speed, because the idle controller in PARK or NEUTRAL is a closed-loop idle controller which merely re-adjusts the amount of air to maintain the normal idle speed of 800 RPM.[Note1]

If the driver now places his foot on the brake and shifts the car into either DRIVE or REVERSE, then the idle speed controller is changed from a closed-loop controller to an open-loop controller which is much more sensitive to the gain of the air control actuator [Note2]. What happens next is completely beyond the control of the driver. The electronic throttle or idle air control valve is controlled by commands contained in a map, or table. While the driver's foot is still on the brake, on the first iteration through the control map, the higher-than-normal actuator gain causes more air to flow into the engine than the control map expects, increasing the engine speed slightly. Ten milliseconds later, on the second iteration through the control map, the higher air flow and higher engine speed cause a different map location to be selected, resulting in a command to the air control actuator to increase the air opening just a little bit more. But, again, the higher-than-normal actuator gain causes more air to flow into the engine than the map expects, increasing the engine speed even more. With each successive map iteration the electronic throttle or idle air control valve opening increases further, causing the engine speed to increase. This causes a runaway engine condition which results in the engine suddenly revving up to the maximum in the map, which can be approximately 3000 RPM or more. The time it takes for this to happen is less than one second, because each iteration of the control map takes only about 10 milliseconds. Therefore, in one second about 100 map iterations occur, which is more than enough to cause the map to be completely traversed to the maximum RPM in the map.

While this takes place, the driver's foot remains on the brake. He knows it is there because he had to put it there to shift out of PARK. Now, with the engine suddenly revving at its maximum RPM, the vehicle begins to move because it is in either DRIVE or REVERSE. Normally, when the car is in either DRIVE or REVERSE, the car would be creeping slightly. But with the engine revving at its maximum RPM, the creep becomes a high acceleration. The acceleration is high because the engine torque is multiplied by a factor of 4 to 5 in either first gear or reverse gear, and by another factor of 2 in the torque converter. And as the driver applies the brake harder to control the car, the brake puts a higher load on the engine, which slows down the engine speed and increases the torque that the engine puts out. The result is that pushing on the brake seems to <u>increase</u> the acceleration (i.e., torque), just like a car in cruise control going up a hill seems to increase the engine acceleration (torque) because the hill is putting a higher load on the engine.

The only thing that stops this runaway engine behavior is to turn off the ignition, shift into neutral, or crash into some object, which puts such a high load on the engine that the engine speed is reduced to zero, causing the engine to stall. But the driver's attention is so consumed by steering the car away from danger that he has little time to turn off the ignition or shift into NEUTRAL. This explains the high number of parking lot crashes, as well as crashes into store fronts, houses, trees, pools, lakes, rivers, and even from high-rise parking lots. The crash happens while the driver's foot remains the brake. It is not a case of pedal confusion, or the driver depressing the accelerator instead of the brake, because the driver knows that his foot has not changed its position since he shifted out of PARK. Instead, it is a case of the vehicle's control system going into a runaway condition because the automobile manufacturer's designers did not account for the case of a negative voltage spike causing a change in the gain of the air control actuator. It

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Note 1. A <u>closed-loop</u> idle controller can reduce the engine speed if it gets too high or increase it if it gets too low because it has negative feedback. An <u>open-loop</u> idle controller gets no feedback of the engine speed, however, so it does not know if the engine speed gets too high or too low. It merely issues an idle command and assumes that the result is what was expected by the design engineer.
Note 2. This sensitivity is why a battery voltage compensation coefficient is needed in the first place, because if the air actuator gain becomes higher, then the engine speed will be made higher than the control map expects, causing a higher creep rate at idle. If the air actuator gain becomes lower, then the engine speed will be made lower than the control map expects, causing the engine to possibly stall.

is not the driver's fault, it is the auto manufacturer's fault because the vehicle's design is defective. This same explanation applies to all vehicles having electronic throttles or idle air control valves because they all use the same basic design for the air control actuators, and in DRIVE or REVERSE the air control actuators are all controlled by an open-loop throttle controller based on an inverse engine map.

The above discussion explains how the engine can go to a maximum RPM condition without the driver stepping on the accelerator pedal and without a diagnostic trouble code (DTC) being set. However, the above discussion leaves several questions unanswered; namely:

1. How can the gain of the throttle motor change when there is no diagnostic trouble code (DTC) to indicate a malfunction in the throttle PID controller?
2. Why is the electronic throttle duty cycle compensated for <u>battery</u> voltage when the throttle motor supply voltage is determined by the <u>alternator</u> voltage while the engine is running?
3. Why can't long duration sudden acceleration events be eliminated merely by sampling the supply voltage more often when creating a compensation coefficient?
4. What node in the vehicle wiring diagram is sampled by the A/D converter when determining the battery voltage for creating a compensation coefficient for the throttle motor duty cycle?

The following sections will now answer these remaining questions.

II. Answers to Remaining Questions

1. <u>Question 1</u>. How can the gain of the throttle motor change when there is no diagnostic trouble code (DTC) to indicate a malfunction in the throttle PID controller?

<u>Answer</u>. When there is no PID controller it is easy to understand how the gain of an electronic throttle motor or idle air control solenoid valve or stepper motor valve can change. Both types of actuators consist of coils of wire which produce a magnetic field that controls the opening of an air control valve. The valve opening varies with the current passing through the actuator. Therefore, if the actuator current changes because the supply voltage increases or decreases, then the amount of air delivered to the engine increases or decreases, causing the engine to speed up or slow down. It is the purpose of the battery voltage compensation coefficient to correct for changes in the supply voltage so that the amount of air stays independent of the supply voltage, keeping the engine speed independent of the supply voltage. However, if an incorrect battery voltage compensation coefficient is applied to the normal supply voltage, then the actuator current will increase when it shouldn't, causing the actuator opening to increase the amount of air delivered to the engine. This increase in the amount of air will persist as long as the compensation coefficient remains unchanged.

What causes confusion is when the air actuator is controlled by a PID loop. In this case, many believe that as long as the PID controller converges stably to the driver-requested setpoint, then the actuator gain remains unchanged. In other words, it is assumed that convergence and stability imply that the PID controller is operating normally. The absence of a diagnostic trouble code (DTC) is cited as further proof that that the PID controller continues to act normally.

The actual operation of an electronic throttle actuator in a PID loop is shown in Figure 1. The PID controllers in all vehicles are designed to converge to within 2% of the setpoint value in less than 100 milliseconds with no overshoot.[2,3,4,5,6] If they converge as designed, then the actuator output approaches the setpoint, and no DTC is set. The amount of air entering the engine is proportional to the area under the actuator response curve shown in Figure 1. But if the actuator gain increases, then the PID loop response has an overshoot as shown in Figure 2.[7] An increase in the actuator gain behaves exactly like an increase in the PID coefficients. Both increase the PID loop gain, which causes an overshoot. It is easy to see that the area under the curves with an overshoot is greater than the area under the normal curve without an overshoot. This means that the engine is getting more air when an overshoot occurs. One can also see that the curves with an overshoot still converge to the original setpoint, causing no DTC to be set. This means that the actuator gain can increase even when no DTC is set.

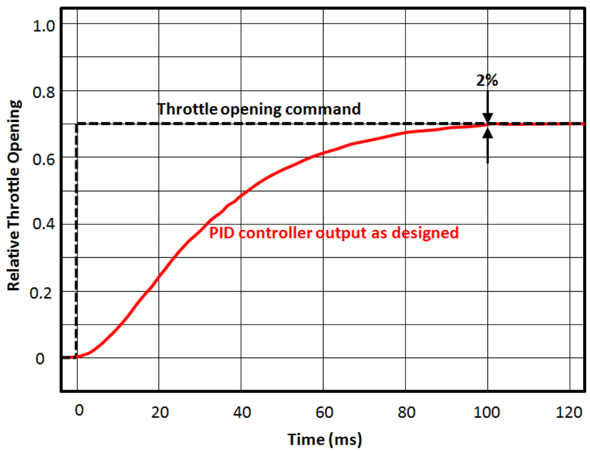

Fig 1. Electronic throttle PID controllers are designed to converge to within 2% of the commanded throttle opening in less than 100 milli-seconds with no overshoot.[2,3,4,5,6] The amount of air entering the engine is proportional to the area under the curve. If the final output differs from the throttle opening command by >2%, a DTC is usually set.

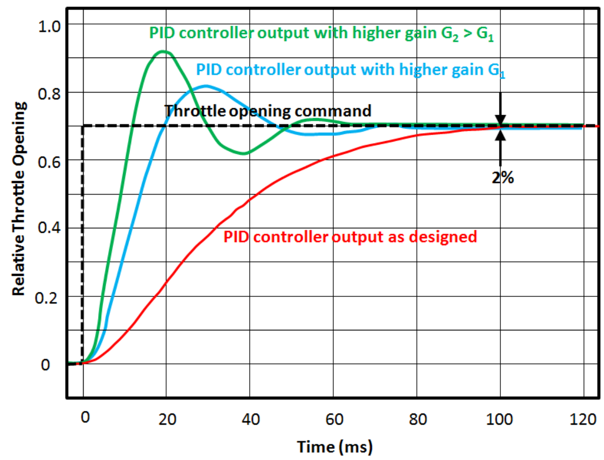

Fig 2. An incorrect battery voltage compensation coefficient produces a higher actuator gain, causing an overshoot in the PID output.[7] The overshoot increases the area under the PID curve, leading to more air entering the engine. If the controller still converges to the commanded throttle opening, no DTC will be set.

Even more interesting is that small increases in the setpoint can have larger overshoots than large increases in the setpoint.[8] This is because large increases in the setpoint leave a smaller overhead above the new setpoint before saturation occurs, while large increases in the setpoint have a much larger overhead above the new setpoint. This may explain why small increases in the setpoint caused by idle-ups are much more likely to cause sudden acceleration than large increases in the setpoint caused by suddenly flooring the accelerator pedal.

Previous researchers, such as NHTSA, NASA, and Exponent Inc have failed to mention that the PID controller output can have an overshoot which increases the amount of air into the engine. This may stem from their atttempt to find a single mechanism (like controller instability) which can cause a large long-term increase in the amount of air entering the engine, thereby leading directly to a sudden acceleration. After finding no such single mechanism, they concluded that sudden acceleration was impossible. They failed to recognize that a two-step mechanism consisting of: 1) a small short-term increase in the amount of air entering the engine caused by a PID overshoot followed by 2) an increase in the loop gain of the higher-level open-loop throttle controller that leads to a runaway increase of the PID setpoint, can lead to sudden acceleration. The increase in the loop gain of the higher-level throttle controller occurs in exactly the same way that the increase in the loop gain of the PID controller occurs; namely, because of a higher actuator gain. The reader is referred to the author's previous papers[1] which explain the operation of the higher-level throttle controller and how it can enter a runaway condition when the loop gain increases as a result of the actuator gain increasing.

2. <u>Question 2</u>. Why is the electronic throttle duty cycle compensated for <u>battery</u> voltage when the throttle motor supply voltage is determined by the <u>alternator</u> voltage while the engine is running?

<u>Answer</u>. It is widely recognized that the alternator sets the vehicle supply voltage while the engine is running. This voltage is normally regulated to be 14.0±0.2 volts at 32°F, which is determined by the

optimum battery charging voltage at this temperature. At higher temperatures this voltage may be up to 0.5 volts lower and at lower temperatures up to 0.5 volts higher. This voltage applies as long as the alternator is supplying all the current that the vehicle needs for all its functions, including charging the battery. This usually occurs when the engine speed is high enough above idle to allow the alternator to deliver its fully rated current. When the engine is at idle, however, the current delivered by the alternator is much lower than the fully rated current, and may not be sufficient to power all the vehicle's functions. In this case the battery must provide the additional current needed, and the supply voltage may drop down to the battery voltage. The battery voltage of a fully charged battery is 12.6 volts, and may even be a few tenths of a volt higher immediately after charging. But if the battery is not fully charged, this voltage may drop down to as low as 11.0 volts or less. When this occurs, the headlights may dim while the engine is at idle, and other electrical functions may be affected. This is all considered to be normal operation of the battery and charging system. If the current needed by all the vehicle's loads permanently exceeds the current that the alternator can provide, even at higher engine speeds, then something may be wrong with the alternator, the battery, or a shorted load.

If the vehicle supply voltage is normally higher than the battery voltage, then one may ask why the throttle motor must be compensated for the battery voltage and not the alternator voltage. Was the author wrong in all his previous papers when he referred to the throttle motor compensation coefficient as a "battery voltage compensation coefficient"? The answer is no, because a similar situation arises with the compensation coefficient for the fuel injectors, which all auto manufacturers refer to as a "battery voltage compensation coefficient". In fact, all the actuators on the vehicle that run off the "12 volt" supply voltage must be compensated for battery voltage and not alternator voltage. Why is this so?

The answer lies in the response time of the alternator to supply additional current when needed. When the demand for current from the alternator increases, there is a delay time before the current is produced because the magnetic field of the field winding in the alternator must be increased to produce the higher current. The rise time of the magnetic field is limited by the inductance L and resistance R of the field winding to be L/R, which turns out to be over 100 milliseconds.[9,10] If the actuators were limited to using this alternator current, then their response times would be limited to 100 milliseconds. This would not be fast enough to perform the functions that the engine needs at higher engine speeds, as shown in Figure 3. Figure 3 shows that at 6000 RPM the time between fuel injections is 3 to 6 milliseconds, depending on the number of cylinders. This means that the response time of the fuel injectors must be less than 3 to 6 milliseconds in order to be able to inject the proper amount of fuel into the engine on time. Similarly, the response time of the air actuator must be less than 2 milliseconds in order to allow it to react to the throttle PID loop time of about 2 milliseconds. If we look at the L/R time constants of the fuel and air actuators shown in Table 1, then we can see that their response times are indeed on the order of one to three milliseconds, which means that they are designed to react much faster than the alternator current response time of 100 milliseconds.

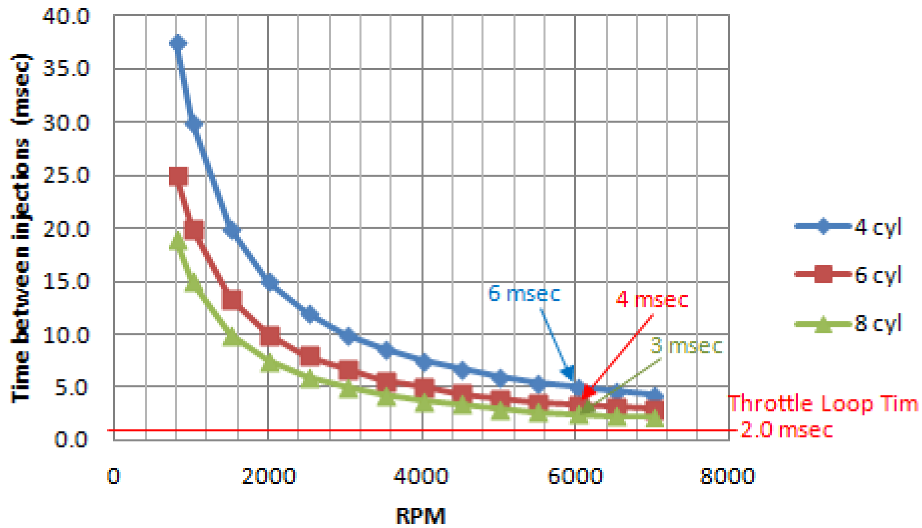

Figure 3. Time between injector events as a function of engine RPM[11]

Table 1. Measured time constants of IAC valves and fuel injectors. These time constants are determined by the inductance and resistance values of the solenoid actuators using the ratio L/R.

Actuator	L (mH)	R (Ω)	Time Constant (msec)
IAC valve (Theidle)[12]	38	49	0.8
IAC valve (Ziesen)[13]	33.5	53	0.6
Fuel injector (low Z)[14]	7.0	4.4	1.6
Fuel injector (low Z)[15]	6.5	2.3	2.8
Fuel injector (high Z)[16]	8.5	15	0.6
Ideal actuator[17]			1.0

So how do the actuators respond in a few milliseconds when the alternator current responds in only 100 milliseconds, which is not fast enough to supply the current needed by the actuators? The answer is that the battery must supply the additional current needed by the actuators, and the battery can respond almost immediately (<1 millisecond). And when the battery responds, the supply voltage drops immediately down to the battery voltage. If the battery is fully charged, this voltage will be 12.6 volts. If the battery is partially discharged, this voltage will be between 11.0 volts and 12.6 volts, depending upon the state of charge of the battery. The lower the state of charge of the battery, the lower the battery voltage and the slower the actuator works unless it is compensated for battery voltage. This momentary dip in supply voltage caused by the actuator is not noticed because it is so short (<100 milliseconds), because it occurs at a different time than when the voltage measurement is made, and because the response time of the voltage measuring apparatus is usually much longer than the dip in supply voltage. But the actuator current responds to the battery voltage, and this is why one must correct the actuator output for the battery voltage and not the alternator voltage.

3. Question 3: Why can't long duration sudden acceleration events be eliminated merely by sampling the supply voltage more often when creating a compensation coefficient?

Answer. From the answer to question 2, we now understand why the actuator is compensated for battery voltage even when the DC supply voltage is normally determined by the alternator voltage while the engine is running. The actuator current is actually determined by the instantaneous current produced by the battery, and not by the DC current produced by the alternator. So how does the engine control system determine the instantaneous supply voltage of the actuator when it can only measure the DC supply voltage by sampling it with an A/D converter? The answer is that the engine control system can't measure the instantaneous current to the actuator. Instead, it can only do the next best thing and measure the DC supply voltage when the battery is setting the supply voltage, which occurs only when the engine speed and alternator speed are so low at idle that the alternator is not putting out all the current needed by all the vehicle loads. This is the only time that the DC supply voltage is set by the battery voltage. This means that once the engine control system measures the DC supply voltage at idle and uses it to create a battery voltage compensation coefficient, then it must assume that this same voltage measurement and compensation coefficient apply until the next possible battery voltage measurement time occurs, which is when the engine is once more at idle. In other words, it is impossible for the engine control system to continually measure the battery voltage and create a new compensation coefficient while the vehicle is moving, because it can't measure the battery voltage unless the engine is at idle. This explains why long-term sudden acceleration incidents occur and why it is impossible for auto manufacturers to eliminate them by sampling the supply voltage more often to create a new compensation coefficient. Once a battery voltage sample is changed by a random negative voltage spike and then used to form an incorrect battery voltage compensation coefficient, this incorrect compensation coefficient will persist until a new battery voltage sample is taken. The battery voltage sample can only occur when the engine is brought once more to idle. The auto manufacturers have no other choice but to sample the battery voltage at idle because at higher engine RPM's the supply voltage will be equal to the alternator voltage of 14.0 ± 0.2 volts.

4. Question 4. What node in the vehicle wiring diagram is sampled by the A/D converter when determining the battery voltage for creating a compensation coefficient for the throttle motor duty cycle?

Answer. No auto manufacturer has ever identified which node in the vehicle wiring diagram is sampled by the A/D converter when determining the battery voltage for creating a compensation coefficient for the idle air control actuator because no auto manufacturer has ever admitted that they are compensating the idle air control actuator duty cycle for battery voltage. In fact, even though all auto manufacturers readily explain in their vehicle service documentation how the fuel injector pulse width is corrected for battery voltage, no auto manufacturer has ever identified the exact node in the vehicle wiring diagram that is sampled to obtain the battery voltage for the fuel injector compensation process. It appears that the auto manufacturers do not want the public to know this voltage sampling information, which is never discussed in any auto manufacturer's service documentation, patents, journal articles, or trade literature. However, after an intensive search for this information over a period of several years, the author has finally found an answer to which node is sampled for fuel injector battery voltage compensation. Toyota has provided the following information[18]

Step 3, Battery Voltage Correction
The final step is a battery voltage correction. The input signal used in battery voltage corrections is: 0 Battery Voltage (+B)

There is an operational delay between the time the ECU sends the injection signal to the driver circuit and the actual opening of the injector. This delay changes with the strength of the magnetic field around the injector coil. The delay increases as battery voltage falls.

To determine final injection duration, the ECU corrects for injector opening delay by using a battery voltage **correction coefficient.**

- The battery voltage correction coefficient increases injection duration as sensed battery voltage falls.

The +B battery voltage is obtained from the EFI main relay as shown in Figure 4[19].

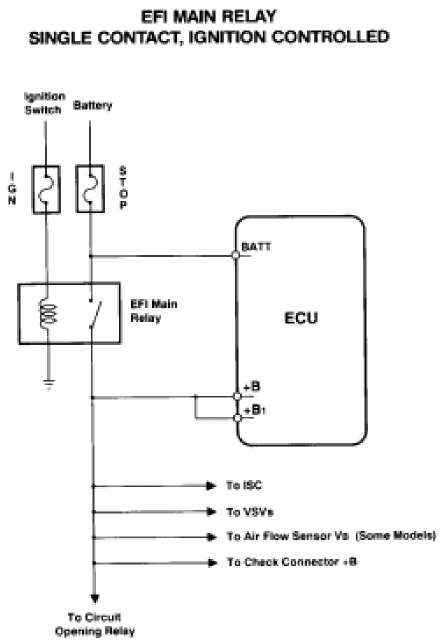

Figure 4. The +B battery voltage that Toyota uses for fuel injector compensation is obtained from the EFI main relay.

Without mentioning the battery voltage compensation process, Toyota clearly states that this same +B battery voltage is used for powering the idle air control valve in fuel injected vehicles without electronic throttles, as shown in Figures 5 and 6. This same information is repeated in Figure 7, which shows a 2003 Toyota Corolla circuit diagram in which an idle air control valve of the linear solenoid type is powered by the +B battery voltage obtained directly from the EFI relay powered by the EFI fuse. From these three figures we can infer that the same +B voltage sample used for battery voltage correction of the fuel injectors is also used for battery voltage correction of the idle air control valve. This +B battery voltage is accessible from the fuse box by tapping into either the EFI fuse or EFI relay shown in Figure 8. Accessing the +B voltage at either of these points avoids the necessity of opening the ECM or tapping into a harness connector.

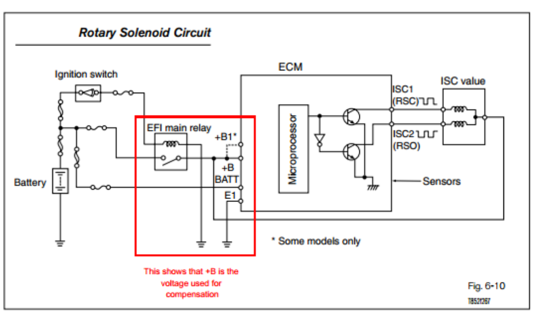

Fig 5. Idle air control valves of the linear or rotary solenoid type are powered by the +B battery voltage obtained from the EFI main relay.[20]

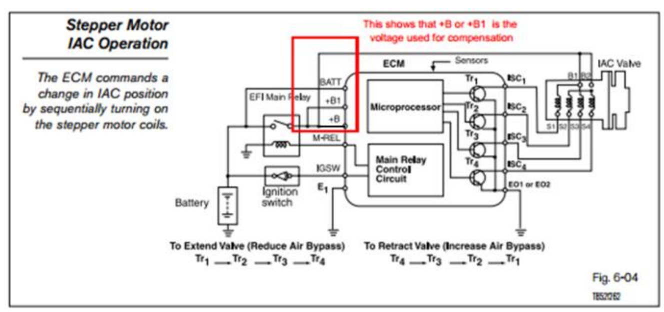

Fig 6. Idle air control valves of the stepper motor type are powered by the +B battery voltage obtained from the EFI main relay.[21]

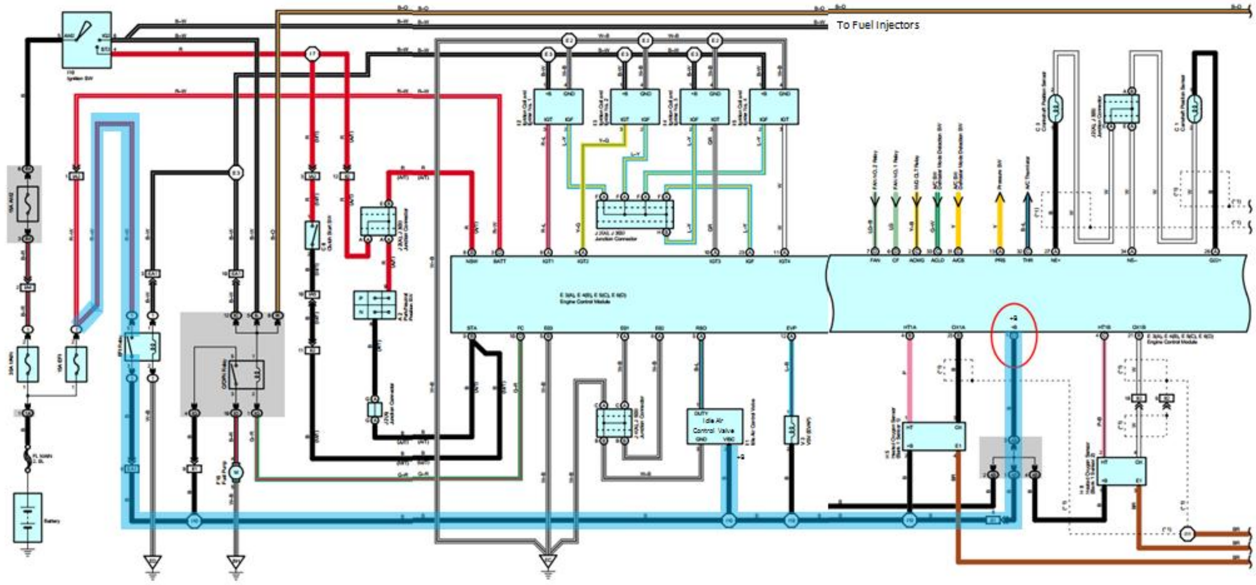

Figure 7. 2003 Toyota Corolla circuit diagram showing that the supply voltage for the idle air control valve comes directly from the EFI relay powered by the EFI fuse[22]. This same voltage is sensed by ECM pin #1 as the +B battery voltage. Knowing that the +B battery voltage is sampled for battery voltage correction of the fuel injectors, one can infer from this diagram that the same +B battery voltage present at pin #1 is sampled for battery voltage correction of the idle air control valve.

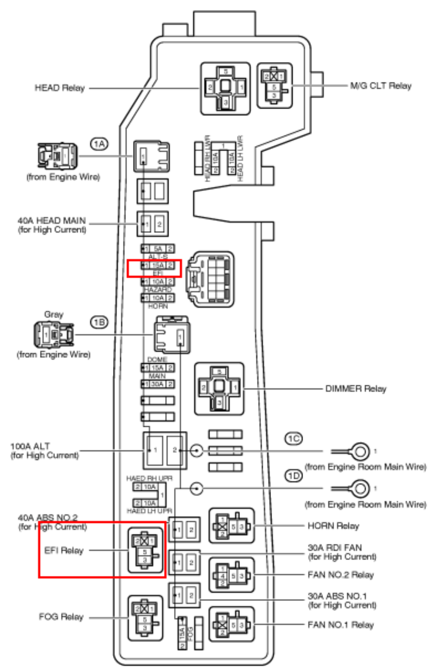

Figure 8. Fuse box diagram for a 2002 Toyota Corolla showing the EFI fuse and EFI relay.[22] By accessing the +B battery voltage at either of these points, one can avoid the necessity of opening up the ECM or tapping into a harness connector.

The Ford Motor Company uses a similar method of powering the fuel injectors and idle air control valve on their 1998 Taurus/Sable automobiles. Figure 9 shows the circuit diagram for a 1998 Taurus.[23] Figure

10 shows that the battery voltage for these actuators is accessible from the fuse box by tapping into either the PCM power relay fuse or PCM power relay shown in Figure 8. Accessing the voltage at either of these points avoids the necessity of opening the PCM or tapping into a harness connector.

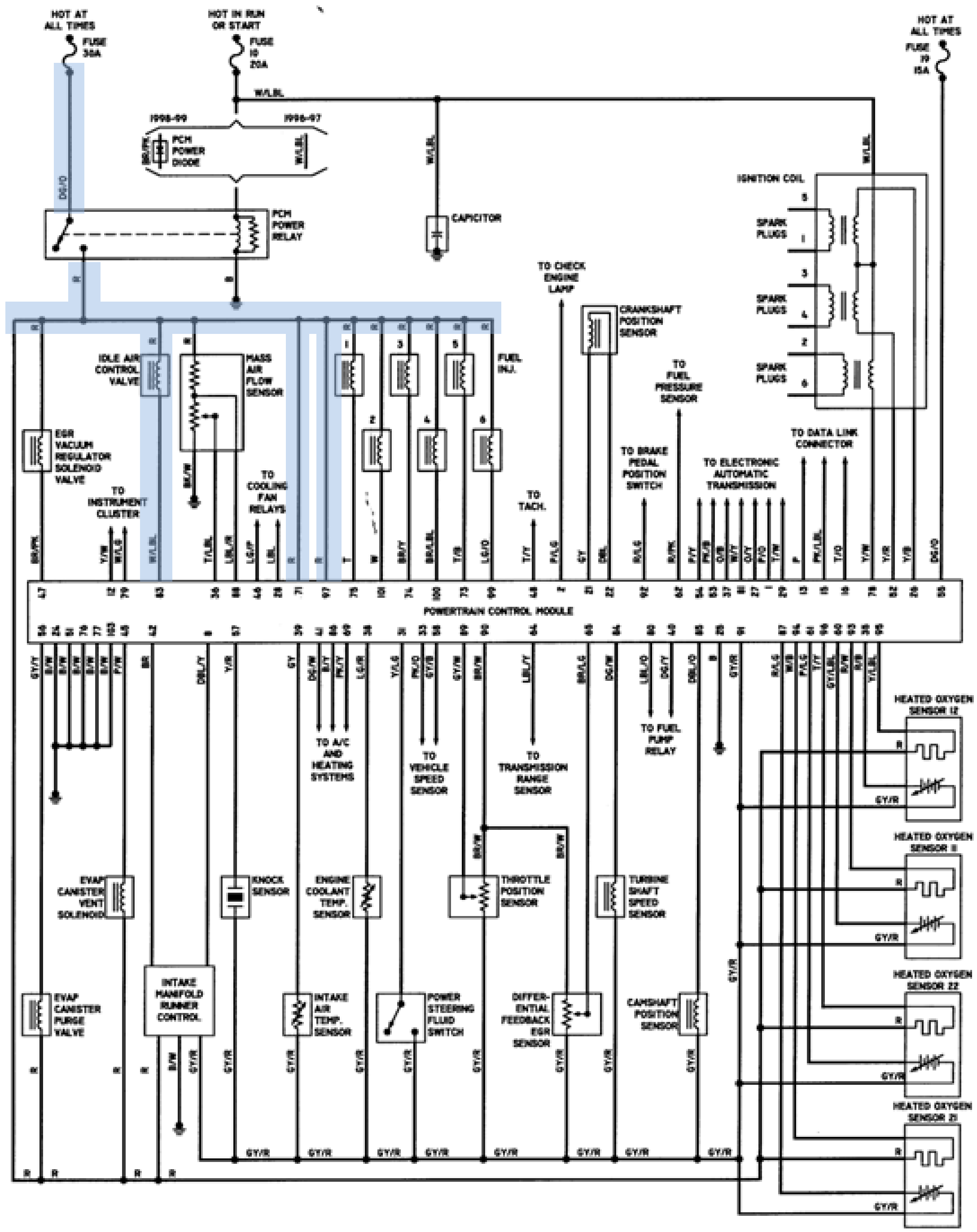

Figure 9. 1996-99 Ford Taurus schematic for 3.0L 4V engine. The idle air control valve is powered from the main power relay along with the fuel injectors and the MAF sensor. The voltage from the main power relay enters the powertrain control module (PCM) at pins 71 and 97. One of these voltages is sampled by the A/D converter in the PCM and used for voltage compensation of the fuel injectors. The same voltage sample is likely used for compensation of the idle air control valve.

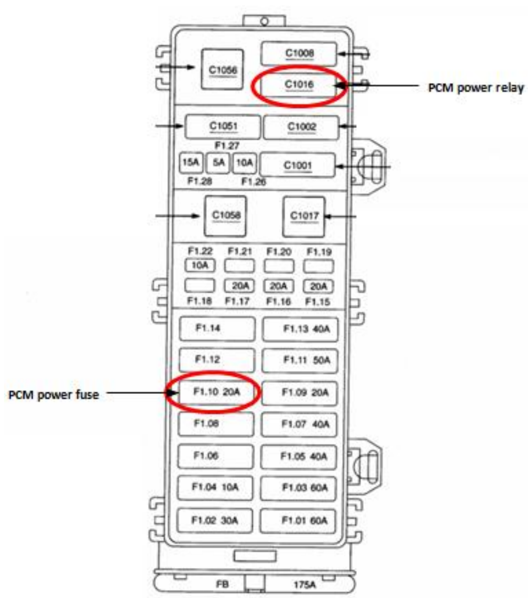

Figure 10. Fuse box diagram for a 1996-98 Ford Taurus/Sable showing the PCM power fuse and PCM power relay[24]. By accessing the idle air control valve battery voltage at either of these points, one can avoid the necessity of opening up the PCM or tapping into a harness connector.

The BMW-designed MiniCooper also uses the same B+ supply voltage from the main relay to power the fuel injectors and the ignition system. The battery voltage measured from this node via the KL30 ECM pin is used to adjust the fuel injection pulse width and the ignition system dwell.[25]

Based on the above information gleaned from the Toyota Corolla, the Ford Taurus/Sable, and the BMW Minicooper, it appears that the same battery voltage from the main relay is used to power all the actuators like the fuel injectors, the ignition spark, and the idle air control valve, as well as the variable valve timing actuators and the turbo wastegate air pressure control. And this same voltage is sampled and used to compensate the outputs of these actuators for changes in the battery voltage. Therefore, it is likely that the same voltage sample is used for this purpose, with only the mapping changing between the sampled voltage and the compensation values used for each actuator. This makes it likely that the electronic throttle actuator uses the same battery voltage and is compensated by the same sample of the battery voltage as the idle air control valve. This commonality is even more likely when one considers that the electronic throttle has been substituted for the idle air control valve in all makes of vehicles, so that the electronic throttle likely uses the same supply voltage as the previously used idle air control valve, and likely uses the same battery voltage sample for compensation as the previously used idle air control valve. After all, auto manufacturers prefer to make as few changes as possible from one vehicle model to another in order maintain high reliability and minimize design cost.

Therefore, we can safely assume that the electronic throttle is compensated by the same voltage sample that is used for compensating the fuel injector pulse width, the ignition dwell, and all other functions that are compensated for battery voltage variations, such as the variable valve timing actuators, and the turbo wastegate air pressure. This means that when this voltage sample is affected by a negative voltage spike, the compensation values of all these functions are affected simultaneously, causing all these actuators to increase their outputs. This can explain why not just the engine air amount (throttle) is changed during sudden acceleration, but also the fuel charge, the spark advance, the turbo boost air pressure, the VVT-I timing, and perhaps other engine values are increased simultaneously. This is why one sees smoke coming out of the tail pipe during sudden acceleration, because the fuel charge has increased to make the fuel-to-air ratio too rich. And the turbo boost air pressure has increased to increase the air charge and cause a higher engine torque. This higher engine torque from a turbo boost increase happens even when the engine has no electronic throttle, but only an idle air control valve (as with the Audi 5000).

It is now clear that the same single voltage sample may be used to compensate all actuators affected by battery voltage variations, and that the ECM takes this voltage sample from the battery voltage coming from the main relay (known as the EFI relay in a Toyota vehicle, or the PCM power relay in a Ford vehicle) and going to the individual actuators. One may now ask when this single voltage sample is taken. Again, the auto manufacturers provide no information about when this sampling occurs. But we know from the answer to Question 2 above that the battery voltage can be sampled only when the engine is at idle, at which time the alternator cannot provide all the current needed by the vehicle functions and the battery must provide the additional current, causing the supply voltage to fall to the battery voltage. This low engine speed normally occurs right after starting the engine, after the engine has returned to normal idle of around 800 RPM following the initial fast idle at around 1200 RPM to warm up the engine, as shown in Figure 11. This happens to be the best time because it samples the battery voltage immediately after the battery has been used to start the engine, at which time the battery state of charge is at its lowest value. However, low engine speed may also occur during a trip when the vehicle is stopped at a stop sign or traffic light, or in a parking lot, when the driver has his foot on the brake and the accelerator pedal is released. This may explain why some sudden acceleration events occur in these situations. And low engine speed may even occur while the vehicle is coasting at a high vehicle speed when the accelerator pedal is released and the engine is at idle, although this is less likely. Finally, voltage sampling may occur while the ignition is off for a up to five minutes or so after the engine has been turned off. But a voltage sample taken at this time may not be representative of the voltage sampled after the vehicle has been started.

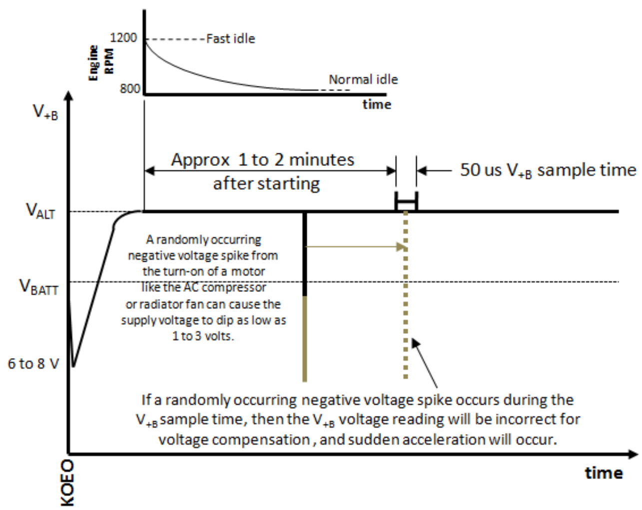

Fig 11. The +B battery voltage is sampled 1 to 2 minutes after the engine is started when the engine is at the normal idle speed of 800 RPM. If a randomly occurring negative voltage spike occurs during this sample time, then the +B battery voltage compensation applied using this incorrect battery voltage reading will cause sudden acceleration.

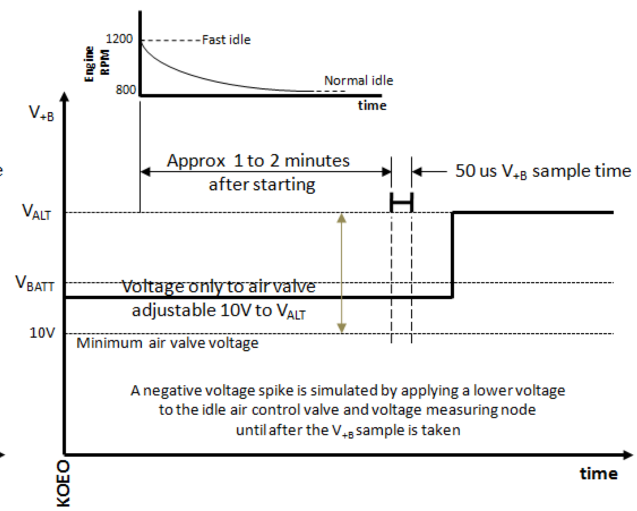

Fig 12. A negative voltage spike is simulated by applying a voltage between V_{ALT} and 10V to the idle air control valve and the V_{+B} sampling node only. The duration of the applied voltage is made long enough to include the unknown sampling time. After the sampling is complete, the applied voltage is raised back to the normal V_{ALT} voltage, which causes sudden acceleration.

If the battery voltage is sampled one to two minutes after the engine is started, as shown in Figure 11, then the probability of sudden acceleration occurring is related to the likelihood that a randomly occurring negative voltage spike occurs during the 50 microsecond long sampling time. We can estimate this probability by counting how many 50 microsecond sampling times occur during an interval of one to two minutes, and then multiplying this result by the number of times the vehicle is started in one year, which we can assume to be once a day. The result is:

$$\frac{50\ us}{120\ sec}\left(\frac{365\ events}{year}\right) = 1.5x10^{-4} \quad \text{events/year-vehicle.}$$

This result can be compared to the statistics[26] for sudden acceleration events found for most cars, which show that sudden acceleration occurs in about 10 vehicles in 100,000 of the same vehicle type each year, which gives a probability of:

$$\frac{10\ events/year}{100{,}000\ vehicles} = 1x10^{-4} \quad \text{events/year-vehicle.}$$

Although this is only a rough estimate, it demonstrates that the proposed explanation for sudden acceleration is easily capable of explaining the observed statistics.

The mechanism described in Figure 11 also suggests a convenient way of testing a vehicle for sudden acceleration. Instead of applying randomly occurring negative voltage spikes to the battery supply line and hoping that one of them will occur during the 50 us sampling time that takes place at an unknown time after starting, one can simulate the negative voltage spike with a longer duration low voltage pulse that stays low until after the unknown sampling time has occurred, as shown in Figure 12. This can be done easily by applying an attenuated supply voltage to the idle air control valve and voltage measuring node through the main fuse or main relay using the circuit shown in Figure 13. This will cause a compensation coefficient to be created which will make up for the low voltage being applied. Then, when the low voltage pulse is raised back to the normal V_{ALT} voltage, the compensation coefficient will be too large for the normal voltage now being applied, and the throttle motor duty cycle will be increased, causing sudden acceleration. This yields a test method which is deterministic. Random voltage pulses, on the other hand, require the test engineer to wait a long period of time on the order of days or months, depending on how often the random test pulses can be applied.

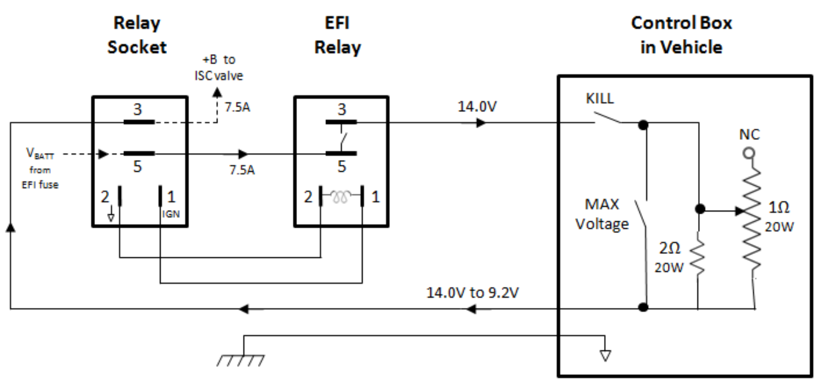

Figure 13. This circuit can generate a voltage between 9.2V and V_{ALT} = 14.0V and apply it to the idle air control valve and voltage measuring node through the EFI relay as shown. An alternative insertion point is the EFI fuse, but in some vehicles the EFI fuse also supplies the keep-alive memory, which one would prefer not to lose the power to.

III. The Reality of Negative Voltage Spikes

If the reader finds it difficult to believe that a negative voltage spike can wreak enough havoc in a vehicle to cause sudden acceleration, then he should read the Society of Automotive Engineers paper "Effective Voltage Sag Ride-Through using Ultra Capacitor for Armored Fighting Vehicle Application - A Case Study".[27] This paper describes how the Bradley fighting vehicle was plagued with sensitive equipment (such as radios, transmitters, GPS positioning equipment, targeting computers, and computerized sensors and displays) suddenly turning off at random times. The problem was traced to negative voltage spikes on the 28 volt power bus produced by the turret drive motor turning on, causing a reset of the computer equipment. The negative voltage spikes were as low as 16.81 volts and lasted for only 96 milliseconds, as shown in Figure 14. These spikes are equivalent to spikes of 8.4 volts on a 14 volt automobile bus, which can be produced by an air conditioner compressor motor. The spikes were eliminated on the Bradley initially by using a large 24 volt battery to supply the transient current of 2450 amps for 96 milliseconds. However, the battery took so much space that it reduced the amount of ammunition that the Bradley could carry. Therefore, a supercapacitor power storage unit was developed that was physically much smaller. This problem was solved because the problem compromised the Bradley's fighting performance and because the government had the resources to develop a solution. The similar problem of sudden acceleration in automobiles has not been solved because the auto manufacturers refuse to recognize that there is a problem and refuse to apply the resources necessary to find the cause of the problem and create a solution.

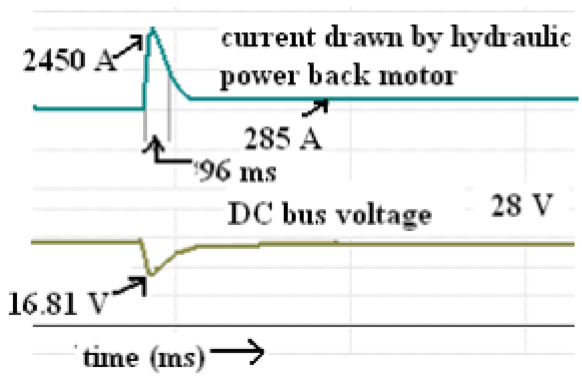

Figure 14. In the Bradley vehicle, a negative voltage spike of 16.81 volts and 96 ms Duration was produced on the 28 volt DC bus by the 2450 amp turn-on transient of the turret drive motor, which normally draws normally 285 amps. This voltage spike caused the random loss of critical electronic functions which compromised the Bradley's fighting performance.[27]

IV. Conclusion

In this paper the author's theory of sudden acceleration has been summarized, and several remaining questions have been answered. It was explained how the air actuator gain can increase without the PID controller going unstable and without a DTC being set when the PID controller has an overshoot that increases the amount of air into the engine. It was then explained why the electronic throttle duty cycle is compensated for <u>battery</u> voltage when the throttle motor supply voltage is determined by the <u>alternator</u> voltage while the engine is running, by the fact that the electronic throttle's response time (1 ms) is one hundred times faster than the alternator's ability to supply current (100 ms response time), resulting in the battery supplying the needed current and causing the supply voltage to momentarily drop down to the battery voltage. In this case, the battery voltage sets the current in the electronic throttle, requiring the electronic throttle to be compensated for changes in the battery voltage. It was then explained how it is impossible to measure the battery voltage except at idle, when the engine RPM is so low that the alternator cannot provide all the current required, and the battery must provide the additional current. In this case the supply voltage drops down to the battery voltage, allowing the battery voltage to be measured. This means that the auto makers cannot measure the battery voltage continuously to form a new voltage compensation coefficient, and must assume the battery voltage for times between measurements at idle. This explains why long duration sudden acceleration incidents can occur. Next, it was explained how the battery voltage sample is obtained from the main relay and how this same sample is used to compensate all actuators that must be corrected for battery voltage. This explains why not just the engine air amount (throttle) is changed during sudden acceleration, but also the fuel charge, the spark advance, the turbo boost air pressure, the VVT-I timing, and perhaps other engine values are increased simultaneously. It was explained further how the battery voltage is sampled one to two minutes after starting the engine after the engine has returned to normal idle of around 800 RPM following the initial fast idle at around 1200 RPM to warm up the engine. A convenient way of testing a vehicle for sudden acceleration was then explained which uses a long duration voltage pulse to simulate a negative voltage spike occurring during the unknown 50 microsecond sampling time. This provides a deterministic test method which replaces a brute force method of applying random test pulses that can require an unreasonable amount of test time. Continuing on, the probability of sudden acceleration occurring was estimated and it compared favorably with the known statistics for sudden acceleration. Finally, a related case of electronics disruption by a negative voltage spike in the Bradley fighting vehicle was discussed, and the solution to this problem was given. This case demonstrates that negative voltage spikes from motors turning on in vehicles are real and that they can have major consequences on vehicle electronics operation.

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