# Comparison of Two Electronic Theories of Sudden Acceleration

by

Ronald A. Belt
Plymouth, MN 55447
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**Abstract:** An electronic theory of sudden acceleration whose root cause is negative-going voltage spikes on the battery supply line is explained and compared with an electronic theory of sudden acceleration whose root cause is either task death due to stack overflow or a full throttle bug in the software. It is concluded that both theories can explain long-term sudden acceleration events, but only the former theory can explain short-term sudden acceleration events like lunges, lurches, and surges. The effectiveness of a brake override system is discussed, and it is concluded that a brake override system based on the assumption of "pedal confusion" as the cause of sudden acceleration is not effective in stopping sudden acceleration caused by an electronic defect. A more effective brake override system for long-term sudden acceleration events can be designed. However, it may be ineffective for short-term sudden acceleration events because the brakes may not be applied in time to prevent a crash.

## I. Introduction

An electronic theory of sudden acceleration has been developed by the author and described in four earlier papers.[1] These papers are difficult to understand because they describe how the theory evolved as the author's understanding of automobile operation increased, forcing the reader to wade through all four papers before being able to see the complete theory. This paper takes a different approach in which the theory is described in its entirety using a top-down approach that is more understandable. After describing the theory in this manner, the theory is compared to Barr's theory of sudden acceleration and some remarks are made on the applicability of a brake override system. To keep the paper short, some details are left out. But references are provided so that the reader can read about these details in the author's previous papers.

## II. Electronic Throttles and Belt's Theory of Sudden Acceleration

A mechanical throttle means there is a mechanical connection between the accelerator pedal and the throttle valve. The transfer function is linear and looks like the one shown in Figure 1.

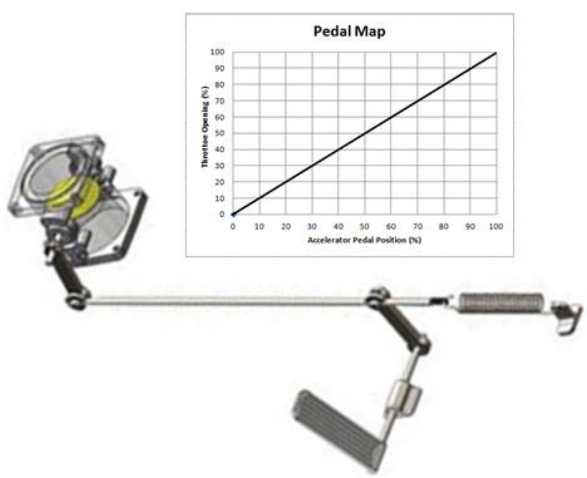


Figure 1. A mechanical throttle allows only a linear transfer function between the accelerator pedal position and the throttle opening

An electronic throttle means that the throttle valve is opened by an electric motor that is controlled by an engine control unit, or ECU. The ECU translates the accelerator pedal sensor output into a throttle opening command issued to the electric motor. Inside the ECU, instead of calculating a throttle opening command as a mathematical function of the accelerator opening, there is a look-up table of accelerator pedal sensor values and their associated throttle motor commands. This look-up table, or pedal map, allows a wide variety of transfer functions and is not limited to a linear transfer function like a mechanical throttle. For example, a look-up table allows a transfer function like the one shown in Figure 2, which makes the throttle less sensitive to accelerator pedal changes when the accelerator pedal is first pressed down. This map results in finer control over the engine when starting up from a stationary position. The use of a look-up table allows the transfer function to have any arbitrary shape, which may be even be non-linear.

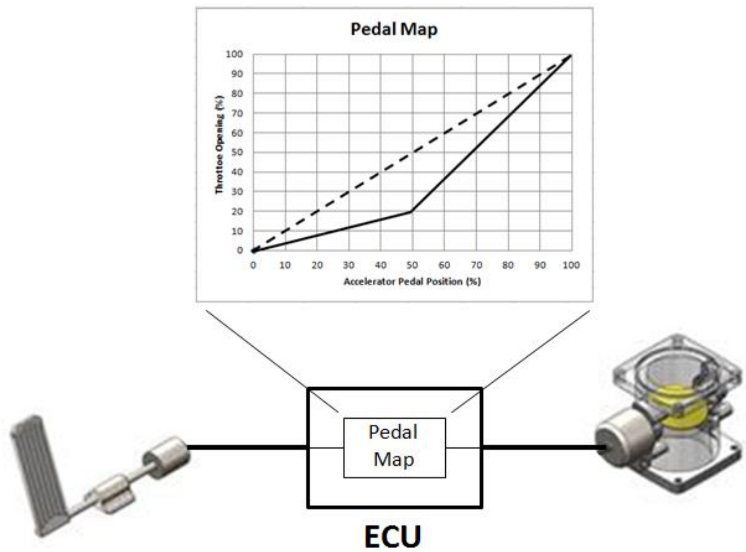



Figure 2. An electronic throttle uses an electronic control unit or ECU to command the throttle valve to open. A simple ECU has only a single pedal map inside.

By using different pedal maps contained in multiple tables that are selected based on engine speed, one can vary the transfer function between the accelerator and the throttle valve as a function of the engine speed while the vehicle is operating, as shown in Figure 3. For example, at low engine speeds one can have a transfer function that gives greater engine control when accelerating from a stationary position, while at high engine speeds one can have a different transfer function that gives greater acceleration while passing another vehicle. Again, the use of multiple look-up tables allows the transfer functions to have any arbitrary shape, which may be even be non-linear.

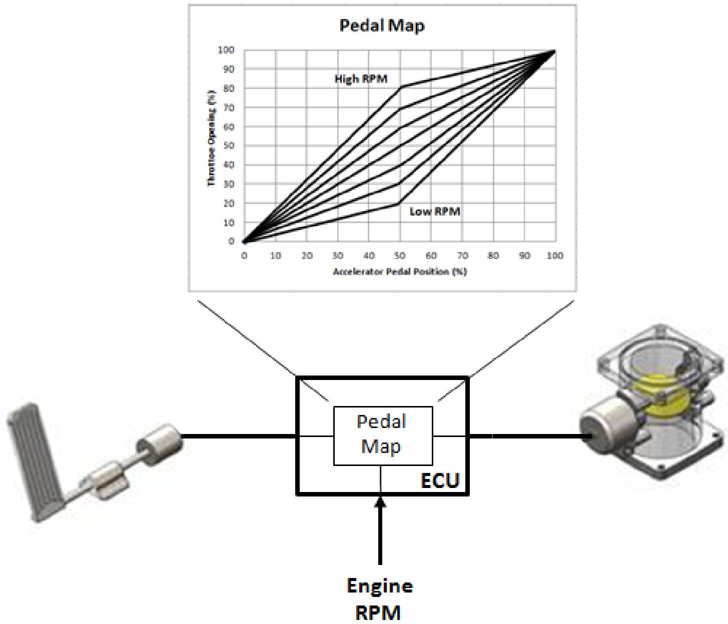



Figure 3.  Most modern ECU’s have several pedal maps inside that can be selected based on the engine RPM.

Auto manufacturers do not use a one-time look-up table inside the ECU to create a pedal map.  Instead, they use two look-up tables in succession as shown in Figure 4.  This allows them to re-use the tables from one engine to another and to more easily modify the mapping.  The way that these two tables are constructed is as follows.[2]  First, the manufacturer measures the transfer function between the throttle opening command and the engine torque as a function of the engine speed.  This measured engine torque table stays the same for all engines of the same construction. The engine torque table is then used in an “inverse” manner to determine the throttle opening command as a function of the desired engine torque and engine speed. Then, the manufacturer uses the original engine torque table in the forward direction to find the desired engine torque, but this time with the accelerator pedal position substituted for the throttle opening.  This new table is called the driver demand map.  If this driver demand map and the “inverse” engine torque map are now used in succession, they give the throttle opening as a function of accelerator pedal position with engine speed as a parameter.  However, the overall transfer function remains linear for all engine speeds.  The manufacturer now works his magic and alters the driver demand map to provide a more optimum torque request as a function of accelerator pedal position and engine speed.  The final driver demand map is equivalent to specifying an ideal engine response where the “ideal” engine can be defined as anything that pleases the driver and makes the driving experience more pleasurable.  This altered driver demand map can now be used with the “inverse” engine torque map to give the total transfer function between the accelerator pedal position and the throttle opening as a function of the engine RPM.

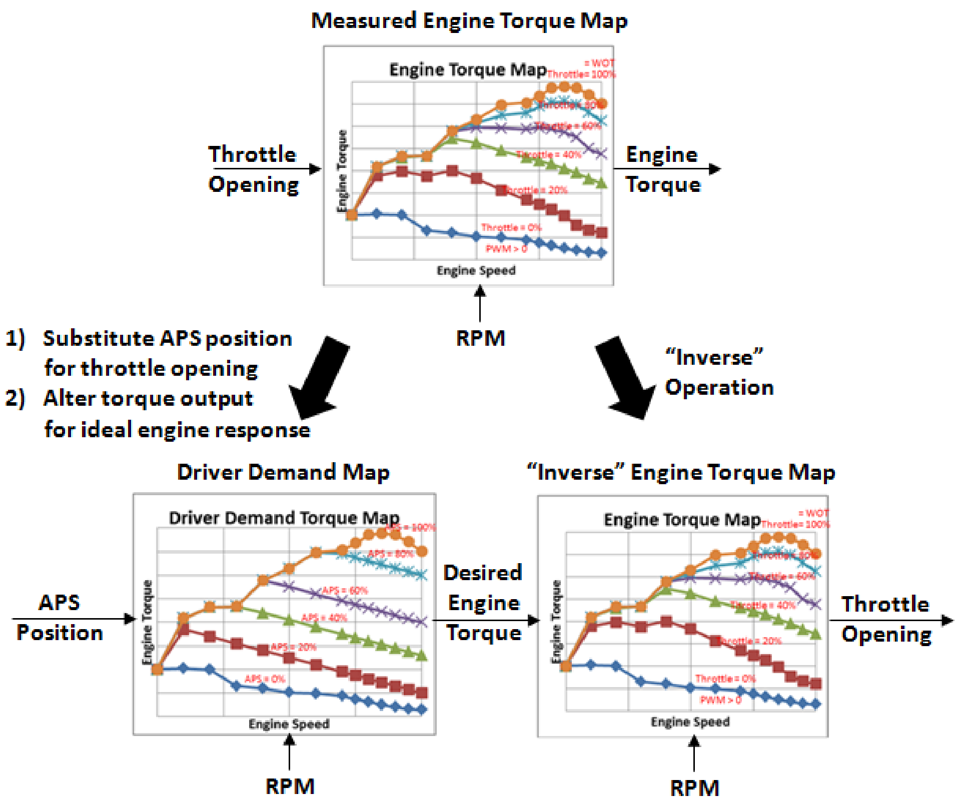



Figure 4. The transfer function between the accelerator pedal position sensor and the throttle opening in all electronic throttles is obtained by using two maps or look-up tables which are derived from a single engine torque map measured on a prototype engine.[2]

Figure 5 shows the two tables as part of an engine control diagram. Note that the engine speed is used in the tables to select different accelerator pedal-to-torque transfer functions as a parameter of the engine speed. This use of engine speed as a parameter is not intended to create a feedback loop because the engine speed produced by the engine is supposed to match the value originally used to compute the throttle opening command. In other words, the loop gain is supposed to be unity. If, for some reason, the loop gain is not unity (i.e., if the engine speed produced by the engine is higher than the engine speed used when selecting the desired accelerator pedal-to-engine transfer function), then a different accelerator pedal-to-engine transfer function will be selected on the next iteration of the loop, and the throttle opening command will be increased even though the accelerator pedal position remains unchanged. This can happen either because of a malfunction in the throttle controller or because the engine performance does not match closely enough the performance of the prototype engine used to derive the two tables. If the loop gain is greater than unity, then each time the processor traverses the RPM loop, the throttle opening is increased. The result is that the throttle opening will go rapidly to its maximum opening value even though the input to the driver demand map remains unchanged as a result of the driver not depressing the accelerator pedal. This is how long-term sudden acceleration can occur in the vehicles of all manufacturers.

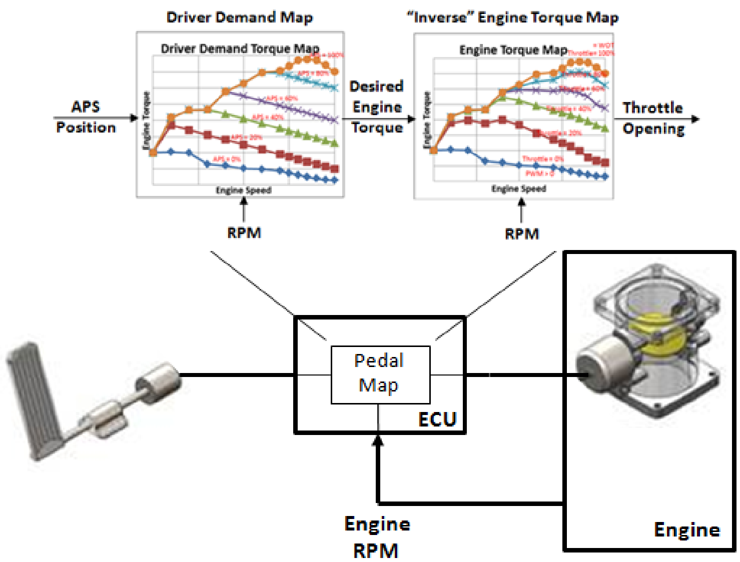



Figure 5. The two maps in an electronic throttle system use an RPM input from the engine, which forms a loop that gets traversed every 8 milliseconds.

There is one key assumption that must be made to obtain an increase in the throttle opening by the mechanism just discussed. The key assumption is that the engine must not be in the idle mode. If the engine is in the idle mode, then the table values selected for the accelerator pedal-to-engine torque transfer function correspond to all zeroes, as shown in Figure 6. In this case, when the engine speed is increased, the re-computed throttle opening stays at zero, so the throttle opening does not increase. It is only when the engine is not at idle that the throttle opening amount is non-zero, allowing the throttle opening to change each time a new throttle opening is re-computed. This non-idle condition can be produced even though the accelerator pedal is completely released by the driver, if the engine RPM is held slightly above idle either by the air conditioner remaining on, or by the accelerator pedal sticking in a position slightly more depressed than the totally released position. It is well-known that sticking accelerator pedals occur in many vehicles having electronic throttles.[3,4] However, sticking accelerator pedals did not appear to be related to long-term sudden acceleration in which the engine RPM's increased to a maximum value because the RPM increase for a sticking pedal is normally just a very small amount above idle. The mechanism just discussed explains how an accelerator pedal sticking at a small depression level can produce long-term sudden acceleration at a high RPM value if the engine RPM value is larger than the tables expect.

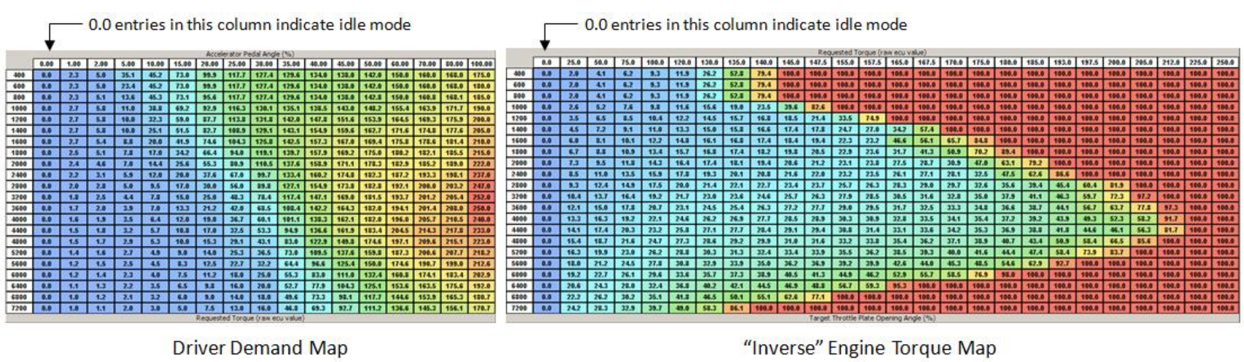


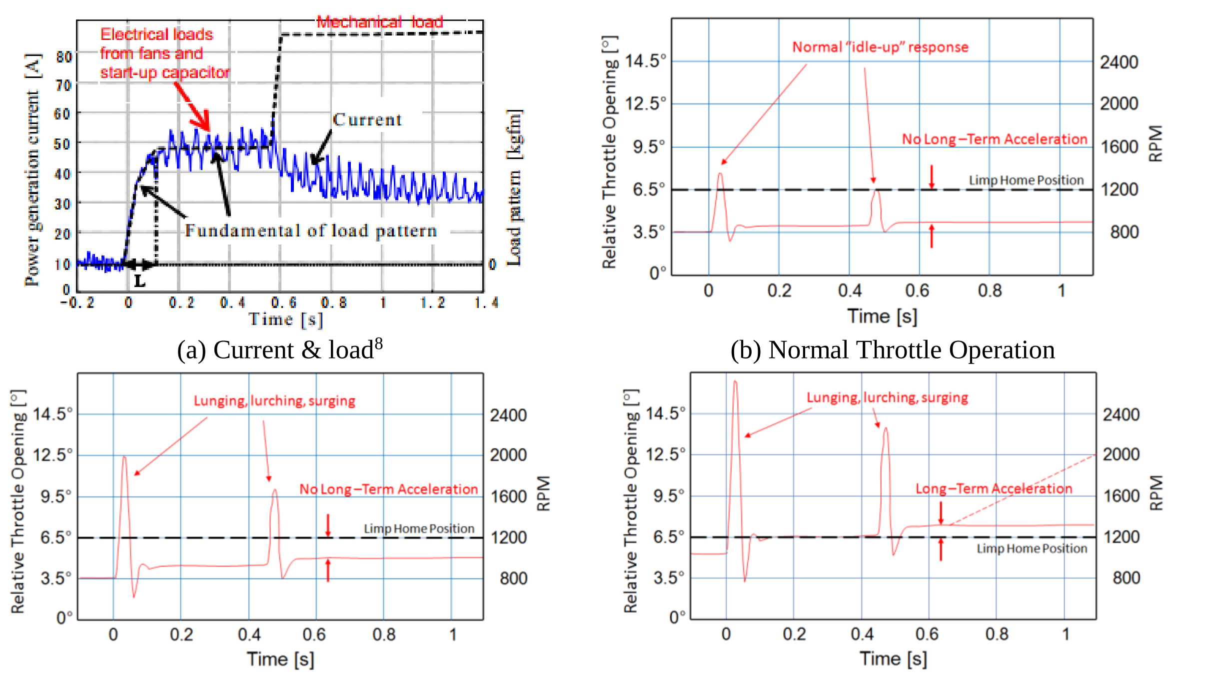

Figure 6. Throttle map tables for a stock 2006 Subaru Impreza with 2.5i engine and a 5-speed manual transmission.[5] The 0.0 entries in one column of each map provide the idle mode when the accelerator pedal is released.[6]

So, what can cause the engine RPM to be higher than the map tables expect? This is just another way of asking what can cause the actual engine throttle opening to be larger than the commanded throttle opening obtained from the "inverse" engine map table (which is derived from measurements on a prototype engine during engine development). To answer this question, it is helpful to consider that the throttle valve is opened by an electric motor, which runs off the 12V battery supply voltage. This motor has less torque to open the spring-biased throttle valve when the battery supply voltage dips below 12V. Ordinarily, a lower battery voltage would cause the throttle opening to be smaller than desired, resulting in more sluggish vehicle acceleration and slower vehicle speed. To prevent this from happening, all car manufacturers apply a correction, or compensation value, to the output of the throttle motor controller (PID controller) which increases the throttle motor's output torque inversely proportional to the decrease in the battery supply voltage.[7] This compensation value then cancels out the decrease in torque ordinarily produced by the low battery supply voltage. In theory, this is a perfectly acceptable method of operating the electric throttle motor. In practice, however, there is one thing that can go wrong.

To calculate the compensation value to the throttle motor output, the ECU must first know the actual battery supply voltage. It does this by sensing the battery supply voltage using an analog to digital (A/D) converter. This sensing process, in theory, can be done every time the correction value is used, which is about once every 12 milliseconds. But doing it this frequently ties up valuable processing resources in the ECU, so manufacturers do not do it this often. They all make the assumption that the battery voltage is a slowly varying quantity that does not change much over a period of several minutes. They also know that the battery voltage only decreases when the car is at idle, or after the starter has been engaged. At higher engine RPM's the battery voltage actually increases because the alternator is re-charging the battery. Therefore, they sample the battery supply voltage only after the car is restarted or after the car is at idle for a given amount of time. In between these times they continue to use the previously measured battery supply voltage. This means that the compensation value to the throttle motor stays the same for many minutes, or possibly up to half an hour.

There is one thing that can go wrong with this voltage sampling process. It is known that the 12V battery supply powers a lot of other functions on the automobile, such as the headlights, rear window defroster, radio, and lots of electric motors that run the air conditioner pump, the radiator fan, the ABS brake pump, and other mechanical functions. Each time one of these electric motors turns on, it puts a negative-going voltage spike on the 12V battery supply voltage. The larger the electric motor, the larger the negative-going voltage spike. Also, a weak battery that is near the end of its life produces larger negative voltage spikes than a new fully charged battery. Some of these voltage spikes can drop the 12V supply line down to less than 4 volts for a period of 200 milliseconds. Ordinarily, this does not cause a problem for any vehicle functions because most functions have a mechanical inertia in them that allows them to continue running during the negative voltage spike. The CPU electronics, however, is more sensitive and could be upset, so it is turned off during any large voltage spike and turned back on after the spike has gone away. But if a negative voltage spike occurs during the A/D sampling process that measures the battery supply voltage, then the ECU will conclude that the battery supply voltage is low even though the supply voltage has actually recovered back to its normal DC value. In this case, the voltage compensation value that is applied to the throttle motor makes the throttle motor output larger than the normal output value. This makes the throttle more sensitive than it normally is. The result is that the throttle motor output torque is increased above its normal value, which means the <u>throttle opening</u> is increased <u>above</u> its normal value. And since the same compensation value is used for several minutes, all throttle opening commands during this time period get increased by the same incorrect compensation value. The driver perceives this as an increased sensitivity of the accelerator pedal, with small changes in the accelerator pedal position having a large effect on vehicle acceleration. If a normal "idle-up" event occurs during this time, then the "idle-up" event will cause a sudden larger-than-normal increase in the engine RPM. This can startle the driver and cause the vehicle to lunge or lurch forward. Such events usually occur while the engine is at idle, which explains why many sudden acceleration events like engine lunging, lurching, and surging occur while the vehicle is stopped at a traffic light, or while the vehicle is coasting at idle in a parking lot. These are times also when the supply voltage is being sampled for the throttle motor compensation process.

Now, it turns out that one very large electric motor in the vehicle not only creates a large negative voltage spike when it turns on, but it also uses so much current while it is on that it creates an extended “idle-up” event. This is the air conditioner pump motor. This motor can turn on at any time when the driver least expects it, because it is designed to cycle on when the cabin temperature gets above a given value. Even worse, the air conditioner pump motor cycles on and off even in the winter when the outside air temperature is low because the air conditioner is used to defrost the windshield. As long as the air conditioner switch is ON, this motor will cycle on and off by itself. When it turns on, it can cause a sudden increase in the engine RPM, as shown in Figure 7. If an “idle-up” event occurs while an incorrect battery voltage compensation value is active, then the throttle will be more sensitive, and the engine RPM will increase more than the manufacturer intended. This can cause a sudden “idle-up” lunge, lurch, or surge when the driver least expects it. It can also cause an extended “idle-up” of larger magnitude than normal which results in a higher engine RPM for as long as the air conditioner pump remains on. This higher engine RPM then gets passed to the throttle map tables, which boost the engine RPM to the largest value in the column of the table currently being used because the higher engine RPM exceeds the value assumed when the table was created from the measurements on a prototype engine. The effect is the same as when the accelerator pedal is stuck down slightly while the throttle is more sensitive due to an incorrect battery voltage compensation value being active. The stuck down accelerator pedal simulates an extended “idle-up” event during which an incorrect compensation value causes a higher than normal engine RPM. When this higher-than-normal engine RPM gets passed to the throttle map tables, it gets boosted to the largest value in the current non-zero column of the table because it exceeds the value assumed when the table was created from the measurements on a prototype engine.




(a) Current & load[8]

(b) Normal Throttle Operation

(c) With throttle sensitivity slightly increased By incorrect battery voltage compensation

(d) With throttle sensitivity increased a lot By incorrect battery voltage compensation

Figure 7. (a) When the air conditioner pump turns on, it produces two short-term electrical transients and a longer-term electrical current which persists until the pump is turned off. (b) Under normal

conditions, the two short-term electrical transients produce two “idle-up” events but no long-term throttle openings. These two “idle-up” events may be felt by the driver, but cause no vehicle motion if the driver’s foot is on the brake. (c) But when an incorrect battery voltage compensation value causes the throttle motor to be in a more sensitive state, two larger “idle-up” events are produced. Depending on how much the throttle sensitivity is increased, a long-term throttle opening may also be produced (c) or may not be produced (d) that lasts until the air conditioner pump turns off. The two enhanced “idle-up” events cause short-term sudden acceleration like lurches, lunges, and surges, while the longer enhanced event causes long-term sudden acceleration. During long-term sudden acceleration the throttle opening continues to increase because the more sensitive throttle opening is larger than the throttle map tables assume, making the throttle opening increase with each iteration through the table.

The mechanism just described explains both short-term sudden acceleration incidents like lunges, lurches, and surges in which the engine RPM briefly rises to a high level and then subsides, and long-term sudden acceleration incidents in which the engine RPM goes to its maximum value of several thousand RPM for many minutes or even hours. They both have the same origin in a larger-than-normal throttle motor output, which opens the throttle more and makes the accelerator seem more responsive. The consequence is that all “idle-up” RPM’s are increased more than normal, resulting in sudden lunges, lurches, and surges. Long-term sudden acceleration events are just “idle-up” events associated with longer duration RPM increases caused by the air conditioner pump remaining on, or the accelerator pedal sticking, which get boosted by the “inverse” engine throttle map each time the throttle loop is traversed, making the engine RPM go to its maximum value of several thousand RPM. Both types of sudden acceleration are eliminated when the engine is turned off and restarted again, because a new correct compensation voltage is created after the engine is restarted. The throttle then resumes its normal sensitivity.

This mechanism explains all the phenomena observed by drivers regarding sudden acceleration. In order to save the reader’s time we will not explain all these phenomena here, but instead refer the reader to a previous paper by this same author which explains them all in great detail. We will make just a few remarks here that might be of interest to all readers.

First, this mechanism involves negative-going voltage spikes that get worse as the battery becomes weaker or more run down. This prediction has led the author to look for evidence of a weak battery in the latest sudden acceleration incidents. Evidence of a weak battery has been found by the author in several cases of RAV4 sudden acceleration incidents[9], and similar evidence has been found by Antony Anderson in his analysis of a Mitsubishi incident[10] and a Toyota Highlander incident[11]. This evidence is hard to come by because most sudden acceleration incident reports do not provide driver identification, making it impossible to contact the driver later for further information.

Second, the association of sudden acceleration incidents with a weak battery also explains the puzzling statistics that elderly drivers have a higher rate of sudden acceleration incidents than younger drivers. This is explained by the fact that elderly drivers, who are usually retired, make shorter trips with their cars (e.g., to the mall, grocery store, church) than younger drivers, who tend to be employed and commute longer distances to work. This means that the batteries in cars driven by elderly people tend to not get fully charged during the shorter trips while the batteries of younger drivers do get fully charged. Over time, the batteries of elderly drivers continue to become weaker, allowing larger negative voltage spikes to occur on the battery supply line. This increases the probability that a sudden acceleration incident will occur. This also explains why sudden acceleration tends to occur more in vehicles that are four to five years old instead of in brand new vehicles, because this is about the time that most batteries become weak and need to be replaced. After battery replacement, the sudden acceleration incidents tend to go away, or at least be greatly reduced.

Lastly, this mechanism explains that the low sudden acceleration incident rate (on the order of 10 to 30 incidents per 100,000 vehicles) is caused by the probability that a negative voltage spike occurs during the time that the battery voltage is being sampled by the A/D converter in the ECU. Since this sampling time is very short (approximately 20 microseconds), and the negative-going voltage spikes are also very short (approximately 200 milliseconds), the chance of the two occurring simultaneously is very low.

## III. Barr's Theory of Sudden Acceleration Versus Belt's Theory

It is interesting to contrast the above theory of sudden acceleration with the theory of Michael Barr, which was used to win the Bookout case against Toyota in Oklahoma.[12] Barr's theory is summarized in Figure 8. His theory assumes that Task X fails to run because stack overflow leads to it not being scheduled. This is equivalent to removing the two throttle map tables, which are contained in Task X. The motor control task then continues to operate normally with the throttle command frozen at some value. The engine continues to run normally because the motor control task is unaffected in Barr's theory. The consequence is that when stack overflow occurs, the engine will continue to run normally at whatever engine RPM it was at when the overflow occurred. Therefore, if stack overflow occurs when the engine is at idle, the engine will continue to run at idle. Or, if stack overflow occurs when the engine is running at 50 mph, the engine will continue to run at 50 mph. The engine will continue to run at whatever RPM it was going before stack overflow occurred until the ignition is turned off and the engine is restarted.

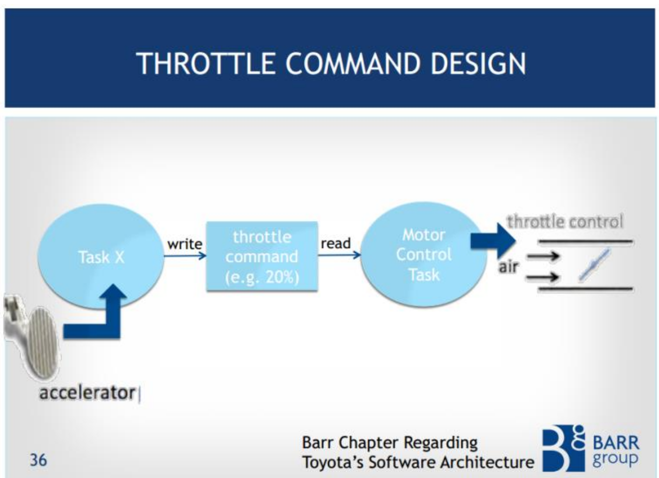



Figure 8. Barr's theory of sudden acceleration assumes that Task X, which contains the two throttle maps, fails to run because stack overflow leads to it not being scheduled. The motor control task continues to operate normally with the throttle opening command frozen at some value. The resulting throttle operation is similar to the driver continuing to press on the accelerator pedal.

This appears to be a valid explanation for what happened in the Bookout case, in which the Bookout vehicle was running at highway speed when the incident began to occur, and the engine continued to run when the driver took her foot off the accelerator pedal and applied the brake to no avail. A 150-foot long skid mark showed that the brakes were applied while the vehicle continued to move forward before the crash. But if we try to apply Barr's theory to other sudden acceleration incidents, we run into a problem. In most sudden acceleration incidents such as those that occur in parking lots or at stop lights, the engine RPM increases suddenly from idle to a higher RPM value. This is what produces a short-term lunge or lurch, or a slightly longer-term surge, after which the engine RPM often goes back down to its original value. In some cases, however, the engine RPM even shoots up to several thousand RPM and stays at this value until a crash occurs or until the ignition is turned off. The reader is encouraged to click on the following links[13] and to listen to the engine noise as it immediately rises to the engine's highest value.

These incidents in which the engine RPM increases from an idle position are not explainable by the simple Barr theory of stack overflow because the engine speed should stay at the original speed it was at before stack overflow.

To explain sudden acceleration events in which the engine RPM increases, Barr has supplemented his theory with another mechanism, which he refers to as the "Full Throttle Bug", or "FTB".[14] The explanation of this "Full Throttle Bug" is murky because the judge in the St. John v. Toyota case would not allow testimony on it in a future St. John v. Toyota trial because the theory was identified too late in the discovery process. But it is said to result from an anomaly that occurs when the calculated throttle angle is subjected to a "bounds check" that has a bug in it. When a low voltage condition exists coupled with the limp-home flag being in a given state, the bug will cause the throttle to ignore the calculated angle and instead override it with a global variable set to 84 degrees. This results in the throttle going from idle to its maximum opening angle of 84 degrees.

Since testimony on the Full Throttle Bug was disallowed in the St. John v. Toyota case, and all discovery materials were sealed, we will never learn more about this mechanism from that case. Conceivably, it is possible for other MDL cases to use the FTB theory if they have a later schedule for discovery. However, Toyota is currently settling all other MDL cases out of court with the agreements being sealed, so further testimony on the Full Throttle Bug may never be made known to the public. This does not prevent us from drawing further conclusions from the material already provided, however.

One thing we know from court hearing documents in the St. John V. Toyota case is that the Full Throttle bug occurs when a low voltage condition exists coupled with the limp-home flag being in a given state. This implies that two logic signals are ANDed together and a decision is made on the result. From this simple observation, we can conclude the following:

a) An analog voltage must be compared to a reference voltage and the result made into a logic signal that indicates whether the voltage is greater or less than some reference voltage. This can be done in two possible ways. Either the analog voltage must be digitized using an A/D converter, after which it is compared digitally to a reference voltage, or an analog comparator output must be sampled at a given time to provide the logic signal. In either case the state of the logic signal depends not only on the DC voltage being compared or digitized, but also on any transient voltage spike that occurs on the DC voltage during the sampling interval. If a negative voltage spike occurs during the sampling or digitizing process, then an incorrect conclusion will be drawn regarding the voltage level.
b) The analog voltage must be the battery voltage, and not the CPU voltage, because the CPU voltage has no meaning in the signal chain of the electronic throttle unit.
c) The comparison of the battery voltage with a reference voltage is probably made to determine if a low battery voltage condition exists.
d) If the limp-home flag is asserted, then the throttle will be in its limp-home state with the throttle valve nearly closed. In this state the battery voltage has no consequence on the throttle opening because the throttle opening is determined by two mechanical springs. Therefore, the only case where the battery voltage has a consequence on the throttle opening is when the limp-home flag is not asserted; i.e., when the limp-home flag is low.

Therefore, we can conclude that the Full Throttle Bug occurs when the battery voltage is low and when the throttle is not in its limp-home state. More specifically, the Full Throttle Bug occurs when either the DC battery voltage is low OR when a negative voltage spike occurs on the DC battery voltage causing the logic signal to <u>think</u> the DC battery voltage is low. When this happens, the calculated throttle angle is ignored and is replaced by a global variable set to 84 degrees. This results in the throttle going from idle to its maximum opening angle of 84 degrees when the battery voltage is lower than some reference voltage.

This sounds a lot like the Belt theory of sudden acceleration. The difference is that Barr's theory of the Full Throttle Bug requires the throttle to go to its maximum opening angle whenever a negative voltage spike of sufficient magnitude occurs during the battery voltage sampling process. Belt's theory, on the other hand, says that the throttle opening will change by various amounts depending upon how large the negative voltage spike is during the battery voltage sampling process, which changes the sensitivity of the throttle by various amounts. When the throttle response is in this more sensitive state, an engine "idle-up" occurring during this time produces lunges, lurches, and surges of various magnitudes corresponding to the incorrect value of the voltage compensation coefficient. Barr's theory of the Full Throttle Bug allows only full throttle events and no smaller lunges, lurches or surges. It just so happens that the vast majority of sudden acceleration incidents are incidents in which the engine RPM increases only a small amount causing a short-term lunge or lurch, or a longer term surge, after which the engine RPM goes back down to its original idle value.

There is another difference between the Barr theory of the Full Throttle Bug and the Belt theory. Figure 9 shows what happens to an engine when the Full Throttle Bug takes place at idle. The engine torque map in Figure 9 is the top map in Figure 4, and shows the response of the actual engine to a throttle opening command. When the Full Throttle Bug takes place, it causes the throttle command to open the throttle immediately to its maximum throttle opening regardless of the engine speed. This makes the engine torque and engine speed increase from idle at point A to some higher speed at point B in a manner exactly the same as when the accelerator pedal is pushed to the floor. It is exactly the same because the behavior of the throttle loop is assumed to be completely normal with the Full Throttle Bug. The path from point A to point B follows the envelope (i.e., outline) of the maximum points on the curves of engine torque versus engine speed. This causes the engine speed to increase slowly because the load on the engine produced by the transmission offsets the torque produced by the engine and slows down the increase in engine speed. The result is that the engine takes several seconds to increase to its maximum RPM. It is well known that the engine speed can increase faster while in NEUTRAL or PARK than in can in either DRIVE or REVERSE. Figure 10 shows what happens in Belt's theory during a long term sudden acceleration event. This event occurs because the actual engine speed is slightly higher than the engine speed assumed in the throttle map tables because the throttle is more sensitive as a result of an incorrect voltage compensation value being present. If the engine speed is slightly above idle due to either a throttle pedal sticking at a small depression level, or because the air conditioner pump is on, then during each pass of the throttle control loop the engine speed gets increased a little more while the engine torque command stays fixed. This means that the engine speed increases rapidly from point A to point B as shown in Figure 10. This increase takes place without producing an increase in the engine torque. Therefore, there is no change on the engine load during the increase in RPM, and the increase in engine RPM can take place very rapidly. In fact, the increase in RPM can take place in less than one second because in one second the throttle controller makes almost 100 passes through the inverse engine map, with each pass causing the throttle opening to get a little larger. This explains how the engine speed can increase to maximum speed so suddenly during a sudden acceleration event, as heard in the videos of sudden acceleration incidents[15], even when the driver's foot is not on the accelerator pedal. Such a rapid onset of high engine speed cannot be explained by normal throttle operation in which the throttle opening increases as a result of the driver inadvertently pressing the accelerator pedal or by normal throttle operation in which the Full Throttle Bug causes a maximum throttle opening command. This also means that re-creations of sudden acceleration events, in which a person holds down the accelerator pedal while applying the brakes to show that the brakes will overcome the accelerator pedal, are not faithful recreations of sudden acceleration incidents.

There is still another difference between the Barr theory of the Full Throttle Bug and the Belt theory. In Barr's theory, the throttle will hang at point B after getting there normally during high speed driving (e.g, by stack overflow causing task death), or after going from point A at idle to point B as a result of the Full Throttle Bug. If no fail-safe operation occurs, the throttle will continue to remain stuck at point B until the ignition is turned off. If a fail-safe operation occurs, causing the resumption of normal throttle operation, then when the driver removes his foot from the accelerator pedal in preparation to slowing down, the throttle opening will decrease back down to idle. If the throttle is undamped, it will go quickly from B to C and then more slowly back to point A, as shown in Figure 9. If the throttle is damped, then it will go slowly from B back to point A directly via some curved path. This is how the throttle normally operates when the accelerator pedal is released. In the Belt theory, when the driver applies the brake pedal during a sudden acceleration event, the increased torque on the engine produced by the brakes causes the engine speed to slow down. But the engine will produce more torque as it slows down because it follows the curve at which the throttle opening stays the same, as shown by the path from B to C in Figure 10. The result is that the driver perceives that pressing on the brake pedal causes the engine torque to increase, which is exactly what it feels like normally when the accelerator pedal is pressed harder. This happens even though the driver's foot is not on the accelerator pedal.[Footnote 1] This is believed to be the origin of many drivers' observations about sudden acceleration that pressing on the brake pedal caused the car acceleration to increase. The effect is the same as when a car operating in cruise control encounters a hill, making the engine torque increase to enable it to go up the hill while keeping the vehicle speed constant. But in the case of applying the brake during a sudden acceleration event, the throttle opening stays constant instead of the vehicle speed.

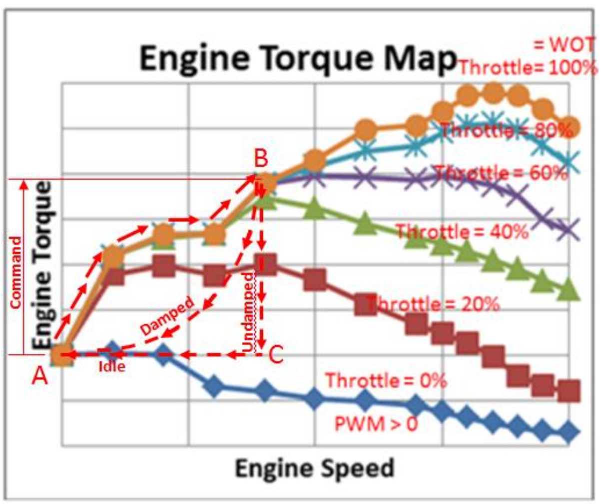



Figure 9. Barr's theory assumes that throttle operation is normal, causing the engine speed to rise from point A to point B with the increased throttle command and to fall back to point A when the throttle command is removed. In a sudden acceleration event, it stays at point B despite the driver applying the brake.

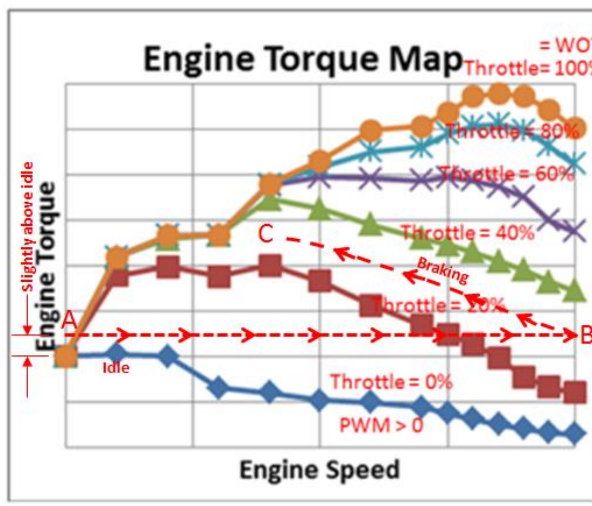



Figure 10. Belt's theory predicts that in a long term sudden acceleration event the engine speed increases rapidly from A to B because the throttle is more sensitive than the throttle maps assume. Braking causes the engine torque to increase to point C, making it seem like pressing the brake increases the acceleration.

But hasn't Barr's theory been tested and proven to be correct? After all, it won a $3 million dollar court case against Toyota in Oklahoma that caused Toyota to settle all its remaining MDL cases. The answer is "yes", his theory was tested on an actual automobile. The MDL plaintiff team put a 2005 Camry on a

[1] If the reader finds it difficult to believe that pressing on the brake pedal can cause the engine torque to increase, and thus increase the vehicle's acceleration, then the reader should know that this is exactly what happens when the data in Figure 10 is obtained by running the engine on a dynamometer. To take the data on a dynamometer, the throttle opening is first set at some fixed value, and the engine is allowed to go to its maximum RPM. Then the dynamometer applies a braking force or load which slows down the engine RPM, resulting in the engine producing a greater torque. This gives the data for one of the curves in Figure 10. This process is then repeated for different throttle openings.

dynamometer and used a TechStream scan tool to flip a bit in the software that killed Task X. This caused sudden acceleration to occur with the data shown in Figure 11. We see that flipping the bit caused task death at about 98 seconds into the test, which caused the throttle to stick at its current opening. This caused the vehicle speed to continue to increase from below 68 mph to over 90 mph 30 seconds after the bit was flipped and throttle control was lost. The loss of throttle control continued even when the brake was pressed intermittently. Throttle control was regained only after the driver fully removed his foot from the brake and then applied it steadily. This finally caused the speed of the car to diminish, with a stopping time of about 20 seconds. Most of Barr's testimony was devoted to explaining task overflow and how it can cause task death due to memory corruption and software design methodology.

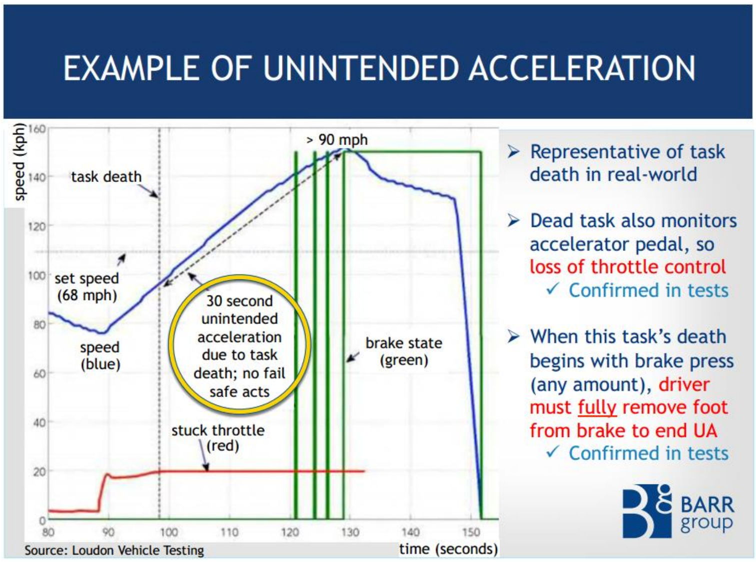



Figure 11. Test data from a 2005 Camry showing how sudden acceleration occurred after Task X died due to stack overflow.[16] The echo test caused the throttle to close only after the driver's foot was fully removed from the brake pedal.

The above test only confirmed Barr's theory regarding task overflow, which can lead to a stuck throttle at the current throttle opening. However, no test has been done yet to confirm Barr's theory of the Full Throttle Bug, which increases the throttle opening to its maximum opening when the car is sitting at idle. This puts Barr's theory of the Full Throttle Bug on an equal footing with Belt's theory of negative voltage spikes that cause the throttle response to be more sensitive. The fact that Belt's theory explains the origin of short-term sudden acceleration events like lunges, lurches, and surges in addition to long-term events while Barr's theory of the Full Throttle Bug does not, makes Belt's theory have more generality. Therefore, Belt's theory seems to be more credible at this time.[17]

## IV. Effectiveness of a Brake Override System

A brake override system assumes that sudden acceleration is caused by pressing the accelerator pedal at the same time as the brake pedal. Therefore, it is designed to sense the simultaneous application of the accelerator and brake pedals and to disregard the accelerator sensor signal, substituting instead a fixed value which brings the engine RPM to idle, leaving only the brake pedal active. This is supposed to eliminate sudden acceleration.

But what if sudden acceleration is not caused by the simultaneous application of the accelerator and brake pedals? Will the brake override system prevent sudden acceleration if the sudden acceleration is caused by an electronic mechanism as described by either the Barr theory of the Belt theory? In this case we ask:

"When sudden acceleration occurs, will applying the brake pedal cause the sudden acceleration to cease? In other words, will the throttle function return to normal idle?"

Let's first consider the Barr theory, and specifically the theory of stack overflow causing the death of Task X. If sudden acceleration occurs because stack overflow happens to cause the death of Task X, then the throttle command to the throttle motor control task is frozen at its current value. If we assume now that brake override is present, then pressing the brake pedal will override the accelerator pedal sensor output and substitute a fixed value. Will this fixed value cause the throttle operation to return to idle? For a 2010 Camry[18], the answer is no, because the brake override function is performed in Task X according to Mr. Barr, who has seen Toyota's software. This means that when Task X dies to cause sudden acceleration, the brake override function dies with it. The sudden acceleration will continue at the current throttle command and the brake override function will be completely useless. The same thing happens with Barr's Full Throttle Bug theory. In this case, the throttle opens after being at idle because a full throttle command is being supplied to the throttle motor as a result of a low battery voltage condition while the throttle is not operating in the limp-home mode. If we assume that brake override is present, then pressing the brake pedal will override the accelerator pedal sensor output, but this will have no effect on the command to the throttle motor because that command is frozen. Therefore, the throttle operation does not return to idle, and in the 2010 Camry, the brake override function is completely useless.

Let's now consider Belt's theory in which the throttle response is in a more sensitive state as a result of an incorrect battery voltage compensation coefficient causing the command to the throttle motor to be larger than normal. If a long-term sudden acceleration occurs, then applying the brake pedal with brake override present will override the accelerator pedal sensor output and substitute a fixed value in its place. But this will not cause the throttle operation to return to idle to make the sudden acceleration stop because the sudden acceleration is being caused by the action of a more sensitive throttle on an "idle-up" produced by the air conditioner pump, which remains ON, and not by the action of the accelerator pedal sensor output. Therefore, for a 2010 Camry, the long-term sudden acceleration will continue when the brake pedal is applied, and the throttle function will not return to normal idle. If a short-term sudden acceleration occurs, such as a lunge, a lurch, or a surge, then the application of the brake pedal will not only be useless in bringing the throttle operation back to idle, but it may also be too late to prevent a crash from occurring because the driver can't apply the brakes in time to prevent a crash.

These cases show that a brake override system in a 2010 Camry is completely useless in preventing sudden acceleration when the sudden acceleration is caused by an electronic defect such as the Barr and Belt theories predict. In general, one cannot design a function to prevent something from happening if one has the wrong idea of what causes that something to happen. In the case of sudden acceleration, the assumption that sudden acceleration is caused by "pedal confusion" is only an assumption. It has never been proven that this assumption is correct. Therefore, it may be false. And if sudden acceleration is really caused by some other means, such as an electronic defect, then not only is the assumption of "pedal confusion" wrong, but the design of the brake override function on which it is based is wrong. Any brake override function that relies on an incorrect assumption of "pedal confusion" will not prevent sudden acceleration from occurring as a result of an electronic defect.

This conclusion becomes more understandable when one looks at the block diagram of a generic electronic throttle control system as shown in Figure 12. This diagram applies to the electronic throttle control system of all auto manufacturers. Assume that Task X dies, making the target throttle command from the inverse engine map to the PID controller stick at its current value. Now assume that vehicle has a brake override system, and that the driver applies the brake pedal. Will this cause the target throttle command to change to a value that will bring the throttle to its idle position? In a 2010 Camry, the brake override function is programmed into Task X, as we are told by Mr. Barr, who has seen the software code. Therefore, if Task X dies, then the brake override function dies with it, and no different value gets substituted for the stuck target throttle command value. It makes no difference whether or not the driver is pressing the accelerator pedal and the brake pedal simultaneously. The target throttle command will stay at its stuck value, and sudden acceleration will continue. The same thing happens when the Full Throttle Bug causes the target throttle command to get stuck at a different value than the current one.

Let's assume instead that the defective throttle operation is caused by an incorrect battery voltage compensation coefficient causing the PWM output of the PID controller to be larger than normal. In this case, an "idle-up" produced by the air conditioner pump can cause a long-term sudden acceleration at a high engine RPM, which stays high as long as the air conditioner pump remains ON. Now assume that vehicle has a brake override system, and that the driver applies the brake pedal. Will this cause the PWM controller output to the throttle motor to change to a value that will bring the throttle to its idle position? In a 2010 Camry, the answer is "no", because even though the substituted value of the accelerator pedal sensor output corresponds to an idle signal, the "idle-up" signal from the air conditioner pump gets added to it, and this "idle-up" signal gets magnified by the throttle loop, which is made more sensitive as a result of an incorrect battery voltage compensation coefficient. Therefore, the PWM command to the throttle motor remains unchanged, and the sudden acceleration continues.

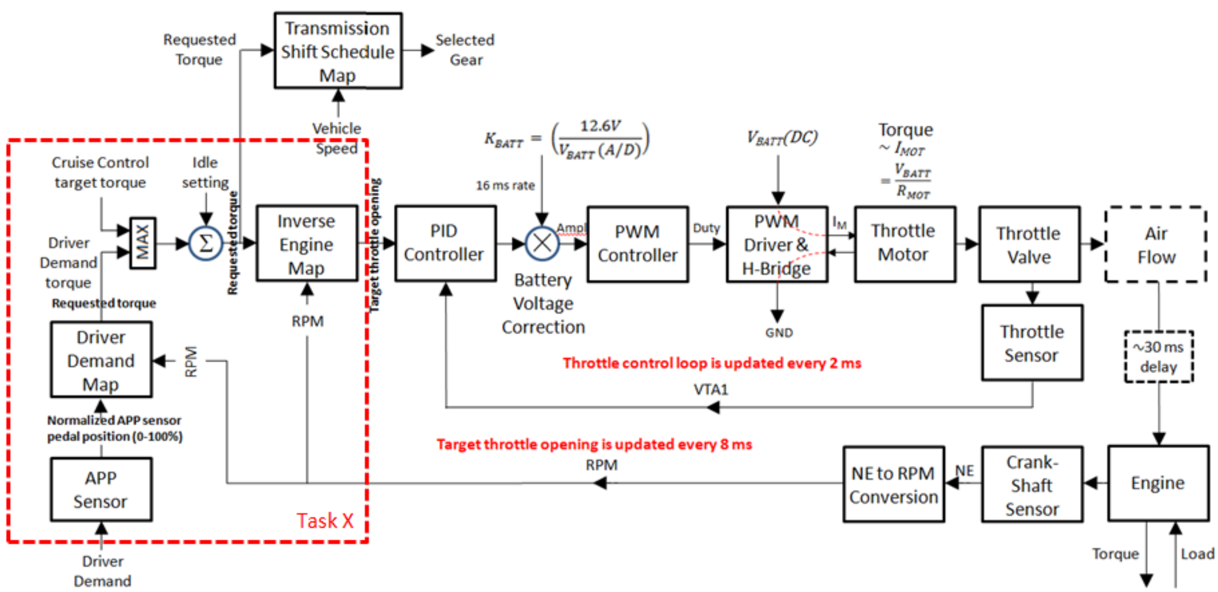



Figure 12. Block diagram of a generic electronic throttle control system for all manufacturers. If Task X dies, the target throttle command to the PID controller is frozen at its current value, producing sudden acceleration. The Full Throttle Bug causes this same command to change suddenly from idle to a full throttle position. If the brake override function occurs earlier in the chain than these changes, then brake override will be ineffective in stopping defective operation and bringing the throttle back to normal idle, because the command to the PID controller will remain unchanged. In Belt's theory, the cause of defective throttle operation lies within the PID control loop, when an incorrect battery voltage compensation coefficient causes the PWM output of the PID controller to be larger than normal. Therefore, any brake override function which takes place outside this loop will be ineffective in restoring normal throttle operation and bringing the throttle setting back down to normal idle.

Is it possible to design a brake override system that really works if one knows the true cause of sudden acceleration? In other words, assuming that either the Barr theory or the Belt theory is correct, then can a brake override system be designed to work properly? The answer is "yes". For example, assume that whenever the brake pedal is pressed, then the throttle opening command between the inverse engine map and the PID controller in Figure 12 is changed from its normal value to a different fixed value that corresponds to the engine idle state. This will stop any sudden acceleration that results from either of Barr's two theories. It will also stop long-term sudden acceleration that results from Belt's theory. But it will not stop short-term sudden acceleration events from happening, which are the majority of sudden acceleration incidents. To stop these events in Belt's theory, one must change the operation of the PID control loop. This could be done by substituting a different fixed value for the battery voltage compensation coefficient whenever the brake pedal is pressed. But pressing the brake pedal may happen too late to prevent a crash from occurring due to these short-term "idle-up" events. The nature of these short-term events may make them nearly uncorrectable by a brake override system.

The above discussion shows that brake override systems are totally ineffective in stopping sudden acceleration unless they are based on the correct knowledge of what causes the sudden acceleration. And it is clear to most drivers that "pedal confusion" is not the correct assumption for what causes sudden acceleration, but that something in the electronic throttle control system is causing the sudden acceleration.

## V. To Learn More

The reader who wants to delve deeper into the author's theory of sudden acceleration and its root cause in negative-going voltage spikes on the battery supply line can do so by reading the author's four papers on sudden acceleration located at http://www.autosafety.org/dr-ronald-belt%E2%80%99s-sudden-acceleration-papers. To save time, the reader can consult the following summaries of the four papers showing the topics covered in each paper.

1. "*An Electronic Cause for Sudden Unintended Acceleration*",16 Mar 2012
    a. 19 observations about sudden acceleration and their explanations
    b. How negative-going voltage spikes on the battery supply line arise in an automobile
    c. How negative voltage spikes get worse as the battery weakens
    d. The origin of inrush currents and their waveshapes
    e. How the ECM power supply deals with voltage spikes to shield the electronics
    f. Brown-out voltage as a possible mechanism for electronics upset
    g. Supporting drivers' testimonials regarding sudden acceleration
2. "A *Detailed Electronic Mechanism for Sudden Unintended Acceleration*", 24 Sep 2012
    a. NASA report's reference to battery voltage compensation of the throttle motor
    b. The purpose of battery voltage compensation of the throttle motor
    c. How errors in battery voltage compensation can cause sudden acceleration in general
    d. The beginning of a test approach for testing the theory
3. "*Sudden Acceleration Without an Accelerator Input*", 1 Nov 2012
    a. Internet links to videos of sudden acceleration events with descriptions
4. "*A More Detailed Electronic Mechanism for Sudden Unintended Acceleration*", 5 Sept 2013
    a. 15 driver's observations about sudden acceleration and their explanations
    b. The cause of short-term sudden acceleration events – enhanced sensitivity of the throttle motor controller
    c. The cause of long duration sudden acceleration events – the air conditioner idle-up
    d. VVT-I operation during a sudden acceleration event and origin of a "tick tock" sound
    e. Injector dwell time and ignition advance are also compensated for battery voltage
    f. Root cause of sudden acceleration -- the battery voltage sensing circuit
    g. A test approach for Belt's theory
5. "*Further Details on an Electronic Mechanism for Sudden Unintended Acceleration*",16 Jan 2014
    a. Some limitations of Barr's theory
    b. How the engine control system uses maps to controlling all engine functions
    c. Block diagram of an electronic throttle control system showing Task X

d. How an electronic throttle control system uses two maps
e. How automatic transmission shifting is controlled by a shift map
f. How the throttle PID controller operates and is changed by battery voltage compensation
g. How changes in the outer throttle control loop cause long-term sudden acceleration
h. How to simulate electronic throttle operation with maps
i. How battery voltage sampling time depends on the driving pattern
j. Solutions for preventing sudden acceleration

## VI. Conclusion

An electronic theory of sudden acceleration whose root cause is negative-going voltage spikes on the battery supply line has been explained. It was then compared with an electronic theory of sudden acceleration whose root cause is either task death due to stack overflow or a full throttle bug in the software. It was concluded that both theories can explain long-term sudden acceleration events, but only the former theory can explain short-term sudden acceleration events like lunges, lurches, and surges. The effectiveness of a brake override system was discussed, and it was concluded that a brake override system based on the assumption of "pedal confusion" as the cause of sudden acceleration is not effective in stopping sudden acceleration caused by an electronic defect. A more effective brake override system for long-term sudden acceleration events can be designed; however, it may be ineffective for short-term sudden acceleration events because the brakes may not be applied in time to prevent a crash.

## VII. References

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[1] http://www.autosafety.org/dr-ronald-belt%E2%80%99s-sudden-acceleration-papers.

[2] Maurizio Bollini, "*F1 Engine Maps*", http://f1framework.blogspot.com/2013/03/f1-engine-maps_28.html

[3] Toyota Motor Corporation – Deferred Prosecution Agreement, "*Statement of Facts*", http://www.justice.gov/sites/-default/files-/opa/legacy/2014/03/19/toyota-stmt-facts.pdf , 19 March 2014

[4] Paul Niedermeyer, *"Exclusive: TTAC Takes Apart Both Toyota Gas Pedals"*, January 30, 2010. http://www.thetruthabout-cars.com/2010/01/exclusive-ttac-takes-apart-both-toyota-gas-pedals/. This article mentions that CTS admits it has experienced a limited degree of stiction at or near the idle point on some of their gas pedals.

[5] http://forums.nasioc.com/forums/showthread.php?t=1537010. Two-dimensional interpolation of the table values is used to obtain a more accurate output from each table. This does not change any of the concepts on how the tables are used.

[6] It is interesting to know that one cannot make the values in the column next to the 0.0 column arbitrarily small. At some limit value above 0.0 the throttle opening will change suddenly from the idle position to a value corresponding to a higher engine speed. It is believed that this position corresponds to where the throttle discontinuity lies (the limp-home position), which is where the command to the throttle motor changes from a negative value to a positive value.

[7] NASA NESC Technical Assessment Report, "*NHTSA Toyota Unintended Acceleration Investigation – Appendix A. Software*", January 18, 2011, (revised April 15, 2011), p. 93 of 134. The following patents also discuss a battery voltage correction process for the electronic throttle motor:

a) US patent 4943758 (Honda)
b) US patent 4982710 (Hitachi)
c) US patent 5033431 (GM)
d) US patent 20120197509 (Mitsubishi)
e) US patent 5281902 (Eaton)
f) US patent 5333584 (Denso)
g) US patent 7122982 (Denso)
h) US patent 7418944 (Denso)
i) US patent 7434565 (Denso)
j) US patent application 20060207552 (Denso)

[8] 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

[9] Private messages with BrianPaul, whose incident is described at http://www.rav4world.com/forums/99-4-3-mechanical/147034-sudden-acceleration.html. The same type of incident was experienced by three other commenters.

[10] Dr. Antony. Anderson, "*Electrical Expert's Report on a Sudden Acceleration/Surge Incident*", http://www.antony-anderson.com/cruise/9.5%20SA%20Links/mitsubishi%20outlander%20sudden%20acceleration.pdf

[11] Dr. Antony Anderson, "*Timeline Analysis of 2012 Toyota Highlander Sudden Acceleration Incident on 16th November 2012*", private communication.

[12] "*Transcript of Morning Trial Proceedings had on the 14th day of October, 2013 Before the Honorable Patricia G. Parrish, District Judge*", Case No. CJ-2008-7969, http://www.safetyresearch.net/Library/Bookout_v_Toyota_Barr_REDACTED.pdf

[13] http://www.youtube.com/watch?v=ON-2fYew37c, http://www.youtube.com/watch?v=Wuv9vo2tUkY, http://www.youtube.com/watch?v=cPJKtXkEEEQ.

[14] "*Toyota Defendants' Motion to Strike as Untimely Evidence Related to the Opinions in the Supplemental Report of Michael Barr (#4012 in MDL 2151)",* Case 8:10-cv-01460-JVS-FMO Document 90 Filed 08/20/13 Page 5 of 8 Page ID #:3839. https://freelibs.org/texts/gov.uscourts.cacd.483648.html The minutes of the court hearing state: "The theory was expanded upon in Barr's July 3, 2013 Deposition. Barr testified that the FTB overrides the calculated throttle angle. (Barr Depo. at 238.) As he explains, the calculated throttle angle is subjected to a "bounds check" that has a bug in it, and in certain circumstances, the bug will cause the throttle to ignore the calculated angle and to instead apply a global variable set to 84 degrees". Footnote 4 on the same page clarifies further that: "At his deposition, Muckenhirn could not recall whether the "limp home" flag had to be set to the "yes" or "no" status for the bug to triggered. He was certain the voltage condition had to be low, but could not recall if the voltage was related to the central processing unit or the vehicle battery".

[15] Listen to the sudden increase in engine speed in the following videos of sudden acceleration incidents:
http://www.youtube.com/watch?v=ON-2fYew37c,
http://www.youtube.com/watch?v=Wuv9vo2tUkY,
http://www.dashcamaccidents.com/car-crashes-into-building-after-unintended-acceleration/,
http://www.youtube.com/watch?v=pk2olY1C0Fo,
http://www.youtube.com/watch?v=s2SETLp-CTA.

[16] *"Bookout v. Toyota, 2005 Camry software Analysis by Michael Barr",* http://www.safetyresearch.net/Library/BarrSlides-_FINAL_SCRUBBED.pdf

[17] OK, I admit that I am prejudiced. You can decide for yourself if this is because I'm in love with my own theory or because my theory really is more credible.

[18] The 2010 Camry is mentioned here because it is the only vehicle for which the internal operation of the brake override function is known publicly, as a result of M. Barr's testimony. It is not meant to single out Toyota vehicles, because the author believes that all vehicles have a problem with brake override overcoming electronically-caused sudden acceleration.