Further Details on an Electronic Mechanism for Sudden Unintended Acceleration

by

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Abstract: Further details are presented on the author's hardware theory of sudden acceleration. The new details show how long term sudden acceleration is created by the target throttle opening changing due to feedback of the engine RPM even when the accelerator pedal is released. Another detail explains why many drivers in longer term sudden acceleration incidents have observed that the vehicle accelerated as they pressed on the brake pedal. The theory also explains why engine surges and longer term sudden acceleration events occur in the vehicles of all automobile manufacturers. Approaches for preventing sudden unintended acceleration are described, and a method of eliminating the consequences of a runaway engine after sudden acceleration begins is presented.

I. Introduction

On October 31, 2013, the Bookout v. Toyota trial in Oklahoma concluded with a jury deciding that Toyota was at fault for the sudden surging of a 2005 Camry while travelling on an interstate highway[1]. The incident occurred after the driver turned off the highway and left a 150-foot skid mark on the exit ramp from a locked right rear tire prior to the crash. The skid mark proved that the driver's foot was on the brakes and not on the accelerator. The jury was convinced that Toyota was at fault after hearing testimony from software expert Michael Barr which appeared to show that the vehicle's surging was caused by a software fault in the vehicle's electronic throttle system. After awarding compensatory damages of $1.5 million to the driver of the vehicle, and an additional $1.5 million to the family of the passenger who was killed in the crash, the jury was about to re-convene for a decision on punitive damages against Toyota, when Toyota proposed to settle with the litigants out of court.

The successful outcome of this trial against Toyota has led many observers to conclude that the cause of sudden acceleration in Toyota vehicles has finally been found. Specifically, the theory elaborated by software expert Michael Barr successfully explains the following aspects of sudden acceleration[2],[3]:

1) it explains that the cause of unintended acceleration is the result of "task death" brought about by stack overflow whereby the operating system fails to schedule a critical software task that determines the throttle angle. When "task death" happens to "Task X", it leaves the throttle opening in a fixed state which continues until the CPU is reset by turning the ignition OFF and then back ON again.
2) it explains how the "task death" fault is a consequence of Toyota's inadequate, and even careless, software design practices,
3) it explains why fail-safe operation does not occur to eliminate the faulty condition, because the fail-safe routines are contained in the same "Task X" that is not scheduled by the operating system due to "task death", and
4) it explains why no DTC's are stored after an unintended acceleration incident because the fail-safe routines which store them are not activated.

It may be noted that Barr's theory of the "death" of "Task X" explains why the throttle angle remains fixed after a fault occurs, but it does not explain why the fixed throttle angle after the fault occurs is higher than the throttle angle before the fault occurs. Conceivably, it is just as likely for the fixed throttle angle after the fault occurs to be ***less than*** the throttle angle before the fault occurs. This may even correlate with real world experience in which temporary engine stumbling and permanent engine stalling has been observed on some vehicles which is eliminated by turning the ignition OFF and then back ON again.

To explain why the fixed throttle angle after the fault occurs is higher than the throttle angle before the fault occurs, Barr's theory makes use of an additional mechanism known as the "Full Throttle Bug" (FTB)[4], which has not yet been fully elaborated to the public due to limitations imposed by the judge in another pending trial (the Ida Starr St. John trial). The "Full Throttle Bug" (FTB) appears to be an anomaly that occurs in a bounds check of the newly calculated throttle angle when there is a low voltage condition accompanied by a limp home flag at either "yes" or "no". This anomaly results in a condition in which the newly calculated throttle angle is changed to a default 84-degree throttle angle, which is effectively full throttle. Since this anomaly can occur even during a full vehicle stop, a higher throttle angle will always result. Both the Full Throttle Bug (FTB) and "task death" have common triggers, including low voltage signals and memory corruption.

It is interesting that the Full Throttle Bug (FTB) will produce a higher engine speed associated with sudden acceleration even in the absence of "death" of "Task X" "Task X death" merely ensures that this higher engine speed continues indefinitely until the CPU is reset by turning the ignition from OFF to ON again.

Despite the apparent successes of Barr's theory of sudden acceleration, it still has some potential limitations:

1) it does not explain why the high engine speeds encountered during unintended acceleration never occur in while in PARK or NEUTRAL, but only in DRIVE or REVERSE, or while shifting out of PARK or NEUTRAL;
2) it does not explain how one can have surges and lunges at lower speeds followed by continued operation of the engine as normal without the driver recycling the ignition,
3) it does not explain why older people have a higher incident rate for unintended acceleration than younger people.
4) it requires that all automobile manufacturers have the same software problem as Toyota, despite having:
    a. different software design teams with differently trained personnel,
    b. different software design disciplines and
    c. different software coding standards,
    d. different CPU chips, and
    e. different software development tools (compilers and simulators).

The last item is considered a limitation because sudden unintended acceleration appears to be a problem experienced by the vehicles of all automobile manufacturers. But it is difficult to conceive how all manufacturers would have the same software "task death" and "FTB" defects as Toyota given the differences in software design noted. It seems that the software design practices which so effectively condemned Toyota during the Bookout trial would be unlikely to be repeated by each and every automobile manufacturer to produce exactly the same software defects. If this is true, then the possibility exists that there is another cause of sudden acceleration in the vehicles of other automobile manufacturers, or that software defects are not the cause of sudden acceleration even in Toyota vehicles. This paper presents an alternative hardware theory which can explain sudden unintended acceleration in the vehicles of all automobile manufacturers.

II. A Hardware Theory for Sudden Unintended Acceleration

The author has presented a hardware theory of sudden unintended acceleration in a previous paper.[5] In that paper, sudden unintended acceleration in vehicles having electronic throttles was found to be associated with the improper battery voltage compensation of the throttle motor PWM duty cycle because the wrong DC battery voltage has been sensed by the ECU. The root cause of the unintended acceleration is the battery voltage sensing circuit, which detects an improper value of the DC battery voltage when the battery supply voltage is being sampled in the presence of a negative voltage spike. Such negative voltage spikes are always present on the power bus of every vehicle, and are increased in magnitude as the battery becomes more discharged. This explains the stochastic nature of unintended acceleration, and the low probability of its occurrence. It also explains why many sudden acceleration incidents occur in parking lots and at stop lights, because this is when the engine is at idle, causing the vehicle's supply voltage to be determined by the vehicle's battery and not by the vehicle's alternator. It also explains why older people have a higher incident rate, because they tend to drive shorter distances and to make fewer trips, so their batteries have a higher likelihood of being not fully charged, which allows larger negative voltage spikes on the power bus.

When this incorrect DC battery voltage is used to compensate the throttle motor PWM duty cycle while the throttle motor is operating with a normal DC battery supply voltage, then the throttle output is increased above the normal value. This increases the engine torque, which causes vehicle acceleration. This all happens while the driver's foot is off the accelerator. There is no need to assume hardware faults, software faults, EMI, cosmic rays, tin whiskers, or any other cause of throttle system malfunction because the throttle system is performing exactly as designed in every way except for the incorrect throttle motor duty cycle battery voltage compensation coefficient. This is why no diagnostic trouble code is ever found. Essentially, this is a design flaw that occurs in all vehicles having electronic throttles. It is not just a problem with Toyota vehicles, but is a problem with the vehicles of all auto manufacturers because all manufacturers use the same hardware design and the same control system design for their electronic throttle systems. A brake override system which assumes that the driver is pressing the accelerator pedal at the same time as the brake pedal, and then gives precedence to the brake pedal, is completely ineffective in preventing unintended acceleration because it is not necessary for the driver's foot to be on the accelerator pedal when this mechanism occurs.

The author's previous paper presents in detail how the proposed hardware mechanism operates to cause sudden acceleration. In this paper additional details are provided on engine control system operation which support the author's hardware theory, and on other details found during preparation for vehicle testing.

A. <u>Engine Control System Operation</u>. All automobile manufacturers use the same basic architecture for their electronic engine control systems. This architecture is shown schematically in Figure 1. It uses tables or maps to control all engine inputs (i.e., actuators) instead of calculating mathematical expressions for engine inputs such as air, fuel, spark, and variable valve timing (VVT-i). Two-dimensional interpolation is used in the maps to get control values which lie in between the values stored in the maps. All the maps use engine speed (RPM) on the horizontal axis. All maps other than the air throttle control maps use engine load for the vertical axis, as measured by a manifold air pressure (MAP) sensor. The air throttle control maps of late-model vehicles all use engine torque for the vertical axis, where the requested engine torque is provided by a second map of accelerator pedal position versus RPM. Some earlier-model vehicles with electronic throttles used cylinder air charge instead of engine torque as the vertical axis of the throttle control map, but later changed to torque after Bosch showed that torque could be better for controlling many other vehicle functions such as transmission shifting, variable valve timing actuation, skid control, and idle control . All actuators must be corrected for changes in the battery voltage because the actuator outputs can change with battery supply voltage even when the map inputs to them do not change.

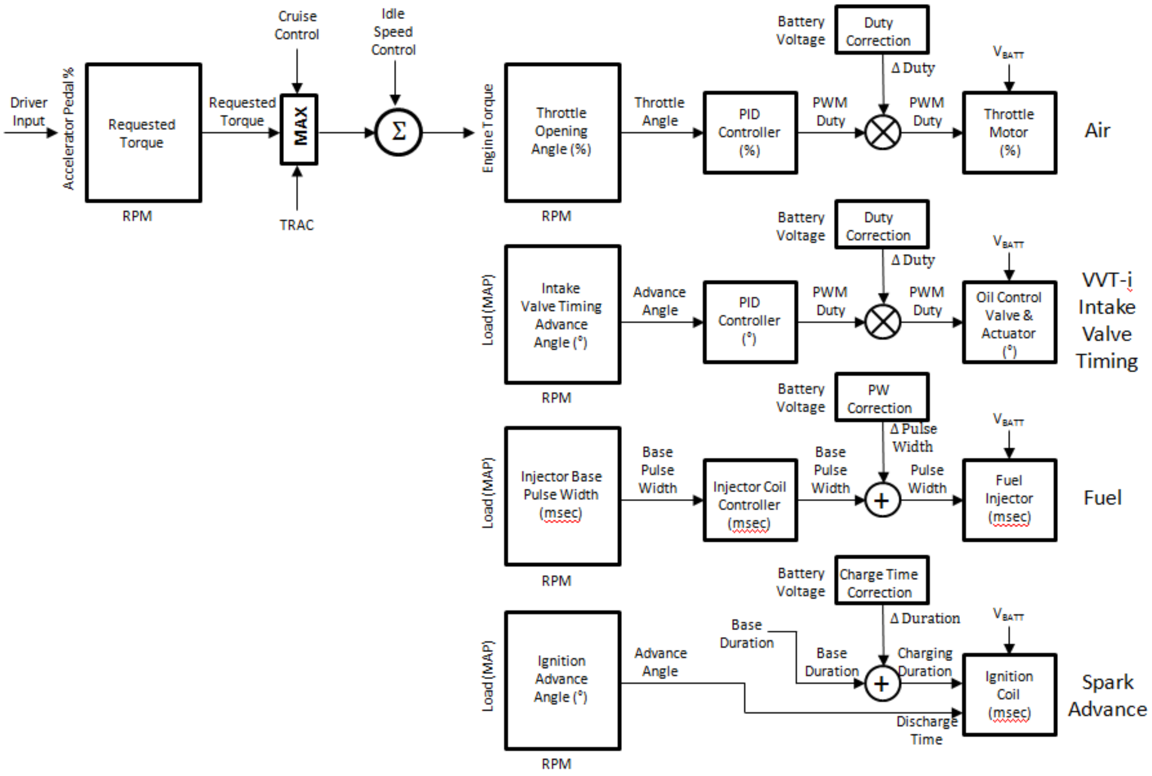

Figure 1. Overview of a modern engine control system showing how maps are used to control all critical engine functions. All actuators must be corrected for changes in battery voltage.

B. <u>Detailed Electronic Throttle Control System</u>. A detailed block diagram of the electronic throttle control system is shown in Figure 2. This same design is used by all automobile manufacturers. It consists of a driver demand map which translates the driver's accelerator pedal position into a requested engine torque. This torque, or the cruise control torque when in cruise control, is added to the engine idle torque to form a total requested engine torque. The total requested engine torque is then translated into a target throttle angle using an "inverse" engine map. The target throttle angle is supplied to a PID throttle controller which controls an electric motor to open the throttle valve to the target throttle opening. The actual throttle opening is measured by a throttle position sensor and fed back to the PID input, to cause the PID controller to drive the actual throttle opening to be the same as the target throttle opening. The PID controller controls the electric motor by a pulse-width modulated (PWM) waveform which turns the motor power supply on and off at a rapid rate so that the time-average of the motor on-time is proportional to the desired throttle opening angle. This means that changes in the motor supply voltage can cause changes in the desired throttle angle. To compensate for these supply voltage changes, the duty cycle of the PWM waveform is multiplied by the inverse of the measured battery voltage, which cancels the change in supply voltage.

Figure 2 also shows which functions are contained in Task X of Toyota's electronic throttle controller, as explained by Michael Barr. If this task is not scheduled by the ERCOS operating system in the CPU, then the target throttle opening does not get updated, and the PID controller continues to use the same target throttle opening as its input until the CPU is reset by turning the ignition OFF and then ON again. Figure 2 shows that Task X also supplies the driver-requested torque to the transmission shift schedule map, which uses it to change the gears in an automatic transmission. This means that the loss of Task X will also cause the transmission gears to remain in a fixed position during a sudden unintended acceleration event. We will have more to say about this later. First, we shall look at the map operation in greater detail.

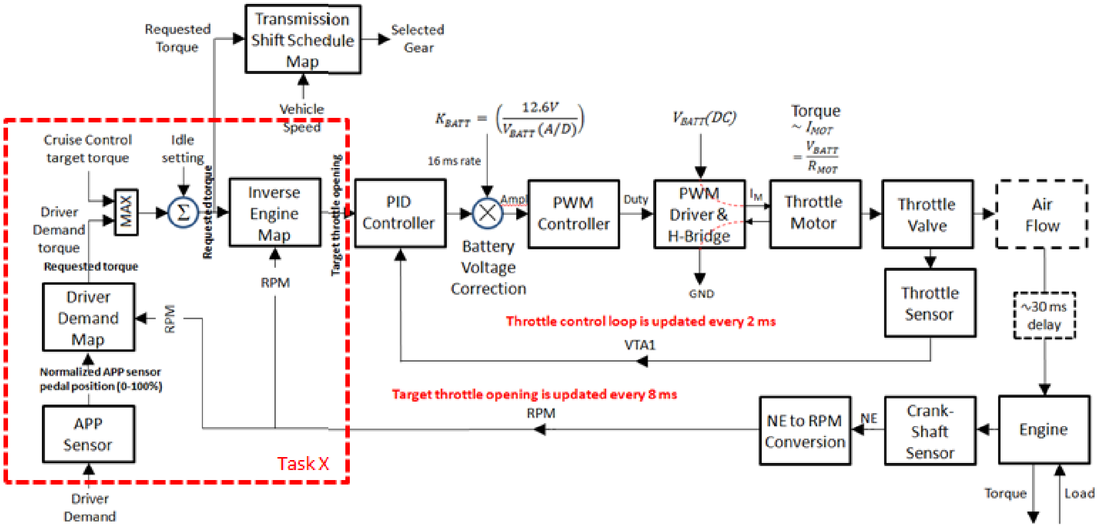

Figure 2. Block diagram of the electronic throttle control system used by all auto manufacturers. The red box shows functions included in Toyota's Task X

1. MAP Content and Operation. The electronic throttle control system uses two maps, a driver demand map and an inverse engine torque map. An inverse engine torque map is shown in Figure 3[6]. It outputs the target throttle opening (in percent) needed for the desired inputs of engine torque and engine speed. The inverse engine torque map is really the same data as an engine torque map, which outputs the engine torque for given inputs of throttle opening and engine speed, but the inverse map merely substitutes the inputs and outputs (i.e. it is not an inverse map in a mathematical sense). The engine torque map is measured on a dynamometer by opening the throttle a given amount, which causes the engine speed to go to the maximum RPM if the only load on the engine is engine friction. Then, an external load is applied to the engine causing the RPM to fall a specific amount, and the engine torque is measured at the resulting RPM. This operation is repeated at different RPM's until one gets various points along a throttle opening curve as shown in Figure 3. This operation is then repeated for different throttle openings. An idealized engine torque map is shown in Figure 4[7].

A driver demand torque map is shown in Figure 5. It outputs the desired engine torque that corresponds to the given inputs of accelerator pedal position and engine speed. It essentially describes the operation of an ideal engine whose throttle opening is determined directly by the accelerator pedal position. This ideal engine can have an improved performance over the real engine, giving greater torque control at lower speeds for snow conditions or higher gas mileage as shown in Figure 6, or higher throttle responsiveness for faster accelerations from a stop as shown in Figure 7. This change in performance can be controlled by changing the driver demand map, either by the driver or by the engine itself, as shown in Figure 8.

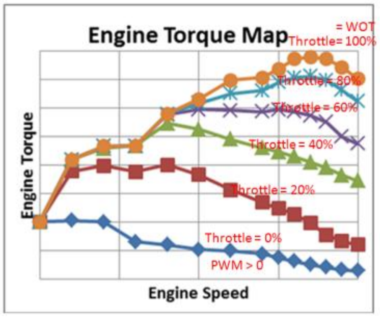

Fig 3. The engine torque map is measured on a dynamometer. The inverse engine torque map uses the same map data as the engine torque map, but substitutes inputs for outputs[6].

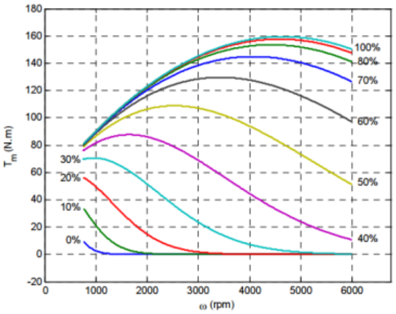

Fig 4. An idealized engine torque map has no bumps in the throttle opening curves as RPM changes[7].

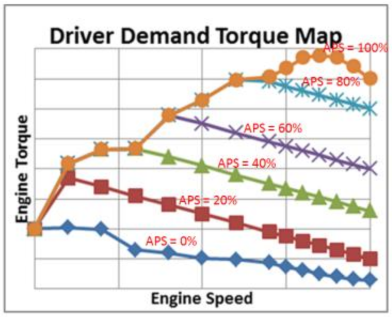

Figure 5. The driver demand torque map describes an idealized engine whose throttle opening is determined directly by the accelerator pedal position[6].

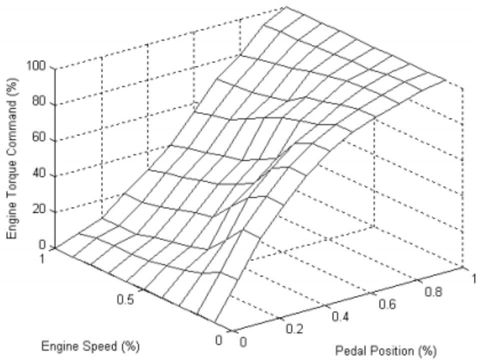

Fig. 6. The pedal map for an economical vehicle ramps up engine torque more slowly as the driver presses the accelerator pedal[8].

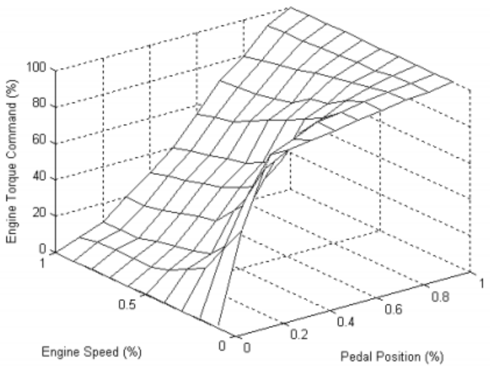

Fig. 7. The pedal map for a sporty vehicle ramps up engine torque rapidly as the driver presses the accelerator pedal[8].

ETCS-I Control modes

- **Non-linear Control**
- **Power mode control**
- **Snow mode control**
- **Shift shock reduction control**
- **Idle speed control**
- **TRAC throttle control**
- **VSC coordination control**
- **Cruise control**

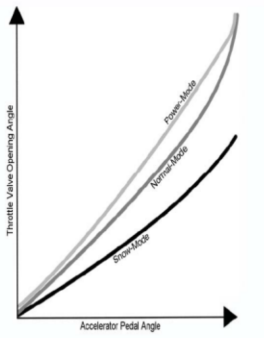

Figure 8. The pedal map can be modified by the driver or by the vehicle itself to provide control modes for different driving conditions by substituting different driver demand maps[9].

The reader may wonder why two maps are used with engine speed as a parameter in both maps, instead of just using a single map that translates the accelerator pedal position into a given throttle opening. After all, this is what a mechanical throttle did in older cars. The answer is that electronic throttles were invented to allow greater throttle control, by the powertrain control module independently of the driver, for smoother powertrain performance during electronic transmission shifting and variable valve timing actuation. Electronic throttles also allow easier (i.e., cheaper) incorporation of cruise control into the vehicle. Later, additional functions like wheel traction control and directional stability control were included because they were easy modifications once an electronic throttle was present. Driver control over the engine was never a primary objective, although it was possible to make the car seem more or less responsive to the accelerator pedal by changing the driver demand map.

All of these vehicle-controlled functions require fine control over the engine torque. Such fine control cannot be achieved using a single map of the accelerator pedal to the throttle opening. This is because the air intake quantity (i.e., cylinder air charge) which determines the engine torque is not a fixed function of the throttle opening area, but varies with engine speed as shown in Figure 9 as a result of the difference in air pressure between the throttle valve and the engine cylinders becoming smaller at higher engine speeds[10]. This means that the transfer function between the accelerator pedal position and the engine torque (i.e., the driver demand map) depends on the engine speed as shown in Figure 10. A driver with a mechanical throttle can easily accommodate these changes in transfer function with engine speed by pressing harder on the accelerator pedal. But an electronic control system cannot do this as easily. Therefore, engine speed must be included as a parameter in the driver demand map and in the inverse engine torque map.

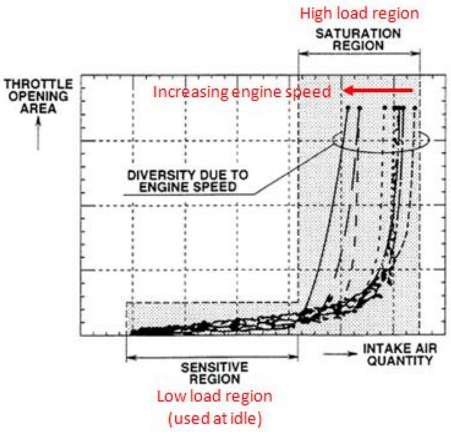

Figure 9. The intake air quantity (cylinder air charge) decreases with engine speed at large throttle openings because of air pressure changes, making engine torque a function of both throttle opening area and engine speed.

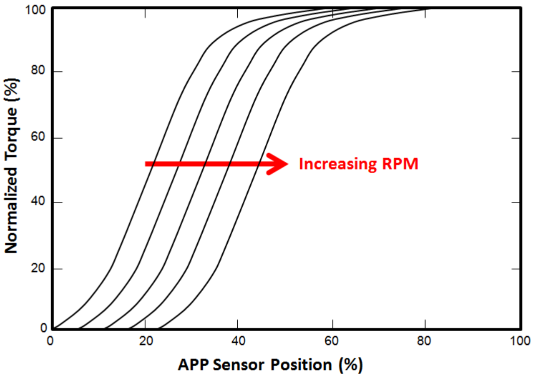

Fig 10. The map of actual engine torque versus accelerator pedal position (pedal map) varies with engine speed, requiring engine speed to be included in the throttle maps.

2. Transmission Shift Control. An electronic transmission (used now by all auto manufacturers) uses the driver-demanded torque and the vehicle speed as inputs to a shift scheduling map to determine when to shift gears, as shown in Figures 11 and 12. The actual shifting is done by electronic solenoids. Older mechanical transmissions used the engine load, or the throttle valve position as determined by a throttle position sensor, as a measure of the actual engine torque instead of using the driver-demanded torque, and used a governor valve controlled by vehicle speed, instead of a crankshaft sensor, to determine the transmission output shaft speed, which then determined when to shift the gears. The actual shifting in a mechanical transmission was done by oil control valves which switched as a function of oil pressure.

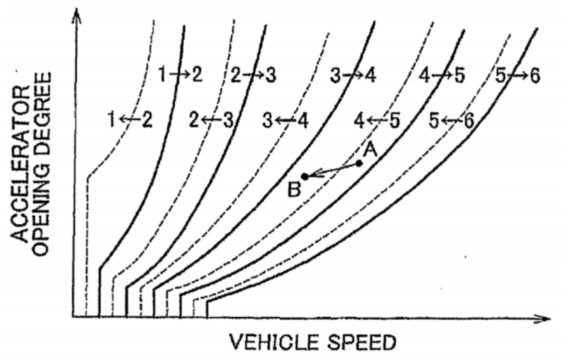

Fig 11. The gear shift scheduling map determines when an automatic transmission shifts gears[11]. Solid lines show up-shifts, dashed lines show down-shifts.

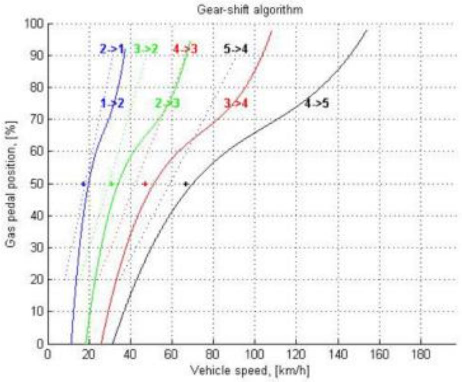

Fig 12. Under higher acceleration (higher torque) demand, the transmission spends a longer time in the lower gears[12].

Figure 2 shows which functions are included in "Task X" as described by Barr's theory. Failure to schedule "Task X" is (partially) responsible for sudden acceleration in Barr's theory. Figure 1 shows that the "death" of "Task X" will also cause the driver torque demand input to the shift scheduling operation to remain at a fixed value, which will prevent the transmission from shifting either up or down, thereby leaving it in its current gear. This does not necessarily put the transmission into its limp-home mode, however, unless the transmission control processor senses that the driver torque demand input is absent or deficient in some way. When the transmission goes into the limp home mode, all electronic transmissions are designed to stay in either the current gear or the highest gear until the ignition is switched OFF and then back ON again. (Note that there are two types of limp-home modes, one for the transmission and one for the engine. They may occur independently from each other as a fault occurs in either the transmission or the engine. If they should happen to occur simultaneously, then this would imply that a common fault is responsible for both limp home modes. The only common fault known at this time is a low voltage condition on the battery supply line. Either the transmission limp home mode or "Task X" death seems to have been triggered during some sudden acceleration incidents, such as the Laurie Ulvestadt incident in a 2012 Kia Sorento in Missouri in 2012[13], the Elez Lushaj incident in a 2011 Hyundai Elantra in Texas in 2012[14], the Marlene Taylor incident in a 2008 Chevrolet Equinox in Kentucky in 2010[15], the Kevin Nicole incident in a BMW 318 in the UK in 2006[16], and an incident in a 2005 Toyota Sienna in Iowa in 2010[17], in which the drivers were unable to shift into the neutral gear during long sudden acceleration incidents. It is not known whether the engine limp home mode was triggered during these same incidents). If Figure 1 is correct, then the "death" of "Task X" in Barr's theory implies that transmission shifting is disabled during all sudden acceleration incidents. This does not appear to happen however, during surging incidents or during some short duration sudden acceleration incidents beginning from a stopped position, after which the engine RPM's decrease again without turning the ignition OFF and then back ON.

3. Effects of incorrect battery voltage compensation on the inner PID throttle control loop. When an incorrect battery voltage compensation coefficient is used to multiply the duty cycle output of the PID controller as shown in Figure 2, the effect is the same as increasing the coefficients of the P, I, and D terms in the PID controller. Increasing the PID coefficients has two consequences: 1) the PID output amplitude is increased, and 2) the PID convergence time is extended. The consequences of increasing the P- and I-coefficients are shown in Figure 13[18]. Increasing the P-coefficient makes the PID output reach the target throttle angle more quickly, giving the driver the impression that the car is more responsive. Increasing the I-coefficient makes the PID output overshoot the target throttle position, and then undershoot it slightly, before eventually converging to the target throttle position, giving the driver the impression of an engine throttle surge. As the I-coefficient gets larger and larger, the PID oscillation becomes more undamped, and the throttle output may even go into oscillation. When the PID controller was designed, the engineers carefully adjusted the PID coefficients to be as large as possible without reaching these undesirable situations in order to give the throttle the best response to driver accelerator input and the smallest overshoot of the target throttle position. They assumed in this process that the correct battery voltage duty cycle compensation coefficient would be used. But if an incorrect battery voltage duty cycle compensation coefficient is used, the carefully adjusted PID coefficients will increase, and the consequence will be a higher sensitivity of the

throttle to driver-induced accelerator pedal changes and engine surges that may be caused by throttle changes that are not intended by the driver, but induced by engine idle-ups, such as an air conditioner turning on.

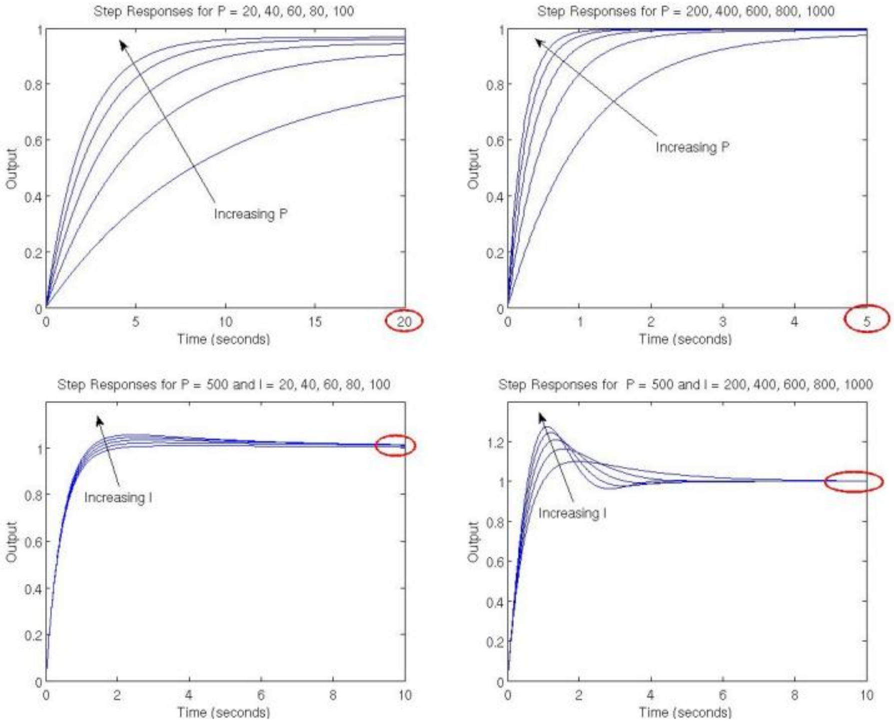

Figure 13. The change of PID coefficients from the IDLE mode to the DRIVE or REVERSE mode makes the throttle controller more sensitive, allowing it to approach the target throttle position more rapidly. Increasing the PID coefficients further by using an incorrect battery voltage compensation makes the throttle controller overshoot the target throttle position, leading to increased throttle sensitivity, engine surges and longer term unintended acceleration events. In many cases, the controller eventually converges to the target throttle position (red circles), but only after an engine surge or longer unintended acceleration event (overshoot) has occurred[18].

The increase of PID coefficients caused by an incorrect battery voltage duty cycle compensation coefficient does not explain how the inner PID control loop can go into a state that that explains long-term sudden acceleration incidents. Control theory teaches that the PID output will eventually converge to the target throttle angle, or else go into a limit-cycle oscillation. Control theory, however, does not place a limit on the PID convergence time. But auto manufacturers do place a limit on this convergence time, forcing the throttle into the limp-home mode if the convergence time exceeds a few seconds or so. Therefore, any failure of the throttle to reach the specified target throttle angle should be detected by the throttle fail-safe algorithms, and long-term sudden acceleration incidents caused by improper operation of the PID loop should not occur. For this reason, the author has looked outside the PID control loop for an explanation of long-term sudden acceleration incidents.

4. Effects of incorrect battery voltage compensation on outer throttle RPM loop. Figure 2 shows that the engine RPM is an input to the two engine maps used to set the target throttle position. The engine RPM is also an output of the engine, whose actual throttle opening is adjusted by the PID controller, thereby determining the engine's torque. Therefore, the PID controller, the engine, and the RPM form a loop. This loop is not intended to be a control loop because it is not intended that the engine change the target throttle opening. The RPM is intended to be only an engine operating parameter which helps select the proper target throttle opening and which varies slowly compared to changes in the inner PID control loop. However, the RPM actually does form a feedback loop that can cause the throttle target opening to change (just like a control loop) if the outer loop changes in a way that is not compensated by corresponding changes in the inner throttle control loop. One does not need an arithmetic operation to compare the feedback value to the input value of a control loop, as the difference operation normally does to create the inputs

to a normal PID loop. Instead, a table look-up can be used to generate the “difference value”, in which case the “difference value” will vary with the table coordinates, such as the RPM.

The PID-generated throttle opening affects both the inner and outer control loops, but affects them in different ways. The PID-generated throttle openings affects the inner loop more rapidly, and ordinarily converges to the target throttle opening before a new target throttle opening is calculated. This means that the RPM produced by the throttle controller acting on the engine matches the RPM used to calculate the original target throttle opening, resulting in the same target throttle opening. But if the PID-generated throttle opening does not converge rapidly enough to the target throttle opening, then the RPM produced by the throttle controller acting on the engine will not match the RPM used to calculate the original target throttle opening. The PID-generated throttle opening can either be larger than the original target throttle opening or smaller than the original target throttle opening, depending upon when the PID-generated throttle opening is sampled. If the PID-generated throttle opening is larger than the original target throttle opening when it is sampled, then the original target throttle opening will be changed to a larger value because the RPM used to calculate it is higher, even though the driver- demanded torque input to the inverse engine map does not change. And if the new target throttle opening has the same thing happen to it because the resulting PID- generated throttle opening does not converge rapidly enough to the new target throttle opening, then a second new target throttle angle will be calculated which is higher than the first. This process will continue until the maximum target throttle opening is eventually reached, which can happen in a very short time because the outer loop is sampled every 8 milliseconds.

There is one condition that must be met before the RPM feedback to the inverse engine map can cause the target throttle opening to increase. The condition is that the other input to the map (the requested torque input) must be above a certain minimum value. Table 1 shows a typical inverse engine map. Notice that the first column contains all zeroes. This is an important feature because the zeros provide a path for the engine RPM to decrease back to the minimum idle speed when the requested torque input is reduced to zero. The zero throttle opening values indicate to the engine controller that the idle speed is desired in these cases, enabling the CPU to assign a negative value to the PID duty cycle to obtain the idle mode. If the RPM input to the table increases while the torque input remains exactly zero, then the throttle opening will remain zero, and the engine will remain in the idle mode. In order to have the RPM input increase the throttle opening while the requested torque input remains fixed, the requested torque input to the table must be above some minimum non-zero value. This can happen without driver intervention as a result of an idle-up increasing the engine torque. Such idle-ups may be produced by the air conditioner, the ABS brake pump, or the cooling fans on the radiator. Ordinarily, these functions cause an idle-up of only a few hundred RPM, which allows the throttle motor duty cycle to remain negative, keeping the engine in the idle mode. But if the PID coefficients are effectively increased as a result of an incorrect battery voltage duty cycle compensation coefficient, then these idle-ups can be larger than several hundred RPM, causing the throttle motor duty cycle to become positive, which takes the engine out of the idle mode. When such an enhanced idle-up causes a minimum torque to be applied, one of the remaining non-zero columns in the table is used, and the table will output an increasing throttle angle as the RPM input to the table is increased. This explains the observation that many drivers have made that sudden acceleration is associated with the air conditioner turning on, or with the ABS brake pump turning on. It also implies that the high engine RPM’s associated with long-term sudden acceleration should last only as long as the idle-up remains active. If the idle-up is removed, such as by turning off the air conditioner, then the high engine RPM’s should go back down to idle.[Footnote 1]

The 30 msec delay in the outer loop is caused by the time it takes for the air to pass from the throttle control valve to the engine cylinders. There is also an additional time delay of several milliseconds between the cylinder filling time and the engine torque pulse, and between the engine torque pulse and the RPM sensor output, which must be calculated from the crankshaft sensor by counting sensor pulses over a fixed time interval and then dividing by the time interval. This RPM value must be sampled to create an input to the throttle control maps. The sampling of this RPM value is equivalent to sampling the engine speed at a given time and, hence, to sampling the PID-generated actual throttle opening at a given time. Clearly, this effective sampling time is different than the sampling time used by the inner throttle control loop for the same PID-generated throttle opening waveform. This means that the outer RPM loop may be sampling the PID-generated throttle opening waveform at a time when the waveform is either

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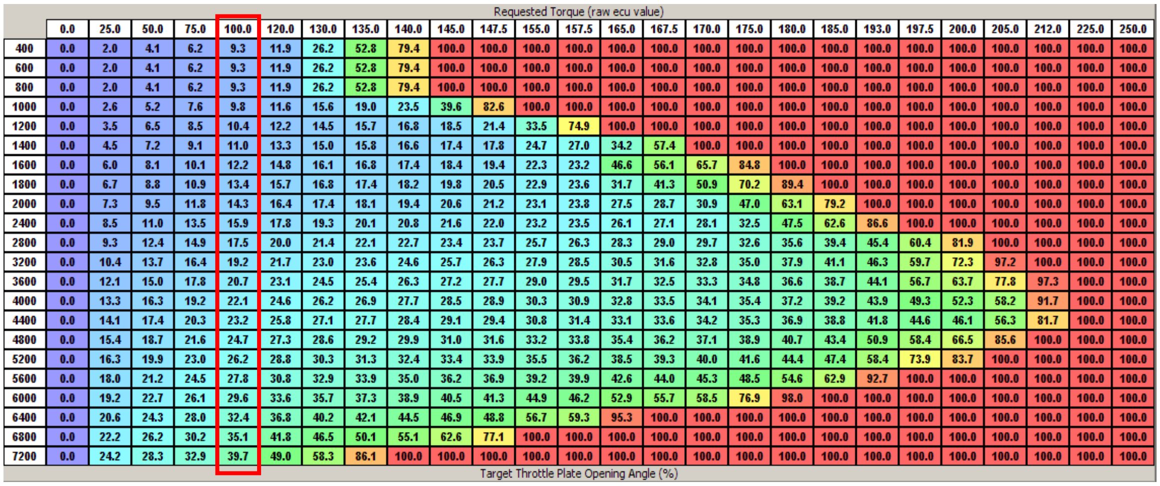
[Footnote 1] A sticky accelerator pedal which does not go completely back to the released pedal position, but instead stops slightly above the normally released pedal position, may create the same condition as an idle-up. Such a sticky pedal defect has been reported by CTS Corporation, a manufacturer of accelerator pedals.

higher or lower than the target throttle opening. If it is higher, then the target throttle opening will be changed to larger throttle openings, resulting in sudden acceleration. If it is lower, then the target throttle opening will be changed to smaller throttle openings, possibly resulting in sudden stalling.

Table 1. A typical inverse engine torque map giving the throttle opening angle as a function of requested torque and the engine speed (RPM)[19]. The zeros in the first column indicate the idle mode is desired.



Requested Torque (raw ecu value)

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

Target Throttle Plate Opening Angle (%)

One can simulate the effects of PID overshoot on the RPM feedback loop shown in Figure 2, where the PID overshoot is caused by the incorrect battery voltage compensation of the duty cycle, by substituting maps that correspond to a given engine design. Figure 14 shows the resulting system to be simulated.

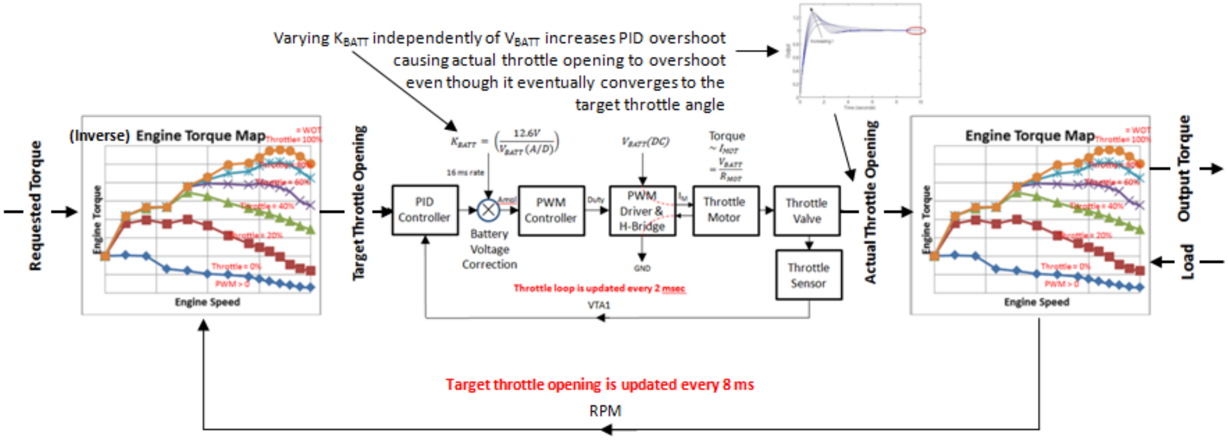


Figure 14. The electronic throttle control system can be simulated by substituting maps for a specific engine type. Engine operation is simulated by the engine torque map which is measured using a dynamometer. The inverse engine torque map is really the same engine torque map data, but the data is just read out differently (i.e. it is not an inverse map in a mathematical sense).

If the battery voltage compensation coefficient, K_{BATT}, varies as intended with the battery voltage, V_{BATT}, the mapping of driver-requested target throttle angle to engine output throttle angle is one-to-one. But if the battery voltage compensation coefficient, K_{BATT}, varies independently of the battery voltage, as it does when a voltage spike causes an incorrect battery voltage to be measured, then the actual throttle opening is higher than the driver-requested target throttle opening, causing the engine RPM to rise. When this higher RPM is fed back to the inverse engine torque map, the map produces a higher target throttle opening even though the driver-requested target torque remains the same. This condition is repeated every 8 milliseconds until the engine speed reaches the maximum RPM allowed by the engine torque map. The effects on engine operation of multiple passes through the RPM loop are shown by the dashed line AB in Figure 14.

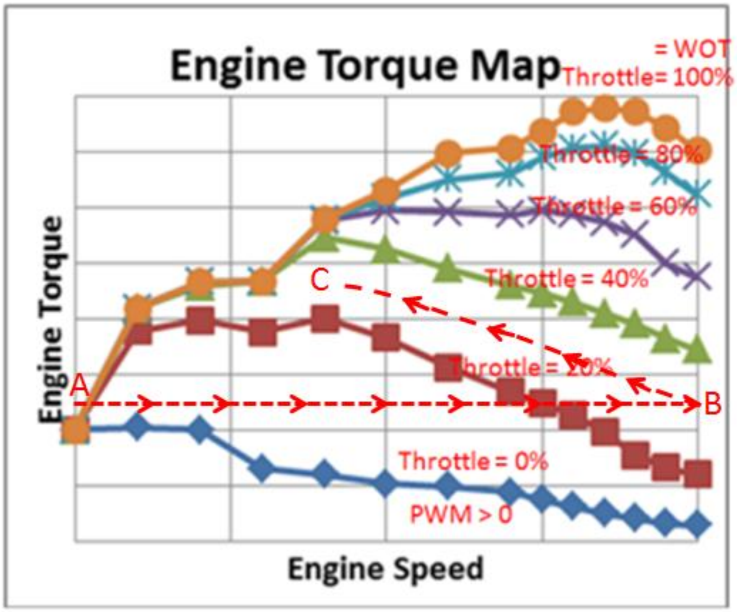


Figure 14. Magnified engine torque map showing how engine speed varies from point A to point B during an unintended acceleration incident lasting several seconds or more.

When the driver increases the load on the engine by stepping on the brake pedal, the engine RPM is reduced by the load, causing the engine to produce a higher torque as shown by the change from point B to point C in Figure 14. The driver perceives this as pressure on the brake pedal causing a higher acceleration. This increase in acceleration when pressing the brake pedal has been noted by many drivers during a sudden unintended acceleration incident. The same effect occurs during dynamometer testing, when the throttle is opened a given amount causing the engine to go to a maximum RPM due to the absence of a load (or with only engine and drive train friction as a minimal load), after which placing increasing loads on the engine causes the RPM to fall and the measured engine torque to increase. This is how the engine torque map is produced and measured.

The reader may now see how the actual throttle opening can increase while the PID controller is still operating well enough to allow the PID controller output to converge to the target throttle opening. The reason is that the target throttle opening is changing as a result of the feedback produced by the slightly increased RPM parameter acting on the inverse engine torque map. The throttle position produced by the PID controller is sampled by the RPM feedback circuit at a different time than the throttle position is sampled by the throttle position sensor feedback circuit, allowing the RPM loop to change while the PID loop operates as normal. Therefore, the electronic throttle unit appears to operate normally because none of the fail-safe measures are triggered.

So, why doesn't the failsafe trigger that compares the actual throttle position with the accelerator pedal position? If such a failsafe indeed exists, then the comparison requires that one translate the accelerator pedal position into a target throttle position and then compare the actual throttle position with the target throttle position. Therefore, if the target throttle position is increased as a result of the feedback action of the RPM signal, the comparison circuitry will assume that the increased target throttle position is the result of the driver pressing on the accelerator pedal. This may be the cause of the event data recorder (EDR) showing that the driver was pressing on the accelerator pedal during many sudden acceleration incidents. It may also be possible that the RPM signal changes the output of the driver demand map in a similar way that it changes the output of the inverse engine map, causing the requested torque output of the driver demand map to increase even though the accelerator pedal input does not increase. Further understanding of the fail-safe operation is needed before one can determine how it is defeated.

5. <u>Sampling of the Battery Voltage to Cause an Incorrect Battery Voltage Duty Cycle Compensation Coefficient</u>.

The author has found many references in the patent literature and in the repair manuals of many auto manufacturers that describe the battery voltage compensation of the duty cycle driving the DC motor in the electronic throttle. However, an intensive search of the same literature has failed to reveal when the battery voltage is sampled and how often it is sampled. This changed during preparations for testing when the author found in a Toyota repair manual[19] that the battery supply voltage to the electronic throttle was sampled after a specific driving pattern as shown in Figure 15. This explains why the battery voltage is not sampled continuously, and why it is sampled only at idle, which explains why many surging events and longer sudden acceleration events begin while the vehicle is at idle. It is suspected that all auto manufacturers sample the battery voltage supply to the electronic throttle motor in the same fashion.

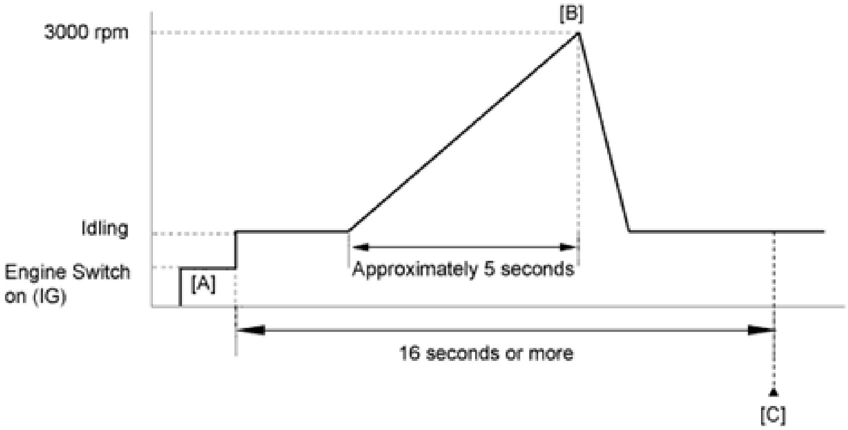


Figure 15. Driving pattern recommended by Toyota to test the +BM supply voltage of the electronic throttle motor[20]. The +BM supply voltage is sampled somewhere between B, the start of idling, and C, when the DTC is read.

III. Solutions for Sudden Acceleration

In a previous paper the author proposed several approaches for preventing surging and sudden unintended acceleration, assuming that his hardware theory of sudden unintended acceleration is correct. These methods included a hardware approach of using an isolation diode combined with a hold-up capacitor to prevent the supply voltage to the electronic throttle unit from dropping temporarily while it is being sampled by the battery voltage duty compensation circuitry, and a software approach whereby the supply voltage to the electronic throttle unit is sampled two or more times several hundred milliseconds apart, and the largest supply voltage measured is used for duty cycle compensation. These methods can be used either singly or together to eliminate surging and sudden unintended acceleration completely before it starts [Footnote 2].

Since writing the last paper, the author has become aware of another hardware approach for eliminating sudden unintended acceleration. The approach, proposed in 1991 by the inventor of the map-based control system of the electronic throttle[21], is to put a normally closed relay switch in the drive circuitry between the H-bridge and the electric throttle motor. The relay can be opened by many techniques that sense when a runaway throttle condition is occurring, such as when the actual throttle opening exceeds a certain value while the accelerator pedal is released. A similar relay approach is used in a commercially available product called the Decelerator, which has been patented by Donald Cook[22] and which can be purchased for about $200. Since the relay is normally closed, the Decelerator circuitry makes no changes to the PID control circuitry, and the vehicle's normal throttle behavior will be unaffected by the additional circuitry. Only when the throttle opening exceeds some adjustable value while the brake is being

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[Footnote 2] The author's first paper mentioned another hardware approach whereby the throttle motor supply voltage is taken directly from the battery instead of sharing a wire connection with other high-current functions. In this case, negative voltage spikes are isolated from the throttle motor supply voltage, and should not be seen by the analog to digital converter sampling the throttle motor supply voltage. See *"An Electronic Cause for Sudden Unintended Acceleration"*, April 2012, http://www.antony-anderson.com/Cruise/belt-hypo/sum.html. Also available at: http://www.autosafety.org/dr-ronald-belt%E2%80%99s-sudden-acceleration-papers-2012.

applied will the relay disable the throttle motor, causing the throttle to go into the limp home mode. This relay approach does not eliminate the root cause of sudden acceleration, but it very effectively eliminates the consequences of a runaway engine. It is far better than the brake override approaches currently used by the automobile manufacturers and recommended by the NHTSA, which assume that the driver is pressing on the accelerator pedal, and which are completely ineffective in stopping sudden acceleration if either author's hardware theory, or Michael Barr's software theory, is correct.

IV. Conclusion

This paper, together with the author's previous paper, presents a hardware theory of sudden unintended acceleration that can be simulated and tested to confirm its correctness. The theory explains how sudden unintended acceleration can occur in the vehicles of all auto manufacturers. It explains many characteristics of sudden acceleration, including why drivers have observed that the vehicle accelerated when the brake was pressed. It also explains why many sudden unintended acceleration incidents begin while the engine is at idle, because this is when the battery voltage is sampled for use by the electronic throttle to compensate the effects of low battery voltage. An incorrect battery voltage reading, caused by a negative voltage spike occurring during the sampling process, leads to an incorrect battery voltage compensation operation, which increases the throttle opening temporarily to cause a temporary engine surge, or a longer term sudden acceleration incident. The author realizes that his theory is unproven until it is tested experimentally, and strongly encourages such testing by independent laboratories, the government, and auto manufacturers. He is willing to assist anyone who is prepared to do such testing.

This hardware theory of sudden unintended acceleration is an alternative to the software theory of sudden acceleration expounded by Michael Barr. Unlike the software theory, which requires all manufacturers to have the same software defect despite having different software design teams, different software design disciplines, different software coding standards, different CPU chips, and different software development tools, the hardware theory explains sudden acceleration in the vehicles of all manufacturers by the fact that all auto manufacturers use the same hardware control architecture for their electronic throttles.

We will eventually find out if the same software "Task X death" and "FTB" defects prevalent in Toyota vehicles are the cause of sudden acceleration in other manufacturer's vehicles. All we need to do is to wait a few years and check whether the sudden acceleration incident rate for new vehicles drops. One would expect that auto manufacturers will correct any known software deficiencies, or else risk future customer litigation and government fines if they fail to fix such safety-related defects. On the other hand, if the sudden acceleration incident rate for new vehicles does not drop in a few years, it would be an indication that software-related defects are not the cause of sudden acceleration in either Toyota vehicles or any other manufacturer's vehicles, and that the true cause of sudden acceleration is still to be determined.

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