A Clear Explanation of Belt's Theory of Sudden Unintended Acceleration

The explanation for sudden unintended acceleration (SUA) given by most skeptics is that SUA is caused by the driver pressing on the accelerator pedal instead of the brake pedal. This is sometimes referred to as pedal confusion. This explanation predicts that all vehicles will have the same SUA incident rate, which is definitely not observed. All attempts to explain how pedal confusion can cause SUA in some vehicles but not in others (say by differences in pedal spacing or pedal positioning) have been unsuccessful as reported by some manufacturers and by NHTSA investigators.

Another theory is that a software error is the cause of SUA. This theory is often stated as a guess without giving any detail as to what the software error is or how it causes SUA. The most detailed theory of software error was given by Michael Barr in a 2013 trial against Toyota. In the trial he explained how Toyota's software development process was so deficient that Toyota's software allowed the loss of information due to stack overflow. This froze the control input to the electric motor opening the throttle, causing a vehicle running at high speed to continue running at a high speed without input from the driver. This theory worked for the 2005 Camry in the trial, which dealt with the vehicle running at high speed when the SUA occurred. But the same theory isn't able to explain how a vehicle operating at low speed can suddenly speed up without driver control. Most SUA incidents are of this low speed variety, such as in a parking lot or at a traffic light. The theory also can't explain why the vehicles of manufacturers other than Toyota also have SUA unless their software development processes are just as deficient as Toyota's, which is difficult to believe. This theory will never be developed further because the court records describing it were sealed at Toyota's request, bringing an end to two years of intensive study of Toyota's engine control software containing millions of lines of software code.

The most reasonable theory of SUA is one proposed by Dr. Ronald Belt. It applies to all vehicles that use electronic throttles. In vehicles with gasoline engines, pressing on the accelerator causes an electric motor to open the throttle, which allows more air into the engine. This makes the engine RPM increase. In vehicles with diesel engines, pressing on the accelerator causes a pressure control valve to increase the fuel pressure, which squirts more fuel into the engine. It also causes another pressure control valve to change the vanes in the turbocharger, which provides more boost by the turbocharger, forcing more air into the engine. Both of these changes make the engine RPM increase.

Both electric throttle motors and pressure control valves are actuators that run off of the 12-volt battery voltage. If the DC battery voltage decreases, then the outputs of the actuators also decrease in proportion to the DC voltage, even though the inputs to the actuators remain the same. This can cause the engine to run at a lower RPM when the DC battery voltage is low. This wouldn't be noticeable if the actuator inputs came directly from the driver, because the driver can compensate for the change of engine RPM by pressing harder on the accelerator pedal. But the actuator control inputs don't come directly from the driver. They come from a table that issues setpoints to the actuators every 10 milliseconds or so, based on <u>both</u> the accelerator pedal position and the RPM of the engine. So, if the DC battery voltage decreases, then the actuator output decreases, causing the engine to run at a lower RPM. This causes the table to select a different actuator setpoint the next time it issues a new setpoint 10 milliseconds later. The result is that, with a low battery voltage, successive setpoints get lower and lower each time they are issued by the table, causing the engine RPM to decrease more and more, making the engine eventually stop. This happens even though the accelerator pedal position doesn't change. To prevent this from happening, the controller samples the DC battery voltage, and then compensates for any decrease in the DC battery voltage by multiplying the setpoint to the actuators by the inverse amount that the DC battery voltage decreases. This increases the actuator input, making the output of the actuator independent of the battery voltage. This battery voltage sampling operation is normally done when the engine is idling at low RPM, with the sampled battery voltage being stored in a memory for long-term use at higher engine speeds.

This voltage compensation function works well as long as the DC battery voltage is sampled correctly. But sometimes an error can occur during the voltage sampling. This can happen when the battery voltage is sampled at the same time that a negative voltage spike occurs on the 12 volt supply line. Such negative voltage spikes can be caused by other electric motors or actuator valves under the hood turning on, such as air conditioner motors, radiator fan motors, or brake actuator valves. When these functions turn on, the inrush current acts like a temporary short on the 12 volt supply line, pulling it down toward zero volts, or ground. The 12 volt supply line may then go down to 10 volts, or 8 volts, or even lower, for a very short time, like a few hundred microseconds or so. This short negative voltage spike does not affect the operation of the actuators because the actuators are sensitive only to the long-term DC value of the applied voltage, which remains at 12 volts. But if the voltage sample is taken during a negative voltage spike, then the voltage compensation function reads a lower battery voltage which it thinks is the DC voltage, but it really is not. When the inverse of this lower battery voltage is used to compensate (i.e., multiply) the actuator inputs while the actuators are supplied with a normal 12 volt DC supply voltage, it <u>increases</u> the actuator outputs above their 12-volt value, causing the engine to run at a <u>higher</u> RPM. This, in turn, causes the table issuing actuator setpoints to issue a new actuator setpoint that is slightly higher, which raises the engine RPM even higher. This means that the engine RPM increases a little bit more each time a new setpoint is issued, which is every 10 milliseconds. This happens even though the accelerator pedal input to the table remains unchanged. The result is that in less than one second the engine RPM increases 100 times, eventually rising to the maximum value stored in the setpoint table, which may be 5000 to 7000 RPM. This is what causes SUA.

The above mode of operation can happen only when the vehicle is operated while in DRIVE or REVERSE. This is because in DRIVE or REVERSE the engine RPM is controlled by an <u>open-loop</u> throttle controller with the setpoint table having inputs from the accelerator pedal and the engine RPM. An open-loop controller can only issue setpoints in response to the table inputs. If one of the inputs is incorrect, it has no way of limiting the engine RPM to some maximum or minimum value. Therefore, SUA can occur in DRIVE or REVERSE if one of the inputs to the setpoint table is wrong. When the vehicle is in PARK or NEUTRAL, the setpoint table is not used and the engine RPM is controlled by a different <u>closed-loop</u> idle controller that compares the engine RPM to some fixed idle RPM (such as 800 RPM). A closed-loop idle controller can increase the engine speed when the engine RPM is too low and decrease the engine speed when the engine RPM is too high. Therefore, SUA cannot occur when the vehicle is in PARK or NEUTRAL because the setpoint table is not used and the closed-loop idle controller adjusts for any engine speed variations, bringing the engine speed back down if it goes too high or raising it up if the engine speed is too low, even though the compensation function may be incorrect. But as soon as the driver shifts the transmission into DRIVE or REVERSE, the closed-loop idle controller is replaced by the open-loop throttle controller with its setpoint table, allowing the engine speed to suddenly increase without limit if an input to the setpoint table is wrong. This is because in DRIVE or REVERSE the open-loop throttle controller has no feedback. This is normally acceptable because the engine RPM is limited normally only by the accelerator pedal input.

It is important to know that the battery voltage cannot be sampled at any time while the vehicle is running. This is because the alternator, and not the battery, is setting the supply voltage to about 13.8

volts when the engine speed is above about 1500 RPM. Only when the engine speed is well below 1500 RPM will the supply voltage become equal to the battery voltage of about 12.6 volts (normally) as a result of the battery being the major supplier of current to the vehicle's electrical needs. This means that the battery voltage can be sampled only when the accelerator pedal is not being pressed and when the engine speed is close to the idle speed of around 800 RPM. This explains why most SUA incidents occur when the engine speed is low, like in parking lots and street intersections.

Also, the battery voltage will be sampled incorrectly only when a 200 millisecond negative-going voltage spike occurs during the 50 microsecond sampling time. This is a chance event that occurs only about once every 10,000 voltage samples, where a voltage sample is taken each time the engine is turned on, and at fixed time intervals after the engine is turned on. This explains the random nature of SUA; i.e., why the SUA incident rate for most cars is about 200 parts per million (ppm). It also explains why SUA ceases when the engine is turned off, and why it does not recur (usually) when the engine is turned back on.

This theory can explain SUA in all vehicles with both gasoline engines and diesel engines. It explains:

1) why SUA is a random event in all makes and models of vehicles. This is because the problem occurs only when the battery voltage is sampled during a negative voltage spike, which is a very infrequent event because the negative voltage spikes are random events, and the sampling time and the duration of the negative voltage spikes are extremely short times on the order of 50 microseconds and 100 milliseconds, respectively.
2) why SUA is seen in nearly all makes and models of vehicles having electronic throttles. This is because all manufacturers have no choice but to compensate the electronic throttle valve for low battery voltage, making throttle valve operation susceptible to errors while sensing the battery voltage. This leads to sudden acceleration as a result of all manufacturers choosing to control the throttle valve in the same way using a setpoint table having inputs from the engine speed sensor as well as the accelerator pedal sensor.
3) why SUA happens most often at a low vehicle speeds when the engine speed is low and the transmission is in DRIVE or REVERSE, because when an incorrect value of the sampled battery voltage is used while in DRIVE or REVERSE, the open-loop controller does not limit the engine RPM. So it keeps increasing, causing SUA.
4) why SUA does not happen when the transmission is in PARK or NEUTRAL, because when an incorrect value of the sampled battery voltage is used while in PARK or NEUTRAL, the closed-loop controller automatically reduces the engine RPM when it starts to increase,
5) why SUA frequently happens just as the transmission is being shifted out of PARK or NEUTRAL and into DRIVE or REVERSE, because the closed-loop controller is replaced by an open-loop controller, which can no longer limit the engine speed. So in just keeps increasing when an incorrect value of the sampled battery voltage is used.
6) why the high engine speed problem goes away when the engine is turned off and then restarted. This is because the battery voltage is sampled again when the engine is turned on, and the new sample is rarely taken during a negative voltage spike.
7) why no diagnostic error code is produced, because everything in the engine is operating normally except for the incorrect value of the sampled battery voltage.
8) finally, it explains why SUA may occur more often when the DC battery voltage is low, because the negative voltage spikes become lower in amplitude when the DC battery voltage is low.

It can even explain why SUA occurred in vehicles having mechanical throttles if they had fuel-injected engines instead of engines with mechanical carburetors. This is because fuel-injected engines without carburetors must use the idle air control valve as a dashpot function to prevent the vehicle from slowing down too rapidly when the driver releases the accelerator pedal in preparation for stopping – a feature that was included on all carburetors prior to fuel injection, but eliminated when carburetors were replaced by fuel injection. And this dashpot function must operate not just at idle RPM, but also at high engine RPM's, to prevent the engine speed from dropping too rapidly when the driver releases the accelerator pedal at high speeds while slowing down the vehicle. This means that the idle air control valve must behave just like an electronic throttle, with opening commands issued from a setpoint table having inputs from the engine RPM. And, just like an electronic throttle, it is sensitive to the battery voltage and must be compensated for low battery voltage when controlled by a setpoint table. This makes it susceptible to errors while sensing the battery voltage during a negative voltage spike. The result is that vehicles with fuel injected engines and mechanical throttles can experience sudden acceleration without a driver pressing on the accelerator pedal in exactly the same way as discussed above for vehicles with electronic throttles.

This theory can explain sudden unintended acceleration in all makes and models of vehicles having electronic throttles or idle air control valves with fuel-injected engines. Specifically, the theory applies to the following vehicle types:

1) all Toyota vehicles with electronic throttles,
2) all Jeep Cherokee vehicles with electronic throttles,
3) all Ford F-150 trucks with electronic throttles,
4) all BMW vehicles with electronic throttles,
5) all Hyundai vehicles with electronic throttles,
6) all Kia vehicles with electronic throttles,
7) all makes and models of vehicles with electronic throttles from all manufacturers,
8) all Mitsubishi Montero Sport vehicles with common rail diesel engines and VGA turbochargers,
9) all Audi 5000 vehicles with idle air control valves and fuel injected engines.
10) all makes and models of (pre-CY2004) vehicles from all manufacturers having idle air control valves and fuel injected engines.

It is recognized that some sudden acceleration incidents may be attributed to causes other than the proposed mechanism, such as sticky accelerator pedals, sticky throttle valves, sticky mechanical linkages between accelerator and throttle valve, moving floor mats pressing on the accelerator pedal, and even to some drivers pressing on the accelerator pedal instead of the brake pedal. But it is believed that a large number of cases in which the driver claims that the accelerator pedal was not pressed during the sudden acceleration incident can be explained by this mechanism. This may even include some incidents in which the drivers thought they caused the incident by pressing wrongly on the accelerator pedal when, in fact, they were indeed pressing on the brake. (The author believes that most people are truthful when describing their actions during a sudden acceleration incident, and that many people will acknowledge they were at fault even when they were not, merely because they have no alternative explanation for the incident other than someone pressing on the accelerator pedal).

A knowledgeable reader may ask why the battery voltage is important for actuator operation when the supply voltage powering the actuators is actually set by the car's alternator, and not the battery. The answer is that the alternator only sets the supply voltage to about 13.8 volts when the engine speed is above about 1500 RPM. It does not set the supply voltage while the engine is running below about 1500 RPM because at lower speeds the current in the alternator's primary winding is too small to generate a regulated voltage output. In this case, at lower engine RPM's the battery voltage sets the supply voltage and not the alternator voltage. So at low engine RPM's, if the battery voltage goes below 12.6 volts, the supply voltage will also go below 12.6 volts, causing actuator performance to be reduced. This same dependence of supply voltage on engine RPM is what makes one's headlights dim sometimes when the car is at idle and the battery voltage is low, or why a high-power boom-box amplifier can cause the headlights to dim even at engine speeds above idle. In these cases, the accessories require more current than the alternator can supply at low engine RPM's, so the battery must supply the remaining current.

Battery voltage is also important in a more subtle way. Most actuators on the car must respond to changes in their inputs within about one millisecond in order to satisfy the needs of the engine control system. But the alternator can respond to changes in current demand only on the order of about 200 milliseconds as a result of the L/R time constant of the alternator's primary winding. Therefore, when the actuator is suddenly turned on by a changing actuator input, causing the actuator's current demand to increase, the supply line gets pulled down to the battery voltage because the battery must supply the actuator current until the alternator's current output can increase. If the battery voltage is a normal 12.6 volts, then the actuator can respond within one millisecond to changes in the input, as needed by the design of the control system. But if the battery voltage is below 12.6 volts, then the actuator response becomes slower, and may become too slow for the needs of the engine control system. This can lead to faulty engine operation.