Self-driving cars and SUA accidents: a very clear understanding of the factors that increase the likelihood of serious accidents in technologically advanced cars

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ABSTRACT

The implementation of a safety interlock mechanism in the operation of cars using an internal combustion engine and an automatic gearbox in the late 80's has been proven to substantially improve road safety, by forcing the driver to press the brake pedal before being allowed to start the car or select forward or reverse gear. Sudden Unintended Acceleration accidents due to driver error (pedal misapplication) were mitigated to a point of being rare and not brand- or model-specific.

In the last few years, the advent of very powerful -but silent in operation- electric cars has brought a new wave of SUA accidents, with the new technology of electric motors and power controllers initially being suspect of software or hardware malfunctions. Following petitions and accident reports, the NHTSA has recently arrived to the verdict that from more than 200 different SUA cases involving Tesla cars, each and every one of them can be attributed to driver error (pedal misapplication), finding no indication of any malfunction in the car itself. Further to this, NHTSA states that "*There is also no evidence of a design factor contributing to increased likelihood of pedal misapplication."*

Well, maybe there is.

By combining Neuroscience and Control Systems Engineering in order to better understand the mechanism behind "driver errors" of young, healthy and competent drivers, we have found very specific patterns that repeat themselves in almost every one of these SUA accidents, all pointing to the same cause of possible confusion and the same lack of appropriate pre-emptive measures in the programming of the Human-System Interface of modern self-driving cars.

INTRODUCTION-KEY CONCEPTS

Research in the field of cognitive neuroscience is mainly focused on effects of advanced age or on rehabilitation from injuries or specific medical conditions. In the field of automotive safety, research in cognitive neuroscience has investigated the effects of sensory overload, of advanced age and of diminished performance due to drugs, alcohol or medication. In the last few years, there have been a lot of reports in the press here a young, healthy and competent driver is involved in a Sudden Unintended Acceleration accident that often leads to serious injuries or fatalities. The investigation into these accidents has failed so far to find any causes other than "driver error" (NHTSA Denial of Petition submitted on December 19, 2019)[1], but no one has been able so far to answer two important questions on the matter:

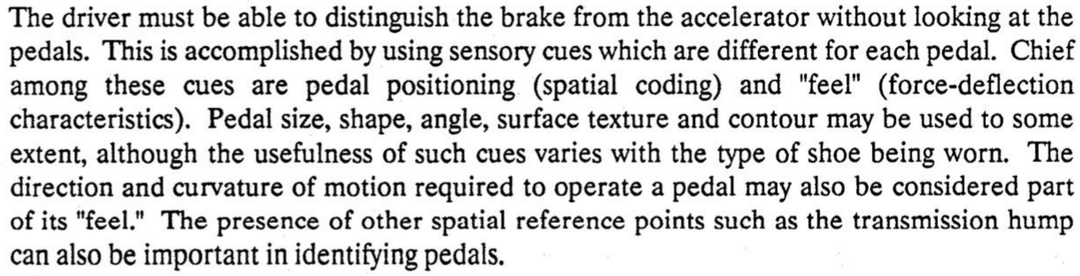
-What causes so many young, healthy and competent drivers to make such unexplainable unforced errors, driving very technologically advanced cars that by definition should be safer than older cars?

-Out of the more than 200 accidents recently investigated by the NHTSA, the vast majority happened during parking maneuvers or when the driver was slowing down and about to stop. Is there a cause behind this clear pattern of circumstances?

Proprioception (or kinesthesia) is the sense that lets us perceive the location, movement, and action of parts of the body. Not to be confused with Proprioceptive Feedback (which provides a neural representation of body mechanics to the central nervous system), proprioception is the sense that allows us to bring a glass of water to our lips in total darkness, without actually having to see. It is something very important for all athletes and a key quality for ballet dancers, acrobats or performers. Good proprioception can be explained as "I can move my body with absolute precision".

Many psychologists and researchers that have worked on the field of automotive safety, believe that proprioception is the mechanism that leads to correct pedal application, which means that all car drivers have already trained themselves that "left pedal=brake, right pedal=accelerator" and they consciously move their foot to the left or to the right accordingly when they want to brake or accelerate.

In the 1989 NHTSA "An Examination of Sudden Acceleration" report by J. Pollard and D. Sussman [2], it is recognized that "the driver must be able to distinguish the brake from the accelerator without looking at the pedals" and offers the theory that this is accomplished through proprioception and feel:



> The driver must be able to distinguish the brake from the accelerator without looking at the pedals. This is accomplished by using sensory cues which are different for each pedal. Chief among these cues are pedal positioning (spatial coding) and "feel" (force-deflection characteristics). Pedal size, shape, angle, surface texture and contour may be used to some extent, although the usefulness of such cues varies with the type of shoe being worn. The direction and curvature of motion required to operate a pedal may also be considered part of its "feel." The presence of other spatial reference points such as the transmission hump can also be important in identifying pedals.

Under this explanation that is also accepted by other researchers (Wu, Boyle, McGehee et al. 2017 [3], Lococo et al, 2012 [4], Rufus et al [5], etc), variations in body position and foot position before the initiation of pedal application may cause a driver to miss the intended pedal and apply the accelerator instead of the brake, classifying this mistake as error of response execution, which involves selecting an appropriate response but carrying it out inadequately or incorrectly (R. Schmidt, 1989)[6]:

> *There is strong support for the view that the right foot contacts the accelerator even though the driver fully intended to press the brake because of inconsistency in foot trajectory generated by spinal- or muscle-level variability. There is considerable evidence that the variable, inconsistent processes that generate muscular forces and their timing are the source of these errors.*

This explanation of pedal misapplication errors, although definitely valid in many actual cases of accidents (there is no single cause and mechanism that covers every PM accident, for example R. Schmidt in his 2010 paper with D. Young [7], revisits the initial question of 1989 and now describes "**two different classes of accidents**" (with the discerning factor focused on whether the driver realizes and admits his mistake or not), fails to explain why, sometimes, a young, healthy and competent driver continues to press the accelerator pedal for several seconds while the car is speeding up and repeatedly crashing into cars or stationary objects, not realizing his mistake while it is happening and not even in his statements in the aftermath of an accident.

Having recognized a second and distinct type of SUA/PM accident, fundamentally different to the older "missing the correct pedal" accident, we now need to specifically concern ourselves with the analysis of this potentially very dangerous situation.

In order to try and explain this bizarre phenomenon, we would like to add an additional layer of understanding in the different ways that a driver can gather and process information in order to operate the different controls of a vehicle, still using neuroscience and introducing Control Theory concepts from the field of Control System Engineering.

From an engineer's point of view, open-loop control is when the control action from the controller is independent of the "process output" (or "controlled process variable"). An example of open-loop control in automotive engineering is found in the old carburettor petrol engine. A carburettor is a device that controls the mixture of air and fuel entering the engine and it is set up to proportionally follow the commands of the accelerator pedal, i.e. "half pedal=half power". There is no feedback in this system, so it is unable to compensate for bad fuel, very hot or very cold weather or any other disturbance.

A more advanced method is closed loop control, where the control action from the controller is dependent on the process output. The output of the system is fed back through a sensor measurement to a comparison with the reference value, so that the controller can readjust to minimize the error (difference) between the reference and the output. Instead of a mechanical carburettor, modern cars use an electronic fuel injection system that take the pedal position as a “request” (as a reference value) and constantly adjust the amount of fuel injected according to the information from the various sensors (temperature, air pressure etc) that is fed back to the controller in order to save fuel, lower emissions and ensure smooth running in all weather conditions.

If we consider the human body as a very complex control system, classified as MIMO (Multi Input, Multi Output), using the central nervous system and the brain as inputs and processing and the musculoskeletal system for its outputs, we can use engineering terms to describe various simple decision making processes or more complex control actions.

For example, the task of throwing a basketball and trying to score a point is a clear example of open-loop control. By the time that the ball leaves our hands, there is nothing to correct its trajectory, so we need the “skill” that we have built by past experience and training and the success of the shot is based on proprioception. If we consider the different actions required to drive a car, an example of open-loop control would be found in shifting gears with a semi-automatic gearbox that uses a pair of electrical switches in the form of paddles mounted on the steering wheel of a car. In this particular setup, we need to deliberately train ourselves in a new human-car interface where we have to press the right paddle to select a higher gear and the left paddle to select a lower gear. There is no feedback, no tactile or optical cues, you have to learn by heart “left paddle-down, right paddle-up”. At the same time, the task of steering the car around a bend is one of the best examples of closed-loop control: we start to turn the wheel towards the intended direction but we don't know when to stop turning the wheel, we adjust the steering angle by observing the results as they happen (position of the car on the road) and compensating in real time as required. An important observation from this example is the fact that any driver can easily drive any new car without any training or practice, no matter how fast or slow the gearing of the steering rack is. Older cars lacking assisted steering have slow and heavy steering systems that require almost 4 full turns from lock to lock and a modern sports car might only need less than 2 full turns. A cart or a racing single-seater car is even quicker in steering, only requiring less than one full turn from lock to lock, but all these different steering angle requirements pose no problem to the driver who can use the closed-loop feedback to immediately adjust to the new steering gearing.

As another example of closed-loop control, let's consider the task of balancing a serving tray, randomly loaded with different glasses of drinks. Each time we pick up the tray, the total weight, the center of gravity and the mass moment of inertia of the loaded tray are never the same as the last time that we picked it up. In order to balance it successfully and walk with it, we need to create a closed-loop feedback process through both tactile and optical cues so that we react to any disturbance, including random events like wind blowing across, someone bumping into us or having to negotiate stairs and tight places. For a young, healthy and competent person, this is obviously a simple task that can be successfully completed without any specific training or any specially developed motor skills. We shall leave it to neuroscientists to research the limits of performance in this task when dealing with very young or very old age or with specific disabilities and medical conditions, since our research is solely based on properly licenced adults fit to drive a car. For this specific demographic, the example of carrying a loaded tray is familiar and self-explanatory to anyone wishing to understand how closed-loop control works with the human brain as controller.

It is interesting to note that open loop control needs time and training for more complex tasks like touch typing, but closed loop control is much quicker and easier to implement: you just need to respond to optical or tactile cues and act accordingly. For example, driving a small city car, immediately after driving a large heavy truck: steering feel, braking effort and braking performance are much different between the two vehicles, but the driver does not really need to train for the different steering gearing or the different pedal response and different effort required, he only needs to follow the feedback from his eyes and his CNS in order to adjust to each vehicle and steer and brake with absolute precision, no matter what size and type of vehicle he is driving.

HUMAN OPEN LOOP CONTROL	***HUMAN CLOSED LOOP CONTROL***
Throwing a basketball	*Gently braking to a standstill in a car*
Playing darts	*Steering precisely a fast moving car*
Touch typing	*Operating heavy machinery (e.g. excavator)*
Operating the turn indicators of a car	*Flying a helicopter (more important than any other craft or vehicle...)*

So, if we revisit the original issue raised by Pollard and Sussman in 1989 [2], we would suggest that "the driver must be able to distinguish the brake from the accelerator without looking at the pedals" maybe not by proprioception and feel, but actually by closed-loop feedback control:

- the driver presses the brake pedal to start the car and the control sequence resets and starts to work in an unbroken sequence of direct feedback
- the driver consciously decides to press the accelerator pedal in order to move off and start his route
- after a minute of driving and after adjusting the speed of the car by occasionally alternating between accelerator and brake, the driver is no longer consciously thinking about which pedal to press
- at any given moment, the driver knows which pedal is activated, by the direct feedback of the closed-loop control sequence: "if I touch the pedal and the car accelerates, then my foot is on the accelerator" and "if I touch the pedal and the car decelerates, then my foot is on the brake pedal".

As long as this feedback loop sequence remains active and unbroken, it is extremely unlikely for someone to make a pedal misapplication error.

Or, if we rephrase this important point:

In order for someone to make a pedal misapplication error of the specific type that is not recognized immediately and not admitted afterwards, breaking the feedback loop by removing the foot from the pedals for at least a few seconds, is a necessary condition.

METHODS

In order to better understand the actual causes of increased risk of pedal misapplication, we will follow a three step process:

1. We will examine available accident and research statistics to verify that a pattern of circumstances can be established.
2. We will use proof-of-concept tests to explain the cognitive control mechanism that requires an unbroken sequence of closed-loop feedback in order to avoid confusion and driver error.
3. We will investigate the lack of linearity that is introduced by specific features of self-driving cars and the risks of breaking the sequence of closed-loop feedback of foot controls, especially without proper driver training and without software interlocks and safeguards.

1. Statistics:

We shall not try to provide general statistical data on the SUA instances around the world versus total population of cars on the road, versus total kilometers covered, versus year or versus brand and model, the reason being is that there isn't a robust universal system of reporting and recording relevant statistics. In particular, we can note that:

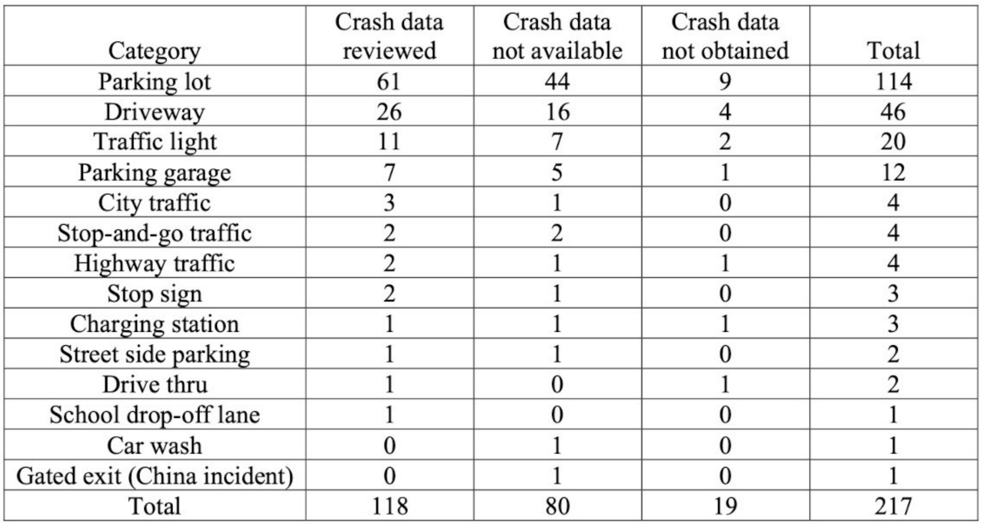
➔ Only very serious accidents with fatalities or serious injuries are properly reported to the authorities and recorded in official statistics. Many more are not reported, recorded or classified properly when they only involve damage to property.

➔ SUA is not an official and universal classification for every country and every jurisdiction, so all available data come from voluntary reports, mostly in the USA and with the Office of Defect Investigation (ODI) of the National Highway Traffic Safety Association (NHTSA).

➔ Published statistics showcasing the safety of specific brands have been criticized as not being scientifically accurate and there is no way to independently verify or correlate unverified data and statistics from such sources.

A useful source of SUA accident records comes from the ODI/NHTSA petitions and its relevant reports. For example, in the January 8, 2021 Denial of Petition submitted on December 19, 2019, by Mr. [redacted] [redacted] to NHTSA's Office of Defects Investigation (investigation nr DP 20-001) [1] we read that out of a total of 246 incidents that were investigated:

> *ODI's crash analysis reviewed 217 incidents, including the 203 crashes identified by the petitioner and 14 additional crashes reported in VOQs that were either not selected by the petitioner (8) or were submitted after the petitioner's most recent submission (6).*
> *Six of the crashes reported by the petitioner were assessed by ODI as unrelated to SUA. These include all four of the crashes occurring in highway traffic, one crash at a traffic light and one of the driveway crashes.*
> *All of the remaining 211 crashes, assessed by ODI as related to SUA, occurred in locations and driving circumstances where braking is expected. Eighty-six (86) percent of these crashes occurred in parking lots, driveways or other close-quarter "not-in-traffic" locations.*
> *Almost all of these crashes were of short duration, with crashes occurring within three seconds of the alleged SUA event.*



Category	Crash data reviewed	Crash data not available	Crash data not obtained	Total
Parking lot	61	44	9	114
Driveway	26	16	4	46
Traffic light	11	7	2	20
Parking garage	7	5	1	12
City traffic	3	1	0	4
Stop-and-go traffic	2	2	0	4
Highway traffic	2	1	1	4
Stop sign	2	1	0	3
Charging station	1	1	1	3
Street side parking	1	1	0	2
Drive thru	1	0	1	2
School drop-off lane	1	0	0	1
Car wash	0	1	0	1
Gated exit (China incident)	0	1	0	1
Total	118	80	19	217

Table 1. Summary of crash incidents reviewed by ODI.

According to the same report:

> *The data clearly point to pedal misapplication by the driver as the cause of SUA in these incidents. Analysis of log data shows that the accelerator pedal was applied to 85 percent or greater in 97 percent of the SUA crashes reviewed by ODI. Peak accelerator pedal*

> *applications were initiated within two seconds of the collisions in 97 percent of the cases. Analysis of brake data showed no braking in 90 percent of SUA crashes and late braking initiated less than one second before impact in the remaining 10 percent. The pre-crash event data and driver statements indicate that the SUA crashes have resulted from drivers mistakenly applying the accelerator pedal when they intended to apply the brake pedal. Approximately 51 percent of the crashes occurred in the first six months of the driver's use of the incident vehicle.*

To the above mentioned cases, we could add a few other instances of serious accidents under similar situations, as reported in the press:

-a Tesla Model 3 fatal accident in Paris, France on December 11, 2021:

> *A driver lost control of his Tesla on Saturday night in the south-eastern 13th district of Paris, killing one person and injuring 20, leaving three people in intensive care.*

-a fatal accident in Chaozhou, Guangdong in China:

> *On November 13, 2022, Jimu News reported that when a man was driving a Tesla vehicle in Chaozhou and preparing to stop, the vehicle lost control and accelerated. The vehicle traveled 2 kilometers at high speed, knocking down two motorcycles and two bicycles, killing two people and injuring three others, according to the report.*

-an accident in Pasadena, USA on January 10, 2023:

> *Pasadena Fire Dept.@PasadenaFD*
> *PFD and PPD are on scene 700 blk. west California Blvd. A Tesla driver hit the accelerator instead of the brake, drove through a wall and into a pool. Three occupants in vehicle including a child. Good samaritans jumped into the pool and rescued the occupants.*

-an accident in Mayagüez, Puerto Rico, August 2019

> *On Saturday, August 10, 2019, a strange vehicular accident occurred on Calle de laCandelaria, former street McKinley, Mayagüez, in front of the bakery massa bakery.*
> *The driver of a Tesla Model X electric car was parking, when suddenly it sped up, initially impacting a pick-up truck.*

-a fatal accident and a similar minor accident in South Korea, both inside parking garages (December 2020 and May 2022)

> *The Model X crashed into the wall of the parking garage of an apartment complex in Yongsan District, central Seoul, then caught fire, on Wednesday. This led to the burning death of the car's owner, who was in the passenger seat.*
> *The driver, who escaped with injuries, claimed "the car suddenly got out of control," raising the possibility of a sudden unintended acceleration as the cause of the accident, according to police.*

-at least two minor SUA accidents that have happened in Greece under similar circumstances in November 2022 (reports from autotriti.gr, newsauto.gr)

Many others from around the world probably remain unreported or unclassified, because a minor accident involving only damage to property would not have been reported specifically as SUA, especially if insurance covers all damages and the driver does not seek any further legal action.

Of all the above mentioned accidents, the clear pattern of circumstances is that they all happen as the car is moving in very slow speed and the driver is about to stop or park the car.

2. Proof-of-concept test: learning to drive with hand controls

Disabled drivers who cannot rely on their lower limbs to operate the pedals of a car, can still drive using specially modified cars with hand controls for every control action required. Instead of a pedal for accelerating the car and a pedal for braking, these cars use a single hand lever operating in a push-pull fashion, where pulling the lever operates the accelerator and pushing the lever operates the brakes.

This is a classic example of closed-loop control when examined from a cognitive neuroscience point of view (i.e. considering the human brain as the controller). The driver pushes and pulls a hand lever and adjusts the travel and the force according to real-time feedback from optical and vestibular system cues, in order to accelerate or brake the car smoothly and precisely.

As a proof-of-concept test, a Toyota Yaris with a petrol engine and automatic transmission, equipped with hand controls for the use of a disabled driver, was used to test the new way of driving a car in real world conditions. With absolutely no previous experience, training or familiarization, the author was very quickly briefed on the new controls and immediately started the car and drove away, operating the car with new and totally unfamiliar controls for the accelerator and the brake. After a few minutes of driving around quiet urban and semi-rural roads, it was clear that driving with hand controls is easier than one would think, with the important observation being that you need to be constantly moving and operating the lever in order not to get confused. If you stop at a traffic light and you take your hands off the controls for a minute, then you need a brief moment of "mental reset" to consciously push the lever to activate the brake and engage forward gear, starting again the unbroken sequence of closed-loop feedback control while on the move.

Interestingly, during this brief test, we found it almost impossible to remember how to operate the new switch setup for the headlights and the turn indicators, a seemingly easy task that proved to be much harder than accelerating and braking!

A Toyota Yaris equipped with hand controls was used for our proof-of-concept test. We found it very easy to learn to drive the car with the single push-pull hand lever (closed-loop control) but much more difficult to learn to operate the turn indicators, the headlights and the windshield wipers (open-loop control).

This proof-of-concept experiment (that can be easily replicated by anyone with access to a car equipped with hand controls for disabled drivers) proves that there are two entirely different processes in action at the same time: a closed-loop feedback control loop (operating the accelerator and brake using a single push-pull hand lever) that is surprisingly easy and quick to master, as long as the driver does not break the sequence of input-output-feedback and another open-loop control system running in parallel, where the driver has to learn a new set of controls for the turn indicators, the headlights, the windshield wipers etc, which is almost impossible to master immediately and without enough training and repetitions.

3. Lack of linearity

The author was asked to investigate a minor SUA accident involving a Tesla Model Y in Athens, Greece, where the car was approaching its usual parking spot in front of an office building. Examining the footage from a security camera overlooking the parking spot, the car can be seen slowly approaching and turning slightly towards the point where it would be expected to stop, select reverse gear and back into the parking space. The brake lights of the car can be seen turning on at about 2-3 meters before suddenly the car lurches forward and speeds across the road before crashing against a low wall.

The driver was adamant that the car took off by itself while he tried to brake without effect. During our interview, he was asked to narrate his actions as recorded on the security camera footage and in reference to the brake lights coming on just before the SUA event. He replied that "I don't brake with my foot because I don't have to, the car understands that I am about to park and brakes automatically, I only have to select reverse gear with the lever on the steering wheel and everything else is automatic, this is how I do it everyday for the past 6 months that I have been driving this car and parking at this same spot".

This was an important breakthrough in this investigation, also because of the particular choice of words: he said "I don't have to" or "it is not necessary" ("δεν χρειάζεται" in greek), indicating that he absolutely believed that he was operating the car properly and exactly as he should, not overriding or ignoring a safety feature and not deviating from common sense and good practice. Also, the nuance of his statement is that he seemed to appreciate and enjoy the advanced features that his new car offered.

A few days later there was another report in the greek press about another minor accident that apparently happened as a Tesla car was approaching a red light in slow-moving traffic and instead of stopping, it lurched ahead and crashed into another car.

A further investigation into a possible pattern behind these SUA accidents brought into our attention similar accidents from various NHTSA investigation reports.

For example, NHTSA complaint 11206155 [1] alleges that a 2018 Tesla Model 3 experienced an SUA event resulting in a crash in the owner's driveway on the evening of May 6, 2019. The complaint states that:

> *"[The driver] turned into [the driver's] driveway and was going to pull into [her] garage to park the car, when the car accelerated suddenly and violently and crashed into the front stone wall of [the] house. The stone wall is damaged and the front right side of the Tesla has significant damages." The driver alleges that the SUA event occurred after the vehicle was "slowed to a halt" and while the driver was "waiting for the garage door to fully open."*

In a July 11, 2019 letter, Tesla provided the consumer with the following summary of its analysis of log data for the crash event reported in VOQ 11206155:

> *"According to the vehicle's diagnostic log, immediately prior to the incident, the accelerator pedal was released, regenerative braking was engaged and slowing the vehicle, and the steering wheel was turned to the right. Then, while the vehicle was traveling at approximately 5 miles per hour and the steering wheel was turned sharply to the right, the accelerator pedal was manually pressed and over about one second, increased from approximately 0% to as high as 88%. During this time, the vehicle speed appropriately increased in response to the driver's manual accelerator pedal input. In the next two seconds, the accelerator pedal was released, the brake pedal was manually pressed, which also engaged the Anti-Lock Braking System, multiple crash-related alerts and signals were triggered, and the vehicle came to a stop."*

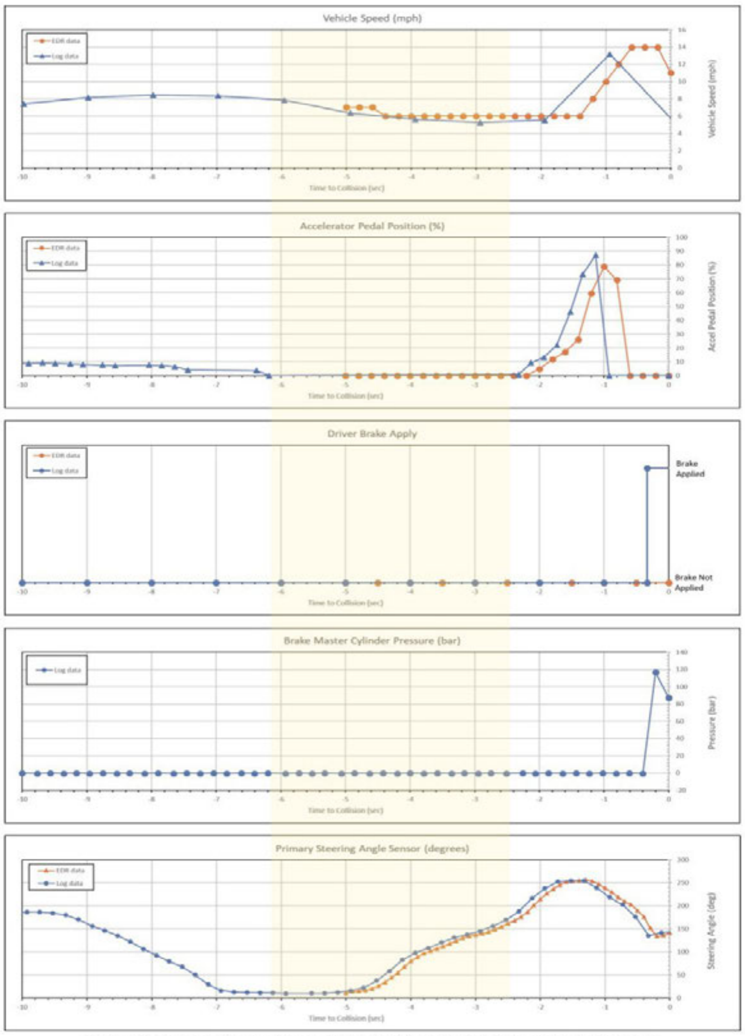


Figure 1. Pre-crash operator control data, from top-to-bottom: vehicle speed, accelerator pedal position, brake pedal application, brake master cylinder pressure, and steering angle.

Feet-off coasting for 3.5sec (yellow area), enough time for confusion and increased likelihood of pedal misapplication.

In the graphs that are included in the report, we can clearly see that as the car is approaching at a very low speed and turning towards the garage, there is no actuation of the brake pedal as it would be normally expected from a driver slowing down and preparing to stop and park the car. The driver turns the wheel and the car is turning and pointing towards the garage door, but the driver still does not apply the brake (at t=-4-5 sec), presumably because he is expecting the automatic brake of the car to operate and fully stop the car (but the car is still coasting as the Autopilot has not decided yet to stop) . At t=-2sec he has arrived at the point that has to stop or he will hit the garage door, but instead of brake application we observe the accelerator pedal being applied instead. Why didn't he brake earlier as normally expected? Probably because he believed that “he didn't have to”, exactly like the greek driver mentioned before.

Automatic braking tests

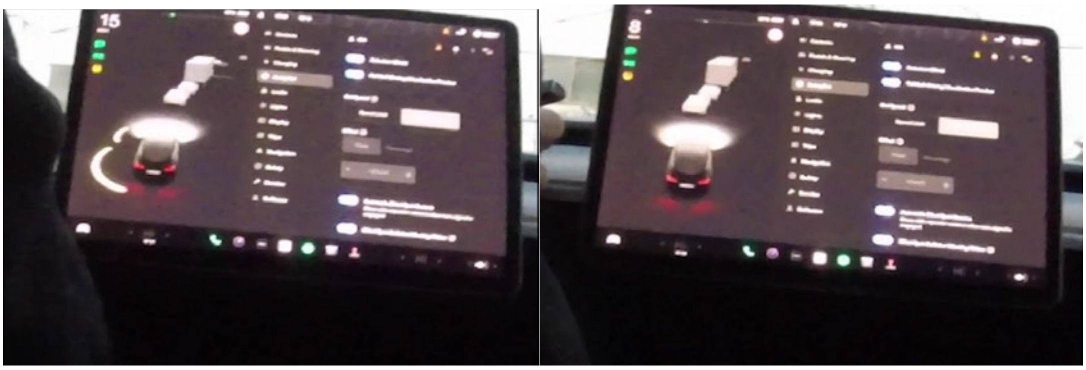
In order to evaluate the non-linear response to inputs and events of self-driving cars, on December 2022 we used a standard Tesla Model Y registered to a local rental car agency in a test drive around the urban and semi-rural streets of the northern outskirts of Athens, Greece.

The test was recorded on video and our observations are listed below:

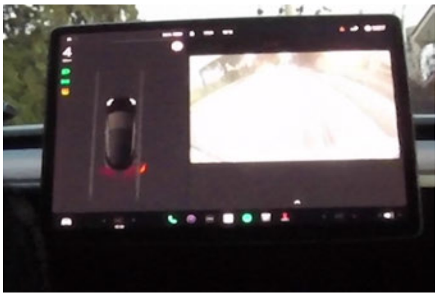
- ➔ Driving along a wide one-way street and doing 50kph, we lift our foot entirely from the accelerator pedal and we observe the car coasting straight ahead and decelerating gently.
- ➔ Driving along a narrow one-way street with parked cars left and right and doing about 40kph, we lift our foot entirely from the accelerator pedal and we observe the car reducing

speed by itself when we approach an intersection and coming to a complete stop just before the intersection, with the brake lights illuminating accordingly.

- Driving slowly along a wide street with randomly parked cars on the right side, we lift our foot entirely from the accelerator pedal and while coasting at about 20kph we turn the wheel towards the parked cars, observing the car to gently slow down by itself (with the brake lights illuminating accordingly) before we press the brake pedal to safely stop.
- Driving very slowly along a wide street with randomly parked cars on the right side, we lift our foot entirely from the accelerator pedal we turn the wheel towards the parked cars and we select Reverse gear on the move without touching the brake pedal, observing the car stopping by itself before we push the accelerator pedal to creep backwards in reverse gear and park the car, without ever touching the brake pedal.



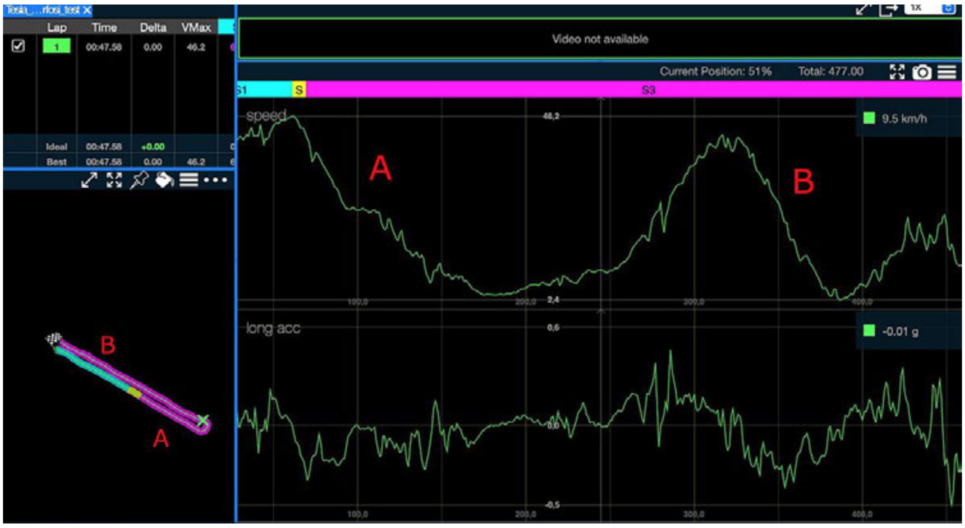
We turn the wheel towards a row of parked cars and the car automatically activates the brakes to slow down without any pedal input. This is not AEB (Automatic Emergency Brake) but normal smooth braking from 15 kph in anticipation for a parking manoeuver.



Driving very slowly forward, we select reverse gear without pressing the brake pedal. The car slows down, stops and selects reverse gear, waiting for the accelerator pedal input to move backwards.

It is clear that the Autopilot software “decides” to either coast, reduce speed or brake to a complete stop, according to the perceived road conditions at any given moment.

These tests were repeated on February 2023 with a different Tesla car so that we could install an external motorsport data logger (VBOX Sport by Racelogic Ltd) and record speed and acceleration data, obtaining detailed graphs that document our observations, i.e. the stochastic nature of the Autopilot response to various road conditions. Even if we drive around the same block multiple times, the deceleration is never constant and never the same as last time.



	Lap	Time	Delta	VMax
☑	1	00:47.58	0.00	46.2
	Ideal	00:47.58	+0.00	
	Best	00:47.58	0.00	46.2

Driving back and forth on the same straight and level two way street, we lift off at about the same initial speed (45kph) but observe a different speed and deceleration graph, probably because the Autopilot evaluates sections A and B as dissimilar.

Simulating pedal misapplication?

It is very difficult to simulate such a rare occurrence of a driver error that might only happen once per thousands of kilometers of everyday driving, and especially as the particular error is not attributed to any factors such as workload, sensory overload, tiredness etc but it is probably due to momentary lapse of concentration, what in layman's terms could be called absent-mindedness or daydreaming. Various researchers have tried to simulate pedal misapplication errors (e.g. Rogers and Wierwillem 1988 [8] and Hasegawa et al, 2021 [9]) but it is clear that s is not easy at all to obtain meaningful data, especially when dealing with young, competent and fit drivers that know that they are being tested for performance, so it is impossible to relax to the point of the onset of absent-mindedness. Despite all this, it is interesting to note that the author has managed to actively confuse himself during real road tests, even if for only a split second, by entirely withdrawing the right foot from the pedals of the Tesla car and then steering the car towards a row of parked cars. The sensation of the deceleration of the car (due to automatic braking) combined with a loss of tactile feedback from the pedals, created a very brief panic feeling of “what is happening now?!!!” that gave us an insight of the disorienting effect of such a situation that may confuse an unsuspecting driver.

RESULTS

Following the three-step process outlined above:

1. We have established a pattern of SUA accidents attributed to pedal misapplication and it is clear that driver error in modern self-driving cars almost always happens in very similar circumstances, i.e. preparing to stop or park the car.
2. We have explained the mechanism of subconscious closed loop feedback control and demonstrated an actual example using a proof of concept test.

We found that it is easy to master a critical skill as accelerating and braking a real car in real road conditions using a totally new and unfamiliar set of hand controls, while at the same time it is much more difficult to master simple tasks like operating the windshield wipers or the turn indicators. Understanding this distinction between open-loop and closed-loop control and understanding the specific mechanism of closed-loop control, we can conclude that the most important requirement for avoiding pedal misapplication is the unbroken sequence of inputs and observations that form a closed-loop feedback control system. When the sequence is broken for any external reason, the driver/operator needs to consciously and deliberately reset the input/observation sequence, for example (in the case of pedal operations considered here) by briefly tapping the brake pedal.

It should be noted here that he new one-pedal regenerative braking operation of electric cars does not break the sequence of closed loop feedback control when used correctly (i.e. with the foot

always poised over the accelerator pedal). Every input on the accelerator pedal (positive or negative) always corresponds to the same output (the driver observes the car to react always in the same immediate and linear acceleration or deceleration). Research in this new one-pedal operation and possible driver errors has identified different types of errors (Rufus et al., etc).
It is important to make the distinction that the function of automatic braking in self-driving cars has an entirely different principle of operation. Our test results have proven the stochastic nature of the brake application of a Tesla Model Y car and the lack of linearity of control input vs output.

As a side note, that automatic braking is not to be confused with AEBS (Automatic Emergency Braking System), a system that is starting to be implemented in many new cars and it is meant to protect the driver from crashing into a stationary or slow-moving vehicle straight ahead by cutting the accelerator and operating the brakes. This is an emergency system that is only activated just before a possible crash and it does not interfere with normal driving.

3. We have established that Tesla cars operate the brakes of the car in a non-linear way when examined against pedal inputs, automatically and stochastically applying various degrees of deceleration according to the perceived road conditions and their evaluation and interpretation by the Autopilot software, even if the car is not in “full self-driving mode”. This introduces a potentially confusing situation of “shared control”, where it is not absolutely clear if the driver is responsible to stop the car or if the Autopilot will do it instead. Also, the feature of automatic braking gradually encourages a novel “feet off and trust me” way of driving that is not observed in any other type of electric or ICE car in the particular circumstances noted above (i.e. preparing to stop and park the car).
We have also established that Tesla cars allow drivers to select reverse gear while still driving forward and without a requirement to activate the brakes, thus removing a safety feature very similar to the brake pedal interlock system that has proved very successful in mitigating early SUA accidents in the 1980's.

DISCUSSION

The research on SUA accidents has started in the 1980's after the apparent increase of such accidents in automatic cars while they start up and during selection of forward or reverse gear. In a 1989 NHTSA report by J. Pollard and D. Sussman titled “An Examination of Sudden Acceleration” [2], we find the recommendation of installing safety interlocks in all new cars, a recommendation that was implemented by the industry in the form of Brake Transmission Shift Interlocks.

> *A BTSI device requires a driver to depress the brake pedal to shift an automatic transmission out of the “park” position. BTSI devices have a significant effect on sudden acceleration incidents; comparisons of accident or complaint data between vehicle models with and without BTSIs indicate that interlock systems result in a dramatically lower rate of sudden acceleration. For example, a NHTSA comparison of sudden acceleration incidents for three automobile models indicated much lower rates for the models equipped with interlocks: 1.7 vs. 16.6 per 100,000 cars for the Ford Aerostar, 4.1 vs. 15.0 per 100,000 cars for the Lincoln Town Car, and 2.9 vs. 17.3 per 100,000 cars for the Ford Thunderbird/Cougar (U.S. Department of Transportation, National Highway Traffic Safety Administration, “Denial of Motor Vehicle Defect Petition, DP99-004,” Federal Register, vol. 65, no. 83 (April 28, 2000), pp. 25026–25037.)*

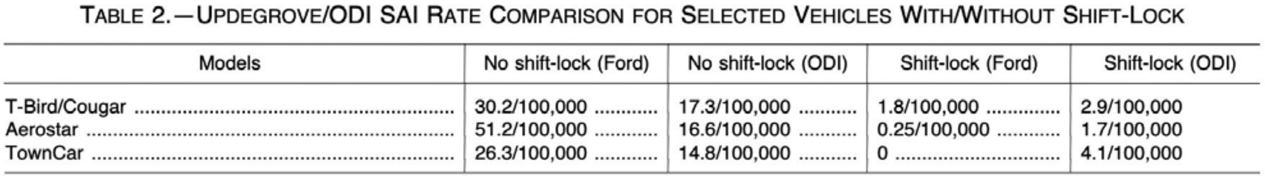


TABLE 2.—UPDEGROVE/ODI SAI RATE COMPARISON FOR SELECTED VEHICLES WITH/WITHOUT SHIFT-LOCK

Models	No shift-lock (Ford)	No shift-lock (ODI)	Shift-lock (Ford)	Shift-lock (ODI)
T-Bird/Cougar	30.2/100,000	17.3/100,000	1.8/100,000	2.9/100,000
Aerostar	51.2/100,000	16.6/100,000	0.25/100,000	1.7/100,000
TownCar	26.3/100,000	14.8/100,000	0	4.1/100,000

> *There were 168 SAI reports for Aerostars without shift-lock and 7 SAI reports involving those with the device in the ODI complaint database. This results in a report rate of*

> *16.6/100,000 vs. 1.7/100,000 Aerostars, respectively. This substantial rate decrease confirms that shift-lock devices are extremely effective at reducing the probability a SAI will occur. Shift-locks, however, cannot eliminate SAI altogether because they do not address all types of pedal-misapplications, including those where the incident was not immediately preceded by a transmission shift out of ''Park''.*

The automotive industry has known for decades the importance of an interlock device that prevents human errors that may cause SUA accidents. In 2010, the BTSI became compulsory equipment for all new cars sold in the USA:

> *Pursuant to a statutory mandate in the Cameron Gulbransen Kids Transportation Safety Act of 2007, NHTSA is placing a requirement in Federal Motor Vehicle Safety Standard No. 114 that certain motor vehicles with an automatic transmission that includes a "park" position manufactured for sale on or after September 1, 2010 be equipped with a brake transmission shift interlock (BTSI). This interlock must necessitate that the service brake pedal be depressed before the transmission can be shifted out of "park," and must function in any starting system key position. The BTSI requirement adopted by this final rule is identical in substance to the Congressional requirement.*

It is clear that the industry and the legislators decided to put safety before marketing, even if an interlock or any other safety feature might introduce minor user inconvenience. Today, it is very important to address SUA accidents that are happening again, but in different circumstances than the old 1980's accidents of automatic cars. Research has proven that SUA accidents do not only happen during start-up, as it is stated in the 2010 paper by R. Schmidt and D. Young [7]:

> *Of the accidents identified, two distinct sets of pedal errors were found: (a) 3740 accidents which were clearly caused by pedal misapplication, and (b) a non-overlapping 39 reports that were NHTSA- defined UA episodes. This represents an important finding, in that our earlier understanding of pedal errors was that they were associated mainly with the start of the driving cycle. With this evidence, it is now clear that pedal misapplications can occur frequently in several additional ways, perhaps as Rogers and Wierwille (1988) have found in simulators.*

Modern extremely powerful -but silent- electric cars pose new risks, as they lack the engine sound and the slight delay of throttle response of ICE cars.

The industry is aware of the problem and there are two different ways to face it: either proactively (installing interlocks and safeguards in order to prevent the error), or reactively (allowing the error and choosing to install a robust system that will always recognize the error and react in time).

In a June 20, 2022 Workshop on Autonomous Driving, Tesla's Autopilot Software Director, Ashok Elluswamy stated (and later posted on Twitter) that Tesla Autopilot software prevents around 40 crashes every day that would be caused by pedal misapplications!

> ***Ashok Elluswamy***
> ***@aelluswamy***
> *These predictions are already used to prevent a lot of collisions. For e.g., Autopilot prevents ~40 crashes / day where human drivers mistakenly press the accelerator at 100% instead of the brakes. In the video Autopilot automatically brakes, saving this person's legs (7/12)*

There is no way to verify the accuracy of this particular statistic, anecdotally offered in the course of a presentation without any further data or references, but it is fair to question ourselves on these obvious issues:

- ➔ If pedal misapplications are not brand- or model-specific and they happen randomly across all brands of cars, then why do we not hear of everyday SUA crashes of other brands, not equipped with the protective Autopilot software, in quantities and frequencies statistically compatible with the estimation of 40 mistakes per day among drivers of only one brand of cars?

- ➔ If these mistakes are indeed brand-specific, then why are there 40 Tesla drivers every day that make a serious mistake that does not happen to drivers of other brands of electric or ICE cars? Is there a specific demographic or other reason that makes Tesla drivers different than the drivers of other brands, or is there some design factor of the car behind this obvious statistical anomaly?

On the matter of software preventing SUA crashes, NHTSA states [1]:

> *Finally, the subject vehicles also contain Tesla's Pedal Misapplication Mitigation (PMM) software which uses vehicle sensor data to identify potential pedal misapplications and cut motor torque to prevent or mitigate SUA crashes. ODI's analysis found evidence of PMM activation in approximately 13 percent of crashes where log data was reviewed for SUA crashes. The effectiveness of the PMM activations have been limited by the fact that the original PMM implementation is designed for conditions where the vehicle is traveling straight forward or rearward toward the collision obstacle. Most SUA crashes reviewed in this petition evaluation involved dynamic steering inputs (i.e., vehicles with steering angles of 180 degrees or greater when the SUA occurs) which the original implementation of PPM was not designed to address.*

In the January 8, 2021 Denial of Petition to NHTSA's Office of Defects Investigation (investigation nr DP 20-001)[1], it is clearly stated that *"There is also no evidence of a design factor contributing to increased likelihood of pedal misapplication."* pointing out that it is not enough for a car to be "legally innocent" of software malfunctions, but the manufacturers should actually seek and implement pre-emptive strategies that mitigate the risks of human error.

It has been proven beyond any doubt that the BTSI, the Brake Transmission Shift Interlock feature of automatic gearboxes of the 80's has successfully mitigated the risk of SUA during start up and successfully trained millions of drivers to be correctly positioned in their seat and in total control of their car, pressing the brake pedal before moving off.

Today, it seems that we are moving in the opposite direction, allowing a driver to select reverse gear while still driving forward without asking for a brake pedal application as a safety feature (thus actively encouraging drivers to enjoy "feet-off automatic braking and parking"). The clear pattern of serious SUA accidents under these exact circumstances tells us that it is imperative for modern cars with self-driving features and non-linear response to driver inputs, to at least include the safety feature of the requirement of an actual brake pedal activation before allowing full stop and reverse gear to be selected. It is also clear that emerging technologies and new self-driving car features do not mix as seamlessly as one would hope with alertness and diligence still required from the human behind the wheel.

As an afterthought:

In the course of this research on automatic braking which constitutes only a small part of the fully autonomous driving package, we have come to understand that there are serious problems ahead in our quest towards fully autonomous driving with the major issue of seamless and safe handover between human driver and autopilot. It is our opinion that we cannot implement fully autonomous driving in public roads unless we have a 100% reliable and double redundant system that can be absolutely trusted in every situation, like the autopilot on a modern commercial aircraft that can be trusted to guide and automatically land the plane on a properly equipped airport. Currently (in early 2023) the self-driving packages of commercial cars are not ready to operate in a safety level comparable to aviation standards and we should always keep in mind that a car should be safe to be operated by virtually anyone with the only qualification needed is just valid driver's license. Asking the driver to "keep his hands on the wheel, just in case" is ambiguous enough to cause similar issues like the ones leading to pedal misapplication accidents. Let's not forget that there have been a lot of aviation accidents due to errors and misunderstandings in the proper handover *from autopilot to manual flying, noting that this involves highly trained professional pilots and absolutely reliable autopilot equipment, none of which is present in everyday commuting in a private car. NHTSA has published a comprehensive report on this issue (Trimble et al, 2014) [10] but in 2023 we are not any closer to dealing with the specific challenges of "shared responsibility" and seamless and safe synergy between human and machine.*

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