

Tesla Human Factors Analysis - 2017 Model X 75D



Figure 1. Model X with “Falcon Wing” doors raised.

Report Overview. This report examines the basic ergonomics, controls, displays, and overall user experience of the Tesla 2017 Model X. Applying relevant human factors concepts, it identifies user experience and safety issues. I then provide recommendations for improvement in each area. For quick reference, a short list of recommendations is provided here. Rationale and full descriptions are contained within the report.

1. Improve a driver’s understanding of the device.
 - a. Provide guidance
 - i. Video tutorials
 - ii. Searchable owner’s manual

- iii. Access to Autopilot’s “thought process” and confidence
 - b. Improve visibility of functions
 - i. How far Falcon Doors will open
 - ii. Signifiers on door handles
 - iii. Better differentiation of windshield/Autopilot stalks
- 2. Improve digital controls for quick access to common functions
 - a. Door controls on home screen
 - b. Rear view camera on home screen
 - i. Always present while in reverse
 - c. User specific customizable control bar
- 3. Enable additional functionality with cameras
 - a. 360 degree view with projected door arcs
 - b. Open trunk on approach/gesture

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Introduction.

Humans have lived with terrestrial vehicles of many varieties for thousands of years. Archeologists date the earliest wheels to the 5th millennium BCE. Transportation has always had a significant shaping effect on societies by enabling trade and often deciding wars. Modern vehicles, however, powered by engines rather than man or beast power, came about in the early 1900s, and revolutionized daily life, at least for Americans, over the course of the century. More people now own cars than houses, a fact which would be baffling just a few generations ago. Motor transportation is now ubiquitous, and lacking the ability to travel distances that would have been impossible in the past can effectively isolate a person. Like all changes, personal vehicular transportation has had both positive and negative effects on society, but one of the biggest changes is the shocking rise in mortality. As a cause of death, vehicular unintentional injuries often rank in the top ten. Many of these injuries occur, simply, because of faulty design. From incorrect mental models coupled with unexpected feedback concerning antilock brakes to poorly constrained radio systems, improved design could save lives.

Though car manufacturers are constantly developing and testing new features, their implementation with consumer-purchasable vehicles lags behind the engineering forefront of what is actually possible. Traditional automotive companies are reluctant to

introduce new technology or roll out the latest and greatest features without extensive testing. The industry follows the tradition of releasing small improvements to previous models every year. Technology for constant-speed travel (uphill or down) has been available since the early 1900s, first introduced by [Peerless Motors](#). Mechanical cruise control became electronic cruise control in the 1960s. [Mitsubishi introduced LIDAR-based ranging in the 1990s](#), but it was not widely released. [Versions of “adaptive cruise control”](#) which used radar sensors and included braking and acceleration to keep pace with traffic only became available on select, top-end models in the mid 2000s, but did not become ubiquitous (and confusingly titled) until 2018 with the integration of this long-possible technology into standard, legacy car maker vehicles.

Disruption to the old model of yearly, marginal upgrades has arrived. Bucking the cautious trends of vehicle development, Tesla has embraced the rapid implementation of cutting-edge technologies in their vehicles [since 2014](#), many of which remain in beta long after initially being released to the public. This has led, in some opinions, to unsafe practices, especially regarding design choices, as many aspects of the vehicles are not fully tested or refined while continuing to drive on the road. Without clear, time-tested design heuristics for many features, it is past time for a full analysis of the driving experience with regard to human factors considerations. The National Highway Traffic Safety Administration (NHTSA) has provided definitions on what constitutes automated driving, and [some guidance on how to implement features](#). This paper will seek to analyze the interaction and implications of design choices pertaining to the aforementioned systems and overall operation of the Tesla Model X vehicle.

I will begin with a rundown of the Tesla user base to couch the analysis. Then, I will address the primary control systems, such as steering, accelerating, and braking. I will move on to the secondary controls and discuss the user interface within the 15" infotainment system. Ultimately, I will conclude by discussing the overall driving experience and the balance of safety hazards and safety features present in the vehicle.

UPDATE: Tesla, via over-the-air update of driving firmware, has enabled features that have improved some of the flaws I identified in the original report, and I have added updates periodically to address these changes.

Front-end analysis - user-centered design and task analysis.

In any design, an early focus on the users is paramount. Examining demographics on customers from, some trends stand out, from which we can infer certain aspects. Most of the customers, who we can expect were specifically targeted by Tesla's design choices and research, are relatively successful and wealthy ([median income \\$100,000+](#), Figure 1).



Figure 2. Tesla Demographics via Teslarati.com

This suggests that they have, compared to the rest of the population, higher levels of education. Surveys also indicate that they are older, with an average age of 54, meaning that they may be less technologically native than younger generations. Still, these customers are largely interested in advanced technology, and have been persuaded by sales personnel and advertising to buy a “car of the future.” The first Tesla in-house production model launched in 2012 and many observers have likened the sleek, aerodynamic aesthetics to a spaceship. So, the prototypical user would be well-educated, older, and competent with newer technologies, as they are early adopters and have paid a high price to obtain the included features. It can be assumed that these users will fit the normal distribution of anthropometric functions, and that

normal proportions have accessibility needs, although the lack of an ability to house a wheelchair will probably negate the possibility of any users requiring hands-only operation of the vehicle.

The geographic distribution of Tesla owners is also important, as will be apparent when battery considerations and controls are discussed. Most owners live in [warm-weather states](#), predominantly California.

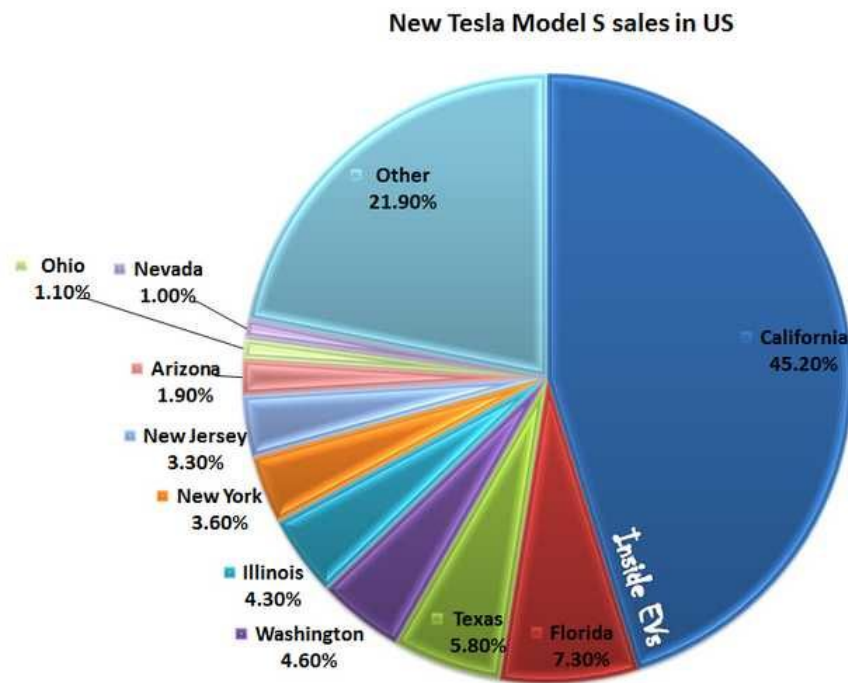


Figure 3. Tesla ownership by state. Via insideevs.com.

Texas and Florida also have higher rates of ownership. With these considerations in mind, the analysis of the systems can be viewed and assessed through the aggregate needs of these users.

UPDATE: With the debut of the Model 3, the demographics of [Tesla drivers are changing](#). The trend is a shift to younger, less wealthy drivers, although Model 3 owners

are still wealthier than most. Tesla's unorthodox designs became more pronounced in the Model 3 with the removal of a traditional dashboard all together - all driving information and most interior controls (including air vent direction) have been relegated to a 15" horizontal touch screen. This suggests that drivers who select the Model 3 are increasingly comfortable with digital interfaces, and more tech-savvy than previous buyers, who would be put off by limited physical controls.

Vehicle Ergonomics.

One of the first things that a new driver in the Model X will notice is how unique the exterior is compared to most vehicles. It is sleek, absent of even door handles. This is often confusing to new drivers and passengers. The doors are operated by depressing the silver trim, which at first brush may just appear to be extra trim. Nothing about the appearance of the control signifies that depressing it will have any effect. Observing people attempting to enter the vehicle for the first time is often an exercise in exasperation. People claw at what they think might be a handle, trying to pry it or slide it, to no effect. Some finally push on it, which is counterintuitive, which does pop the door open. A better signifier in this case, while keeping with the sleek look, might be subdued, stylistic arrows. Adding a >> << design to the handles would be subtle, and it could help new passengers figure out what to do with the "handle." When it does, if the prospective passenger is standing too close to the door, it will resist further opening - a feature designed to use sensors to prevent hitting things, but which can frustrate new users. The experienced users, on the other hand, can configure the vehicle to pop the door open as they approach, or use the fob to enter. In this way, experienced users will

likely be delighted when they “crack” the code and learn to use the entry methods effectively. It is satisfying to have a door open for you without intervention, as long as you understand where to stand. After using the automatic doors for several months and being confronted with a vehicle that does not open the doors automatically can be strange and disappointing.

The rear “Falcon” doors open up spectacularly. Articulated joints maneuver them upward, above the vehicle, leaving lots of head room and negating the need for a passenger to duck while entering. They are supposed to be able to open with only 12” of clearance, and have sensors embedded to detect nearby objects. Unfortunately, these sensors are easily confused - and when opening from the outside, it is common for users, especially new passengers, to misunderstand how the door will behave based on their distance from the vehicle. Often, the novelty of the doors are enough to emotionally placate a confused user, but the performance can become tedious to an experienced driver who is just trying to let somebody new into the back of their vehicle. Even an experienced driver with a well-developed mental model of their operation can be surprised when they fail to identify a neighboring vehicle’s side view mirror and clip it - without any clear explanation why. The owner’s manual mentions this: “Model X falcon wing doors have several sensors to detect the presence of an object in the door's path. In most cases, when an object is detected, the door stops moving. However, the sensors are unable to detect all areas under all circumstances, particularly when closing, Therefore, you must monitor the movement of falcon wing doors to ensure the door's path of movement is free of obstacles, staying prepared at all times to proactively

intervene to stop the door from contacting an object (including a person). Failure to do so can cause serious damage or bodily injury.” Monitoring rear doors from the driver’s seat, especially two at once, is a difficult task that involves rotation of the neck, and could cause a strain, if the movement is jerky looking from side to side in an attempt to see as much as possible at once. A solution would be to have a surround camera with projected arcs for the doors. Many vehicles have incorporated these 360 degree cameras that show the ground around a vehicle, and the Tesla’s 7 cameras should more than suffice to perform the same task.

With active air suspension, the vehicle can adjust to the user’s most comfortable height for entry, with the suspension rising to a maximum height of 7.6” off the ground and a minimum of 5”. With an adjustable seat capable of an additional 6” of vertical travel, the entry will be easy a driver of any height and hip/knee/back mobility. Older, less flexible drivers greatly appreciate this adjustable entry - the vehicle will even configure itself automatically for easy entry after being unlocked.

The windshield is massive, sloping back over and behind most users’ heads when in a driving position. Unfortunately, this does lead to some issues with sun glare. Despite the proprietary, heavy tint present at the top of the windshield, there is no way to prevent a sun from beaming in uncomfortable rays. The sun visors that would provide an extra 3-6” of sun blockage in a regular vehicle must be folded in from the sides (confusing many users) and only cover a thin strip in the middle of the windscreen. Providing a further extension in the form of a stick-on cover or a roll-out shade would be a good addition to prevent glare. Most users adjust to this shortcoming quickly (good

sunglasses), and the views of the sky are unparalleled, except in some convertibles and glass-roofed vehicles.

The mirrors are small, and present some visibility issues. Designed with the use of the rear-facing cameras to detect vehicles and pedestrians in mind, Tesla has considered removing the side view mirrors on their vehicles completely to reduce drag. This is currently not legal, so the mirrors that do exist are tiny, including the rear view mirror. Only a sliver of road is visible through the rear windshield, and some of that view is obscured by the spoiler. Fortunately, the back up camera can be enabled while driving to provide a large picture, and the side view mirrors are adequate, if diminutive. Tesla has not yet enabled live video feed from rear facing side cameras.

The vehicle itself is very quiet at low speeds. The crunch of the tires is often the only indication that the vehicle is approaching. Pedestrians outside the vehicle are habituated to hearing the louder noise of internal combustion engines (ICE) running, which can lead to confusion on the pedestrian's part about how fast the vehicle is moving, and even if it is there at all. Some kind of additional [noise making device should be incorporated - and will soon be required legally](#).

Primary Controls: Acceleration, Braking, Steering, Shifting.

In some ways, Tesla has dealt with the legacy problem by simply ignoring convention, but it has also bowed to historic traditions for other features. This makes for a confusing mental model - will a feature behave as "usual" in a car? Or will a familiar action result in some unforeseen consequence? To begin to answer these questions, the primary driving mechanics must be observed and assessed. With a push of the

“gas” (“go” pedal is more accurate for an electric vehicle), one will immediately find that the Tesla offers a surprisingly different feel than most other vehicles. Even the low-end model can reach 0-60 mph in 5.7 seconds and that is jarring, as the power is instant and there is no auditory feedback from the engine revving, just a faint whine of electric motor. While distracted by the sensation of g-forces pushing a driver back into the seat, and perhaps the instant exhilaration, a driver can quickly reach an unsafe velocity as perception of speed lags behind actual conditions. The go pedal on a Tesla is a high-gain control, meaning just a small deflection results in a large rate of change. There have been [multiple reports](#) of sudden unexpected acceleration (SUA) in Teslas. SUAS are almost always result from driver error, in which an operator believes they are engaging the brake, but have inadvertently committed a capture error by placing their foot on the accelerator. In traditional vehicles this is a problem, but especially so in Teslas, with their instant power.

UPDATE 09/18: Tesla introduced Object Aware Acceleration, which uses ultrasonic sensors to detect nearby objects in front of the car and electronically disable the amount of power that is available to the motors in close-quarters. Anecdotally, this is causing [some issues](#) with driver expectations and understanding of the system, but it can be disabled to fit driver needs. This cannot be done on the fly, however, so adding an icon, perhaps close to the speed indicator, indicating that the power is reduced,

would help a driver's mental model of the acceleration mode.



Figure 4. "Object Detected - Acceleration Limited" notification possibility.

Fortunately, the go-pedal is a first-order control with very little lag, meaning the deflection of the pedal directly corresponds to the power directed to the motors. It is important to note that the braking is regenerative, which leads to very different performance characteristics than internal combustion engine vehicles (ICE), which can help return a speeding vehicle to a safe speed quickly. Whereas acceleration might normally lead to a gliding forward at a consistent rate as kinetic energy slowly bleeds off, upon release of the go pedal, the regenerative braking automatically kicks in, causing deceleration. While this can lead to some oscillation reminiscent of second-order acceleration controls, most drivers adapt [quickly](#), based on testimonials and reviews from new drivers.

Update 2/18: A new acceleration mode called "Chill" has been added to the vehicle. When enabled, it reduces power available to the motors for slower acceleration.

It is likely helpful for newer, less experienced drivers to make the transition from ICE to electric.

The steering ranges from very stiff to forgiving, which is another human factors issue a driver might encounter, especially considering mental models. There are three modes of driving: Standard, Sport, and Comfort. This increases or decreases the gain in the steering wheel, which greatly influences the second order task of switching lanes. The drive mode also affects the characteristics of the air suspension. From the user manual: “ADAPTIVE SUSPENSION DAMPING: Choose from STANDARD or SPORT to adjust the feel of the suspension system. STANDARD provides a softer and more fluid ride whereas SPORT provides a firmer, more controlled ride that increases driver engagement.” Drivers can set their own preferences, and save it to a profile, but an unexpected change in the driver settings, such as an inadvertent activation by a key fob, can cause some confusion.

Driver settings, including drive mode, are paired to different key fobs, but if the vehicle is being operated from a phone key rather than a fob, the new settings will not be applied. The seat position provides a check and redundant indicator of the driving settings, and the driver profile is displayed when entering the vehicle at the top of the center touch screen (CTS), but it soon fades.

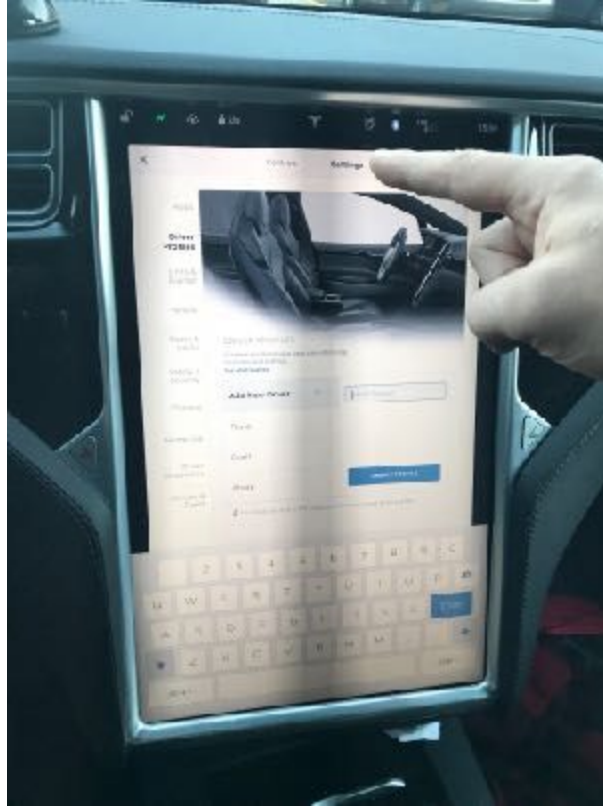


Figure 5. Driver Settings - Selected profile not clearly visible

The layout of the CTS design will be discussed in the monitors section, but the driver profile requires some effort to discern, lacking clear discriminability (Figure 3).

UPDATE 2/18: The driver profile is now displayed permanently at the top of the CTS.

Finally, to finish describing primary controls, shifting into drive, reverse, or neutral must be addressed, because of the departure from the norm. A Tesla has only two “gears” for its electric motor: Drive and Reverse. The current gear is prominently displayed on a central display, but there is no redundant information in the world to signify the mode of drive because the shifting stick is purely digital - one pull downward

will put the vehicle into drive, from there, a push upward will shift into neutral, and another nudge will reverse. The amount of force needed to shift the vehicle from gear to gear is difficult to gauge for new Model X drivers, and can even defy experienced drivers, especially when they are in a rush, such as in a car wash drive-through. To make matters worse, the lack of a physical position can lead to mode confusion when any driver's attention is shifted outside the vehicle. While shifting is usually something that takes place when the vehicle is stopped, most ICE vehicles can be shifted into neutral on the fly by moving the shifter into a new physical position. The Tesla's inability to shift to neutral while driving might make performing [certain trick driving maneuvers](#) more difficult, but I was unable to find anybody who has attempted any of these.



Figure 6. Shifter stalk.

The lack of redundant information about the gear provided via visual or haptic information, as is standard in most vehicles, is highly problematic, and could result in a mode-error slip, such as accelerating backward when a driver intended to proceed forward. A physical shifter that remains in place when manipulated would alleviate this problem. Currently, the only secondary indicator is whether or not the vehicle is displaying rear-view camera information. The rear-view camera can, however, be blocked by other information on the screen, such as a map or other driver setting configurations. The rear-view camera can also be turned on when the car is in drive, which can further confound a driver. It is my opinion that when the car is in reverse, the rear-view camera should be prominently, permanently displayed on top of all other windows.

Secondary Controls.

After speed, steering, and shifting, there are additional controls that a driver needs to conduct safe travel. Seat adjustments follow recent conventions that include excellent mapping. Even the angle of the headrest can be configured, which ergonomically could prevent whiplash if properly configured. Emergency lights are well signified using a standard symbol, and mapped to a button near the center screen. The glove box is opened using a push button next to the glovebox itself, but operation could be improved by putting a handle or the button itself directly on the glovebox to improve mapping, correct the signifier design flaw, and afford the direct opening of the box without searching for a button. Ultimately, a

push-button glove box is unnecessary and may invite the need for unnecessary maintenance as electronic catches wear out over time - a physical handle and latch seem simpler. Mirror adjustments are intuitive but unremarkable as well. Interestingly, the side view mirrors can have a separate setting for when the vehicle is in reverse, making it easier to see a curb when parallel parking. This touch does improve the driver experience, and delights drivers who enjoy technology for technology's sake.

Windshield wipers are controlled in the standard fashion with a stalk to the left rear of the steering wheel, but the stalk is conspicuously close to a similar stalk to engage cruise control or Autopilot. Also present, but much less prominent, in the same physical area is a steering wheel adjustment nub.



Figure 7. From top to bottom: windshield wiper stalk, steering wheel adjustment nub, and Autopilot stalk.

The proximity of the stalks to one another is a problem, and it is compounded by the lack of constraints: they both afford the same movements. Both move up, down,

forward, backward, and have twisting controls at their tips. This invites description-similarity slips because of the lack of discriminability between the controls. That is, a driver might turn on the windshield wipers when trying to adjust Autopilot settings, or visa versa - a distracting mistake. Over time, a user becomes adept at distinguishing the stalks, but the design problem could be easily solved by providing a different encontrol, like a button, to engage the Autopilot features. Such a button could even be presented on the touchscreen when Autopilot features become available (above 18 mph when the cameras have a clear view of the road). The saving grace is the different feedback from manipulation of the controls, as one sprays the windshield with cleaner, and the other gives a combination of audio cues that autopilot features have been engaged. The tech enthusiast users of Teslas do not struggle with the discrimination because of their frequent use of the Autopilot features, but novice users are frequently confused, especially when first learning about the controls - which is probably the worst possible time to encounter problems. It is easy to imagine a prospective owner taking a test drive, trying to activate the feature, and spraying the windshield, reducing visibility, and being so confused and frustrated with the Autopilot that they do not decide to purchase. They might walk away thinking, "If Autopilot is supposed to make my life easier, why is it so hard to turn on?" Creating some poka-yoke constraints that would deconflict the stalks such as putting them on opposite sides of the steering wheel would be a major design improvement. Because shifting is not possible while in motion, as mentioned above, pulling down on the shifter as if putting the car into a new gear (Autopilot gear) would be another solution.

Seat heat, thermostat control, ride height, radio tuning, and backup camera activation are all completed via touch screen, which will be discussed in the display section below. Tesla would certainly benefit from additional refining of the controls for these systems, and by using [jidoka](#), or the persistent asking of “why did this happen?” when their testers reported capture slips or control-related issues. [Reports indicate](#) that their own employees are utilized as testers on a regular basis. Choosing testing personnel from drivers who are less knowledgeable with the technology and design of their vehicles would be a better way to get feedback on user perceptions and would probably identify many of the control issues addressed above.

Control Displays.

There are two primary displays that act as both control panels and driver aids. The attention capturing 15” vertically oriented touch screen and a more traditional looking driver dash display (DDD) are both digital and contain their own user interfaces, allowing multiple modes to display information and interact with features. Most vehicle functions are accessed through the large touch screen. The secondary controls mentioned above are mostly represented by a different mode of the display. Ride height, for instance is accessed through a Settings Menu. This is also where driving mode settings exist, but it is not easily distinguishable from the Controls Menu. While options concerning the operation of each system are present in the Settings component, it is easy to confuse this with the Controls - for instance, child locks are enabled through settings, but door opening is controlled through Controls.

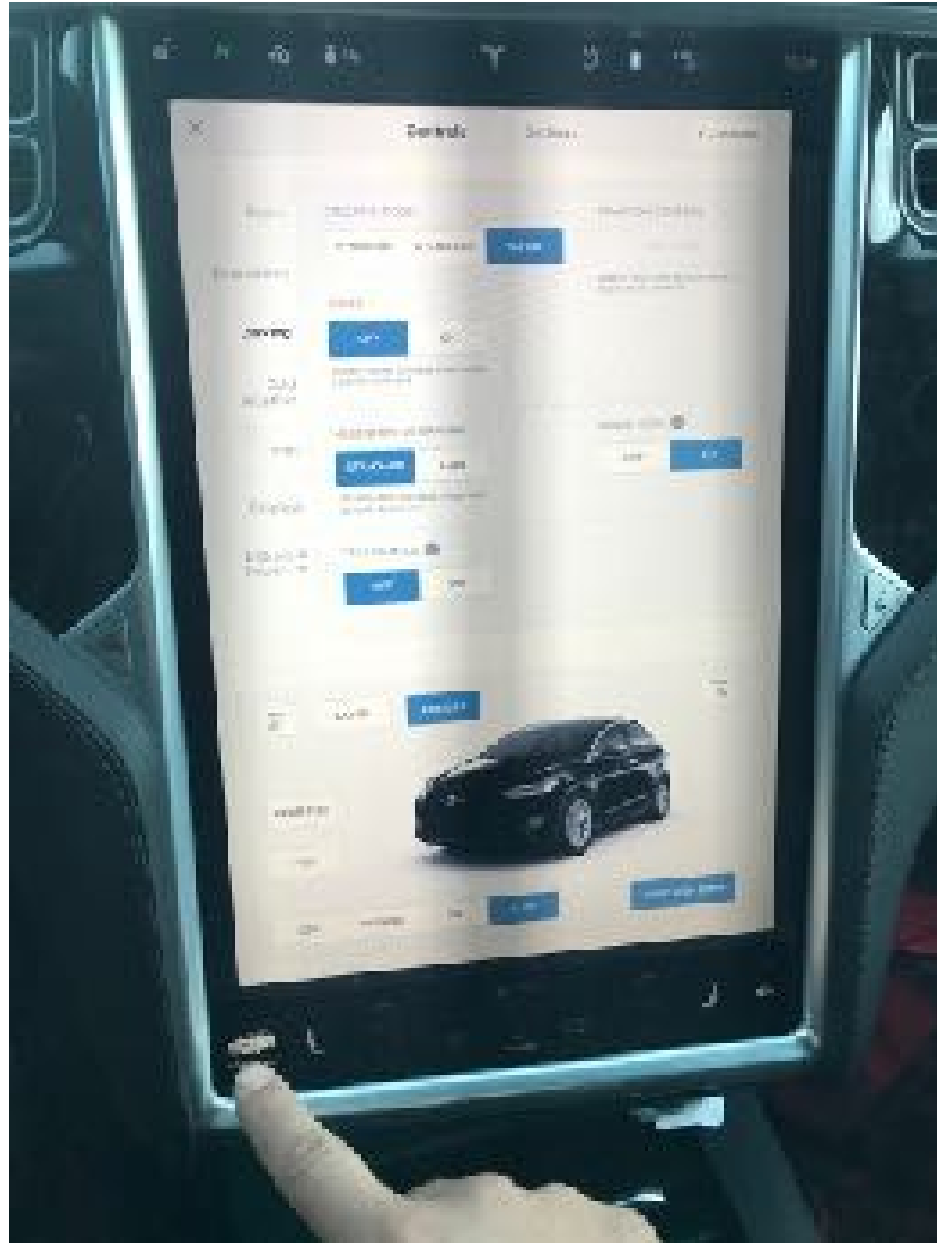


Figure 8. Location of controls menu.

This leads to a less efficient design because a user must remember where which menu exists, rather than being able to clearly see a menu for all options pertaining to doors - violation of the proximity compatibility principle. The psychological refractory period in these switching tasks, or making separate one-bit decisions is longer than it

would be if the driver could make one larger decision to access all relevant settings. The frequency of the decision to access controls does not trade off with the complexity of the decision about which mode the driver is trying to access. That is, a driver must frequently use the CTS close or open the doors, and the navigation is unnecessarily complex to make that happen. The CTS is used to lock, unlock, open, and close doors by touching the corresponding part of the vehicle. In this case, it adheres well to the principle of pictorial realism and principle of the moving part as the status of the doors and trunk can be viewed in real time, aligning with intuitive mental model about how doors work.

(UPDATE 9/18: The CTS user interface has been completely redesigned. More controls are now quickly accessible from a bar that has been added permanently to the bottom of the screen. The bar itself can activate the door/quick controls screen, music, an additional controls bar (probably intended for less frequently used controls), seat heat, climate, defroster options, and stereo volume. It is easy to turn on the seat heat when trying to adjust the temperature due to the close proximity of these touchscreen controls, and seat heat is not frequently used for most users who live in [warm states](#).

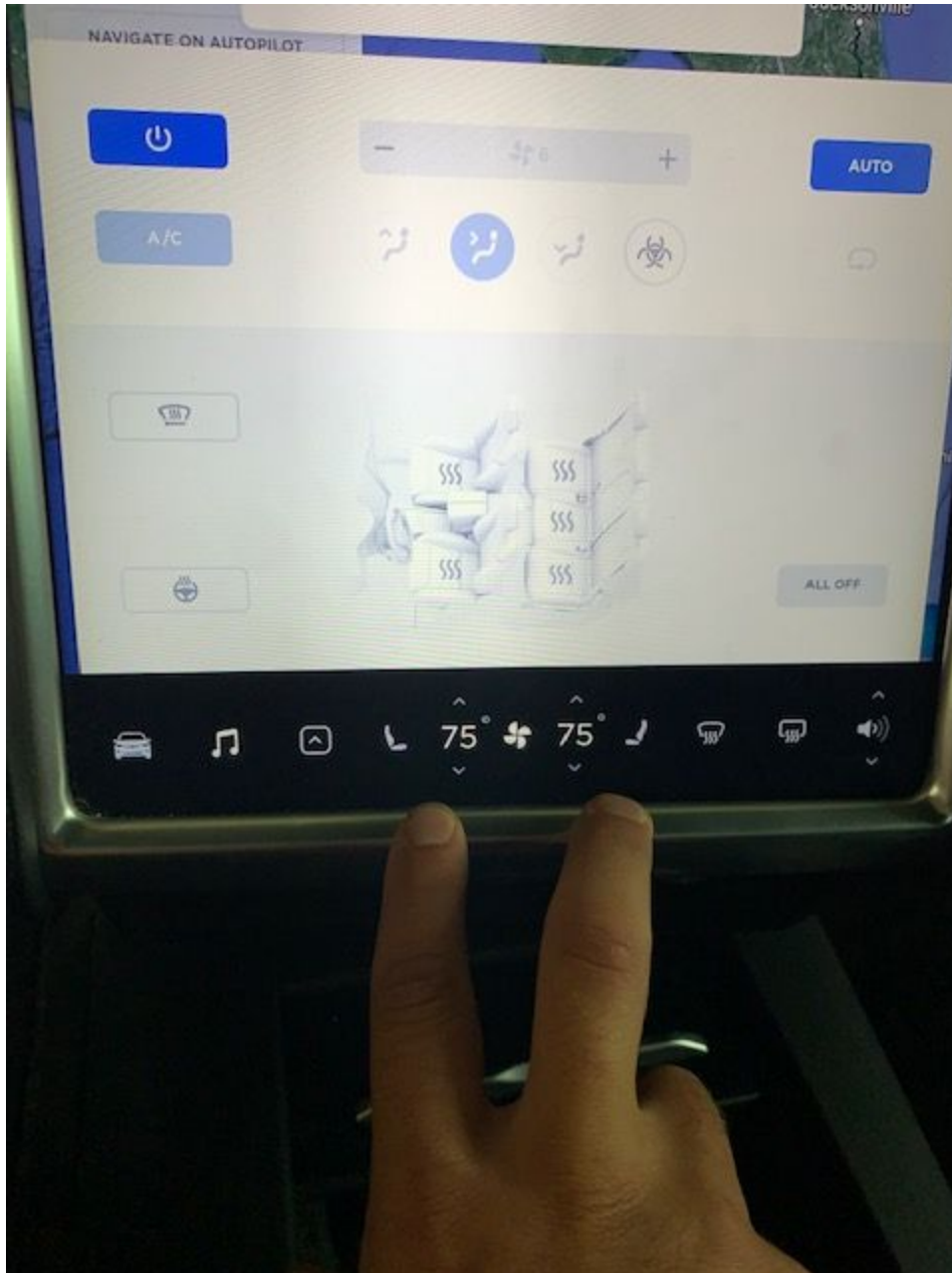


Figure 9. Permanent controls bar. Note proximity of seat heat to climate controls.

The climate control screen above would suffice for seat heat controls.

The seat heaters and defrosters take up space on the screen that could be used controls that might be more useful without navigating to any new pages. Unlocking and opening the automatic doors still takes multiple touches. Left rear and right rear door

buttons would be a welcome addition for some drivers who are, for instance, picking up children at school. While the Model X is the only vehicle that has mechanically actuated doors that can open without physical manipulation and the interface has now been standardized across the entire Tesla range of models, having door controls persistent on the screen would still make the process of opening and closing doors easier and require fewer touches. This is particularly important for the Model X because the mechanically actuated falcon doors take longer than traditional doors to open. The combination of operating the door controls and then waiting for rear doors to open can be an inconvenience, especially if the driver and passengers are in a rush. A traditional vehicle can come to a stop, a passenger can quickly pull the door open, and shut it behind them, and be inside the vehicle and ready to go in 3-5 seconds. The same process, because it requires the Model X to be put into park, can take 5-10 seconds. This may not sound like much, but the delay for ingress or egress is noticeable.) A single touch and then a confirmation (if the car is not in park) button would speed the process. Even better, Tesla could enable user customization of the bar.

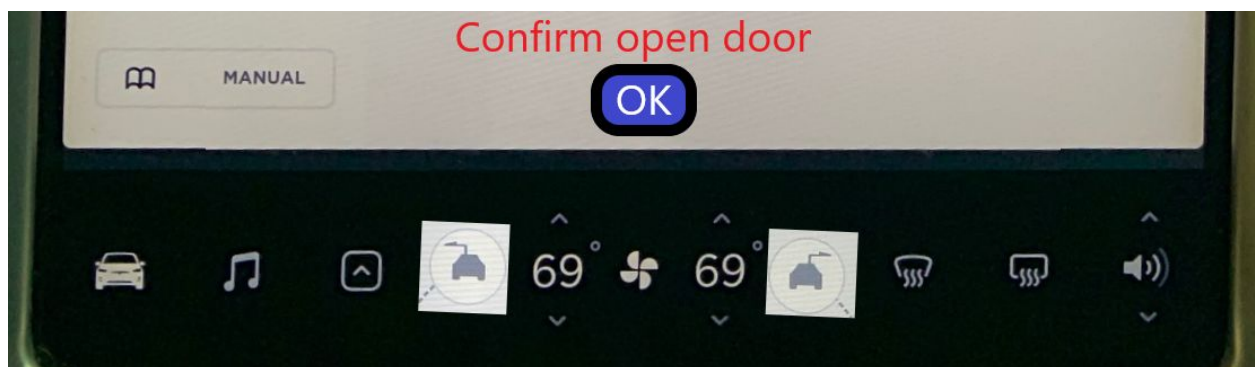


Figure 10. Potential rear door opening buttons in control bar.

Overall, the new CTS interface is an improvement because it relies less on the user's memory for access to certain menus. The suspension is clearly labeled, separately from other controls. Autopilot, driving settings, and lights now have separate menus for customization of each without going several menus deep and guessing at which controls might be in which menu.

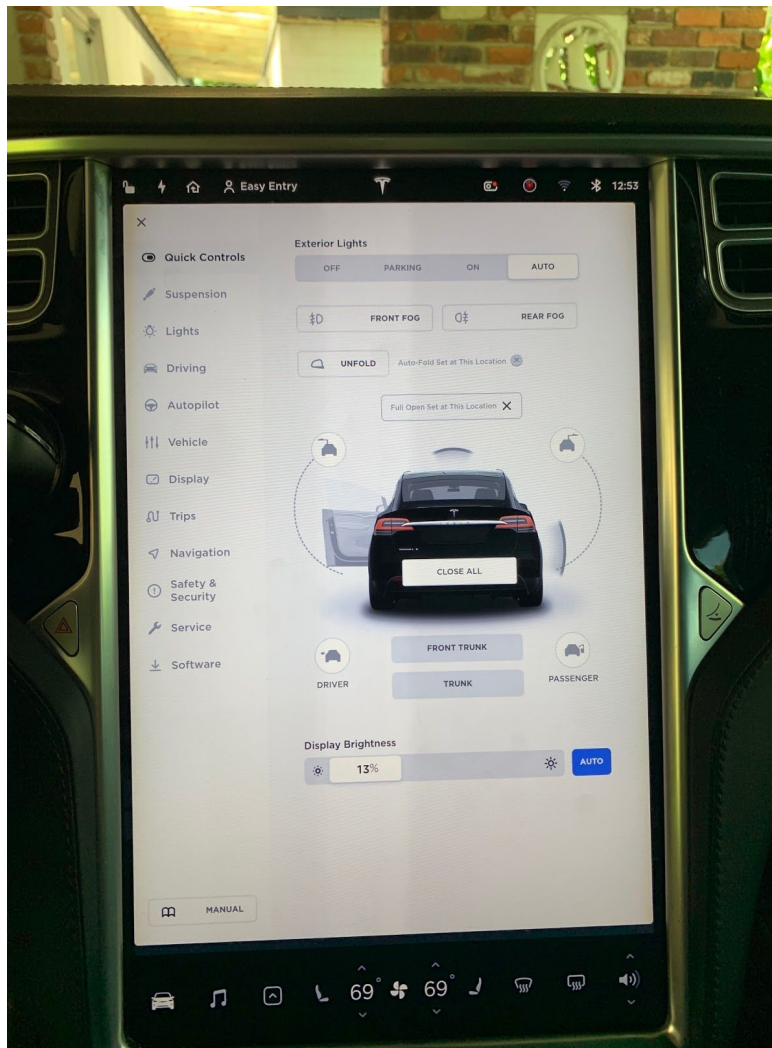


Figure 11. Quick controls menu screen separate from suspension.

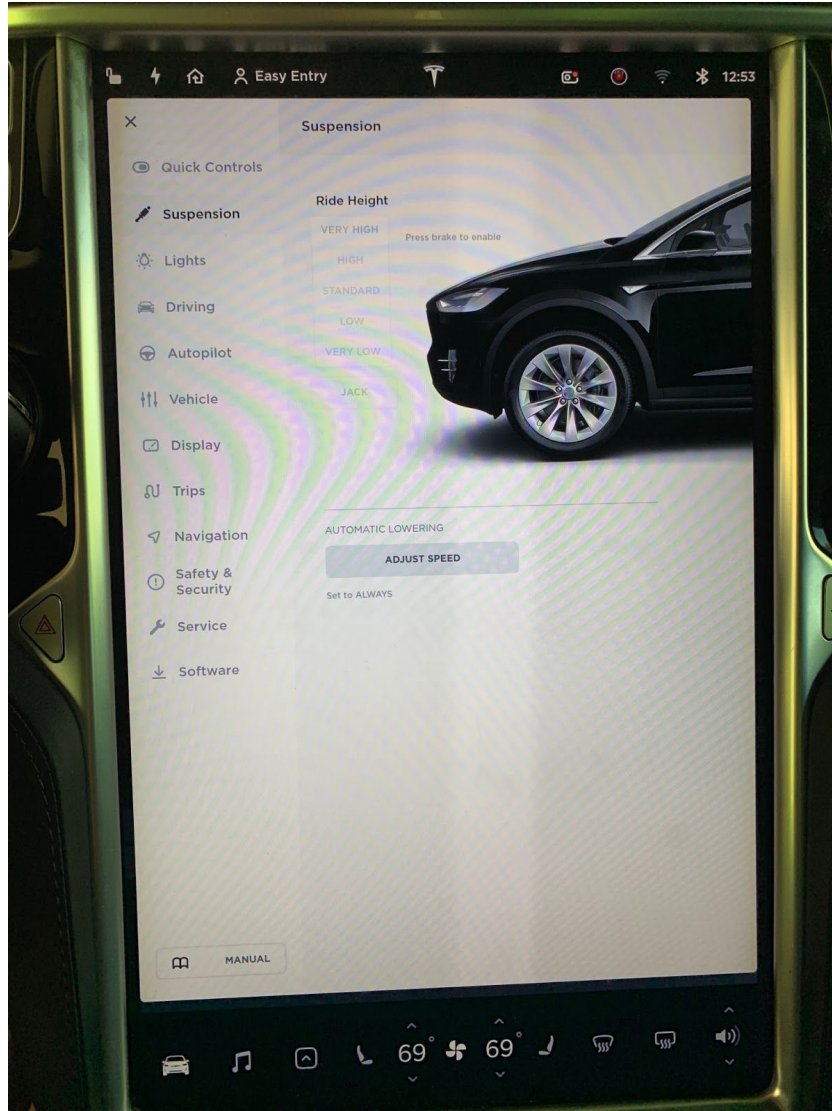


Figure 12. Suspension controls separated in new user interface.

The new CTS interface, however, has removed an important feature. Most menus now rise up from the bottom of the screen when selected. The rear view camera slides up, and when music controls, for instance, are selected simultaneously, that menu slides up underneath. These both cover the map, which is persistent in the background. The old interface allowed customization of the screen - rear view camera could be on top, map on the bottom. Now, to view the map and camera at the same

time, the rear view camera must be on the bottom. This can take a driver's attention out of the windscreen and increase reliance on peripheral vision to sense what is going on in the front of the vehicle. Being able to pin the useful camera to the top of the screen while continuing to view navigation on the map below would be preferable.

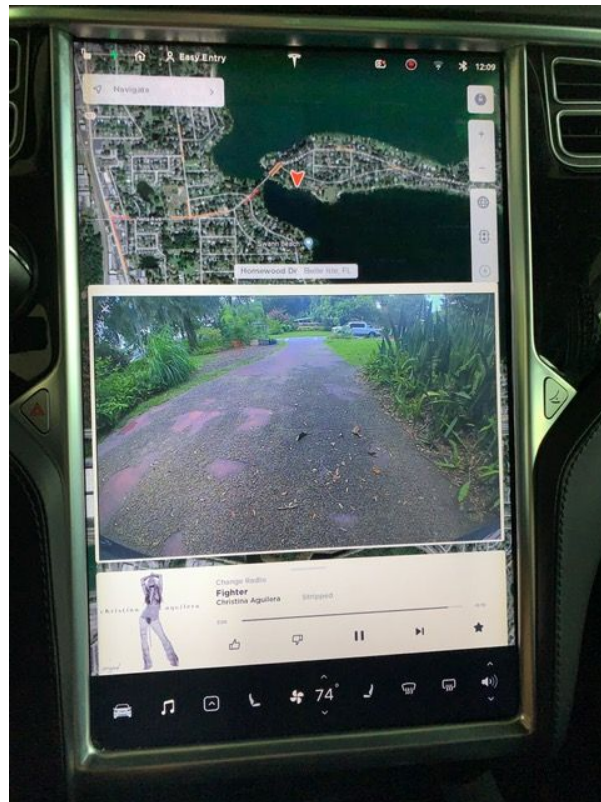


Figure 13. Rear view camera and navigation display combo now only available in nav on top, camera on bottom.

The diminutive dimensions of the physical rear view mirror and the small rear window have always made it preferable to use the rear view camera rather than the mirror. Further iterations of the CTS interface could also make it easier to access the rear view camera. Currently, dash-cam controls are present at the top of the CTS. Adding a rear view camera option would not only put these camera functions in a

similar, easy to remember location, but enable easy access to rear-facing visual information, which is more difficult to obtain from the small rear view mirror.

Autopilot Displays.

Attention from the driver is especially important when it comes to speed, and situational awareness of the road environment. In these cases, the displays are largely lacking. In the center screen of the driver dash display (DDD) lies a representation of the vehicle, displayed in 3D, including lane position and other vehicles sensed by the radar, cameras, and ultrasonic sensors. This particular display would be great, if it could be trusted. Instead, it often displays incomplete information a car ahead is detected and represented on the screen, but other vehicles are not, and are instead represented by small curves emanating from the vehicle, suggesting the presence of something, but these do not inform whether the objects are other vehicles, cones, pedestrians, or side rails. This can lead to switching costs of attention between the inside of the vehicle and visually scanning the environment, both of which are visual tasks, and which, using Wicken's shared resource model, will interfere with each other in most drivers. Objects surrounding the Tesla should be displayed as what they are: cones as cones, barriers as barriers, etc. This would assist in the analog judgment of judging relative distance and position to the dynamic stimuli present in the driving task.

(UPDATE 1/19: New visualization has been added to the DDD. Other vehicles are now animated as closely to their size and position as possible. A car now resembles a car, a bicycle or motorcycle appears accurately, vans and pickup trucks are larger,

and semi trucks are shown with their trailers if detected. The cameras and the software are not perfect, though. Cars often jump about the screen when parked at a stop light, as the Autopilot software and processor try to decipher exactly what is going on. This can be disconcerting to a user who is constantly trying to decide if the Autopilot is working correctly or not. Vehicles do display more smoothly while driving, but the glitchy appearance of the vehicles at a stop could dissuade a user from engaging the Autopilot at all. This is bad for the Tesla brand, and also bad for the long term plans: Tesla records data from [hundreds of millions of miles of driving](#) from users who have Autopilot engaged. The data is used for deep learning to improve each subsequent build of the software. It behooves Tesla to keep drivers using the software, and, without clear understanding of why cars may be flitting in and out of the picture on the DDD, drivers are less likely to engage it at all.)

The DDD also violates pictorial realism. Speed is displayed only digitally, rather than with a traditional speedometer. Without a needle, rapid acceleration towards a goal speed is harder to identify. Compounding this issue, the height of the driver can vary widely. Between the seat set to the lowest setting and the vehicle at lowest suspension to the highest potential position, the eye height of the observer can vary up to 20 inches. This will affect the global optical flow rate, and could result in speeding if a user is accustomed to driving in a low seat low suspension setting but finds the vehicle a.

Perhaps the most damning aspect of the display is how dependent the controls of many features are. The need to divert visual resources to perform what should be

simple tasks, controlled by manual buttons, creates layers of unnecessary risk for drivers.

Autopilot Technology.

One of the most prominent marketing features of the latest generation of Teslas is the promise of full-self driving capability (FSD). Currently, the vehicle is rated at [Level 2 autonomy](#), meaning it can keep pace with traffic and stay within most lanes. It requires the driver to stay alert, but is intended to allow the driver to relax during certain portions of a trip, such as on a highway or on a two lane road. Level 3 and Level 4 are supposedly within the grasp of the current suite of hardware but are not yet software enabled or [legal](#). Still, at Level 2, the vehicle performs so admirably, it can lull the driver into a false sense of security. This could be a major detriment to the vigilance task of driving, as decreased arousal will lead to a criterion shift in the form of reduced sensitivity. While the effect may be offset by reducing fatigue on the operator, and improving overall driving performance, the driver may divert attention elsewhere. Reports of drivers [sleeping](#) or [watching movies](#) while driving are disconcertingly common. If it gets disrupted by external circumstances such as camera blockage or a confusing traffic pattern, the system will alert the driver with a shrill auditory alarm and rapid blinking, a signal enhancement technique. This redundant information coding will help alert the driver to immediately take over, and the vehicle will immediately begin to brake if it believes a collision is imminent to provide more reaction time for the driver, but this may not be enough.

If the Autopilot system would continually update the driver of its confidence about sensing the road ahead, the overall safety would be increased. Such an alerting system could use a bright green indicator on both displays when it had high confidence, and as the driving situation became more volatile, it could shift all the way to red to indicate that it might require driver takeover at any moment. The display could take advantage of peripheral vision, in case the driver's attention was focused downward or even out the windows. The only visual indicator of whether the autopilot is performing as expected is whether or not lane markings are displayed around the vehicle on the egocentric panel of the DDD. Haptic feedback in the steering wheel when the vehicle began to be "confused" could also be useful. Addition of the described feature would result in a positive redundancy gain for identifying system confidence, and would likely benefit the user's conceptual model of how the autopilot system actually works, enabling the driver to increase vigilance as conditions became less favorable to the sensors.

UPDATE 7/19: Autopilot has undergone multiple upgrades since this report was written. The most recent version includes a "Navigate on Autopilot" feature. Notable improvements include blind spot notification using a red-colored lane when driving and the ability to suggest and even perform safe lane changes while driving on the highway. I continue to recommend that the Autopilot system constantly appraise the driver about how it is "feeling" while driving. Knowing more about what the car can detect and what it cannot would be immensely helpful for drivers and safe operation of the system. It is helpful to have other cars now represented accurately on the road, but curbs, traffic barrels, and stop signs/lights should also be represented. Essentially, the DDD should

animate anything that it sees that is relevant to the driving experience, and indicate any confusion that it is experiencing to the driver. Until FSD is out of beta, the more information about the system's confidence that can be provided to the driver, the safer the entire trip will be.

It should be noted that, despite designing their vehicles to embody a sleek, futuristic look, Tesla eschewed the growing trend to implement head-up displays in vehicles. This was an excellent choice regarding the autopilot feature, because the lane markings and vehicle positions could easily interfere with visual processing of the actual world and lead to confusion, effectively decreasing reaction time to relevant stimuli in the driving environment.

Additional Safety Enhancements.

Tesla has provided some additional automated features to reduce mental load without compromising safety, as well. Automatic high beams sense oncoming headlights and switch off and on as needed, greatly improving night time visual range in the focal area, improving overall visual acuity. Turning at night, which is dangerously over reliant on peripheral vision in other vehicles, is improved here with the use of headlights that add extra illumination in the direction of the turn which can help detect pedestrians and obstacles in the way of the turn with more accuracy. This system takes advantage of the more advanced parvocellular system to discern danger than the less refined magnocellular vision, which might trigger a stress response in a situation of oncoming motion in a turn at night, especially if the outline is human.

When driving without Autopilot engaged, the vehicle continually monitors the lanes using the machine vision technology, and will alert the driver using haptic feedback by shaking the steering wheel when decreased leads to drifting into a neighboring lane.

Navigation.

There is nothing radically different about the GPS navigation in the Tesla, as it largely conforms established conventions. A pursuit 3D display is active in the left side of the DDD, if providing directions, and it utilizes a perspective display to highlight the intended route. Sometimes, when approaching an exit, it will switch to a visual image of the exit and which lane to occupy to reach the destination. The CTS defaults to map mode and is used to enter a desired destination. It can be controlled by simulated keypad on the display, or by activating the voice control feature with a button on the steering wheel and stating "Navigate to...". However, it will not respond to "Give me directions to..." or "Look up," which can lead to frustration from drivers. Failing to issue a voice command, the driver might turn to the center keypad while driving, occupying the majority of the visual-spatial sketchpad, utilizing precious central processing resources, and requiring manual input. It is undoubtedly a danger to have such a frustrating voice control system and a touch screen that can be manipulated while the car is in drive. To improve the navigation design, some constraints could be added - such restricting address input while driving, until the Autopilot is engaged or finalized. Mass sensors in the seats are currently capable of detecting passengers, and if a

passenger is available to enter a destination using the CTS, this suggested restriction could be relaxed.

Overview.

Overall, the Model X is a futuristic looking, fun car to drive with exciting technology but Tesla's design choices have likely created some holes that may only be discovered using the swiss cheese examination of an accident report. It is easy to imagine a perfect storm of multiple failure modes leading to a catastrophic event in which a driver has engaged the unfortunately named Autopilot 2.0, is complacent, fatigued, and distracted by in cab infotainment which leads to what amounts to a non-driver. Coupled with any malfunctions (such as a [failure to detect a crossing truck](#)) in the vision autobraking system, debris (such as as dead insects) blocking the radar, and without warning that the Autopilot is struggling to function, the outcome could lead to multiple fatalities and extensive property damage in a highway driving situation. The Tesla, with large crumple zones and a [near perfect safety rating from the NHTSA](#), might protect the driver and passengers, but anybody else involved in the mishap would likely not fare as well. Despite the design-induced risks, vehicles equipped with Autopilot are performing [more safely than human drivers](#), even with the features in beta. From the Tesla website: "we registered one accident for every 2.87 million miles driven in which drivers had Autopilot engaged. For those driving without Autopilot, we registered one accident for every 1.76 million miles driven. By comparison, NHTSA's most recent data shows that in the United States there is an automobile crash every 436,000 miles."

These statistics are heartening and further refinement of the features, addressing some of my above concerns, the system could become even safer.

Final Recommendations and User Experience Improvements.

Redesigning the car's ergonomics is likely a bridge too far at this point. The turn signal, steering wheel nub, and Autopilot control lever are probably going to be clustered together for the production life of the vehicle. Likewise, the dimensions of the mirrors cannot change. Tesla has, however, already addressed many of the concerns from earlier in the paper. "Chill mode" and "obstacle aware acceleration" have been added, blindspot warnings via salient graphics on the DDD are now available, and Autopilot continues to improve. What drivers using the advanced features need more than anything is more information about what the vehicle is "thinking." Tinkerers, hackers, and curious owners have tapped into the [Autopilot machine-vision feeds](#) and now have access to recordings of footage with overlays of what the cameras are detecting, and what the FSD chipset is deciding they are. This data should be available to any driver who requests it. The Early Access Program allows some drivers to access features that are pre-release, and requires confidentiality agreements. If Tesla could provide more drivers with access to the information their vehicles are processing, it could essentially crowdsource additional improvements, allowing users to flag and annotate footage that needs review to improve the machine learning. This would have the additional benefit of improving drivers' mental models about how the vehicle is operating.

Tesla should also make it easier for drivers to know and learn what the different components on their vehicles do, and what limitations they might have. There are channels on YouTube, [Reddit](#) threads, and internet forums run by drivers who are very interested in how the different hardware, cameras, and software are changing their driving experience. To peer inside the black box that is the overall vehicle often yields more questions than answers: there are two versions of the Main Computing Unit, and it is difficult for owners to determine which version they have unless they rigorously test the performance of their web-browser and conduct research on what easter eggs are available. Making such information readily available would further shape driver expectations, resulting in less confusion and frustration when confronted with the lack of a feature.

Constraints to the CTS should be added to prevent usage while driving. While unlikely considering Tesla's minimalistic design trajectory, future models should include more manual controls for things like seat heat, temperature control, audio settings, and toggling of displays while driving. Improving voice navigation would not only reduce the use of the touch screen, but it would result in an improved user experience all around.

Tesla also has the hardware already added to all vehicles to add additional functionality, some of which is found in other high-end vehicles already. From a safety perspective, the back up camera(s) should identify incoming cross traffic on either side and alert drivers who are in reverse. Currently, the only notifications come when the ultrasonic sensors detect an object within a few feet of the vehicle. Incoming traffic and pedestrians could be displayed when detected. From Tesla's website:

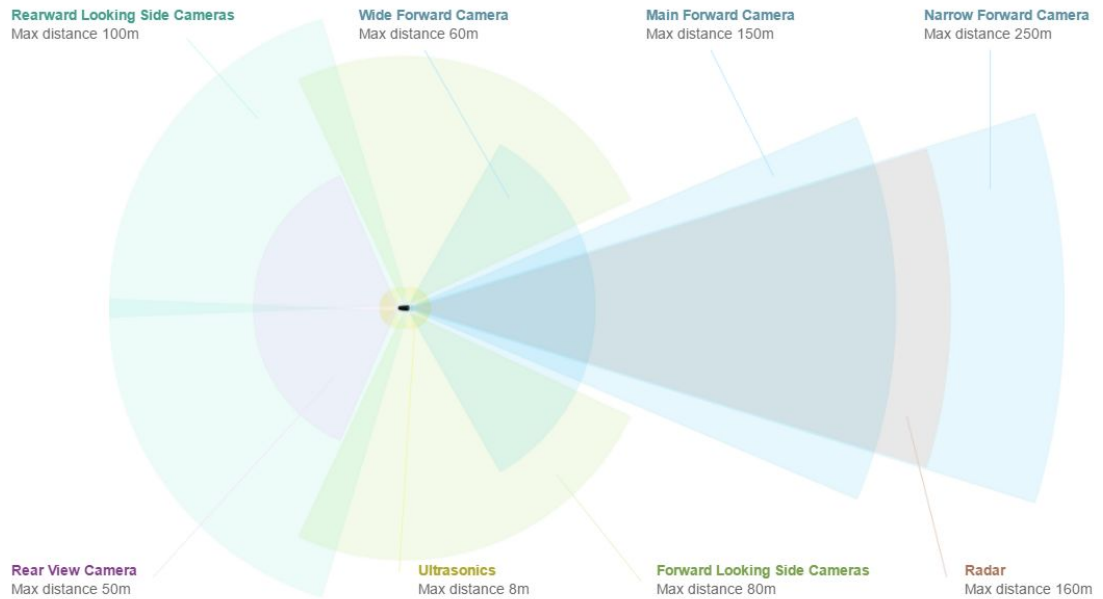


Figure 14. Tesla sensor field of view.

With progressively more powerful hardware (the new Autopilot graphics processing unit is custom-built for the task) capable of detecting turn signals, predicting pedestrian paths, and more, the cameras could be used to allow some gesture controls from outside the vehicle. The trunk could open if approached directly from behind, especially if the driver (with key in close proximity) is carrying objects. Falcon wing doors could be actuated in a similar manner, possibly with arm movements.

Conclusion

Self driving vehicles are undoubtedly coming, and companies from Alphabet (Google's umbrella company) to Volvo are pursuing the technology. In the near future, manual driving of vehicles may even require special endorsements on a license, and the feature will have to be "unlocked" by manufacturers. The technology is not here yet, though, so legal, ethical, and safety issues abound. To any drivers of the Tesla Model

X: extreme caution is advised in the use of the systems, and the same goes for any drivers who happen to find themselves next to a Tesla on the road. An unpredictable, if well-intentioned, AI may be driving.