2020 Tesla Round-up: Recap of VSI Tesla Research and Latest Developments in Tesla

October 8, 2020 · by Danny Kim · Technology Brief

Introduction

VSI Labs has examined all aspects of Tesla and its Autopilot technology by looking at its evolution in hardware and software architectures, enabled functionalities via over the air updates, and data management infrastructure. On top of analyzing those technical evolutions, we have also tracked Tesla's performance as a company and its long-term viability.

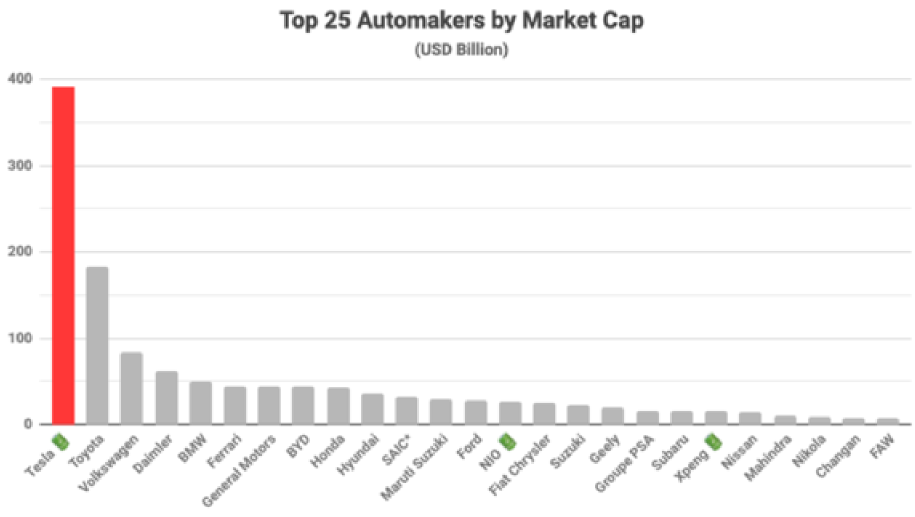
This Technology Brief will recap VSI Labs' earlier research on Tesla's technologies and find where they are at now by connecting the past research with the latest developments from the company with regards to:

- Tesla as an Auto Company
- Tesla Autopilot HW Evolution
- Tesla Autopilot Feature Improvements from the OTA Update
- Tesla Software Architecture Evolution with Data Management Infrastructure
- Tesla Autopilot SW Rewrite and the future of FSD (Full Self-Driving)

How is Tesla doing as an auto company?

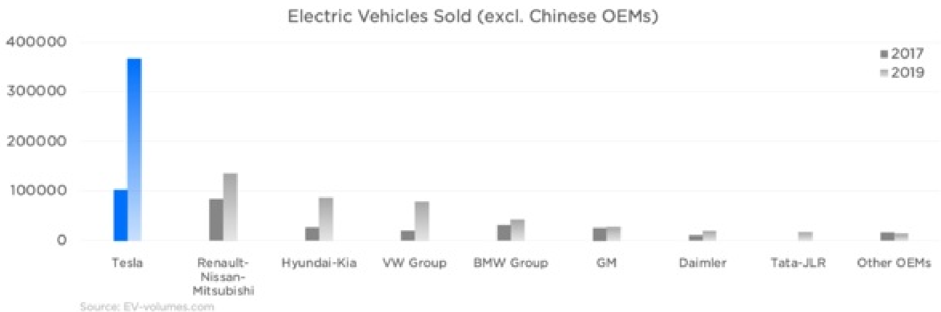
Earlier this year in this Tech Brief, VSI questioned if Tesla is an auto company or tech company. Having long surpassed Detroit's "Big Three" to become the most valuable car manufacturing company in the United States, Tesla made history this June by surpassing Toyota to become the most valuable automaker in the world.

Tesla's share price soared in the past 12 months, boosting the company's valuation to more than 17 times its revenue for the trailing twelve months. Toyota is currently valued at around 0.6 times its annual revenue, which is why many people consider Tesla overpriced. While Tesla delivered less than 400,000 cars in the 12 months ended March 31, Toyota sold nearly 10.5 million vehicles during the same period. Maybe the company is not being valued as a car company, but rather as a technology company that happens to build cars.



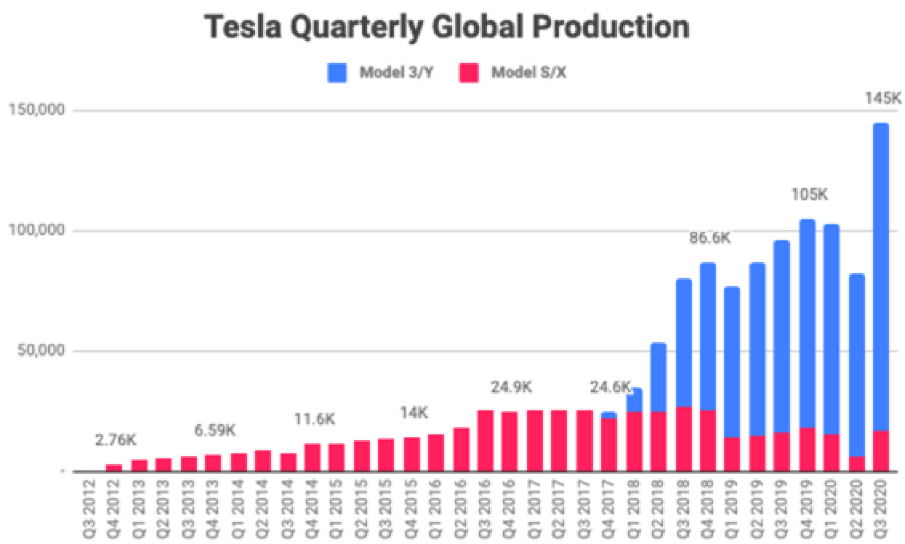
Top 25 Automakers by Market Cap as of Oct. 7 2020 (Source: Real-time view Here)

As an electric vehicle manufacturer, Tesla is a clear leader though. In its "Impact Report" published at the end of 2019, Tesla said "while many OEMs introduced new EV models in the past two years, their actual global deliveries of EVs increased only marginally."



EV Sales Comparison: Tesla vs. Others (Source: Tesla Impact Report 2019)

Tesla delivered 139,300 vehicles in the third quarter 2020 and produced 145,036 vehicles, setting a new quarterly record for itself. Tesla's gross profit margin was 20%, compared with 17% at Toyota and Volkswagen, and less than 10% at General Motors, Ford and Fiat Chrysler. Tesla's past inability to turn a profit stemmed from its focus on building niche luxury vehicles (Model S/X), but it invested a lot to get its first vehicle aimed at a more mass market, the Model 3, into production. The Model Y was profitable in its first quarter of production this year as well, a first for the company. Tesla is forecasting the Model Y will have a higher profit margin than the Model 3.



Tesla Quarterly Global Production (Source: Real-time view - Here)

In the long run, the most important thing is whether Tesla keeps expanding its automotive operations while also finding new and exciting markets that can benefit from the company's vision.

Tesla Autopilot Hardware

One of the notables from Tesla's Autopilot HW updates is, although it had to swap three generations of Autopilot computers (excluding the Mobileye-based computer AP1.0), its sensor configuration has been identical – 8 cameras, 1 radar and 12 ultrasonic sensors.

Tesla Autopilot HW Updates

Generation	Production	Computer	Cameras	Other Sensors
AP HW 1.0	September 2014 – October 2016	• ADAS: Mobileye EyeQ3 SoC • Connectivity & Infotainment: MCU 1.0	1 front-facing Camera	Bosch radar with 525 ft range & 12 sonar sensors with 16 ft range
AP HW 2.0	October 2016 – August 2017	• ADAS: One Nvidia Parker System-on-Chip (SoC), 1 Nvidia Pascal GPU, 1 Infineon TriCore CPU • Connectivity & Infotainment: MCU 1.0 then MCU 2.0 (Beginning in March 2018)	8 total: three front-facing, two side-fwd facing cameras in the b-pillars, two side-rear facing cameras under the front fender badges, and one rear-facing camera	Bosch radar with 525 ft range & 12 Sonar Sensors with upgraded 26 ft range.
AP HW 2.5	August 2017 – March 2019	• ADAS: 2 Nvidia Parker SoC, 1 Nvidia Pascal GPU, 1 Infineon TriCore CPU. • Connectivity & Infotainment: MCU 3.0 (Intel Atom x7-E3950-based)		Continental Radar with 558 ft range & 12 Sonar Sensors with 26 ft range.
AP HW 3.0	Beginning in March 2019	• Tesla's Full-Self-Driving (FSD) Computer • Connectivity & Infotainment: MCU 3.0 (Intel Atom x7-E3950-based)		

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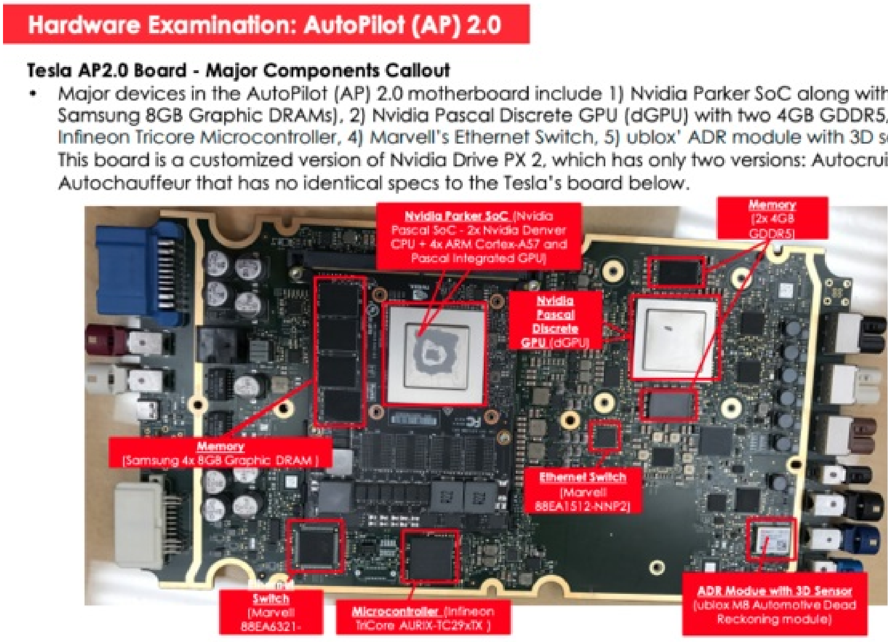
Tesla Autopilot HW Updates (Source: VSI Labs)

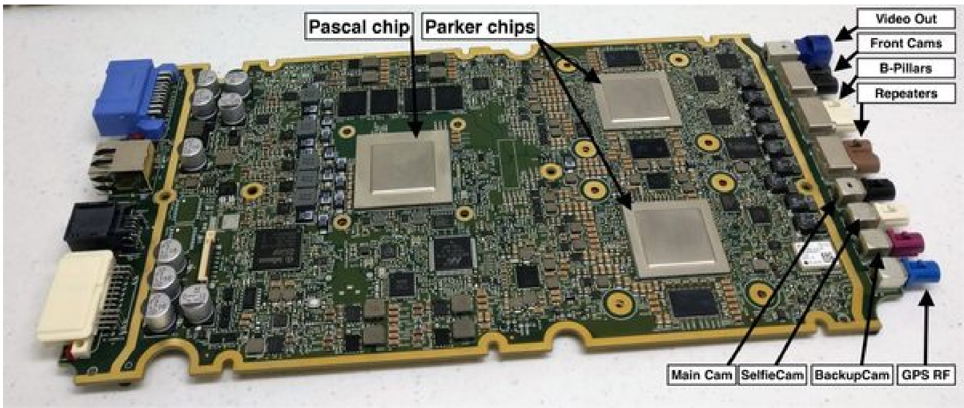
This Tech Brief written in 2018 explains how Tesla independently (from Mobileye-based AP HW 1.0) started developing its own vehicle network between a Nvidia SoC-powered ADAS domain controller and the MCU connectivity/infotainment computer. The significance of it is that 1) the central domain architecture of Tesla is truly a state of the art, still up to this point and 2) by all definition, Tesla is a software defined car where any function can be updated at any time with an OTA push.

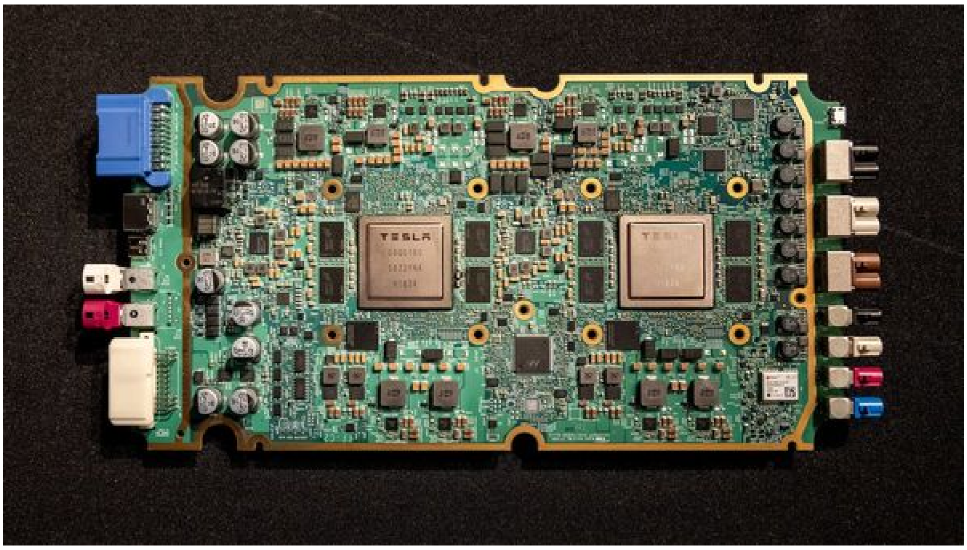
Another notable from Tesla's Autopilot Hardware suite is that the use cases of existing cameras evolve over time. For example, forward-facing side cameras located on the B-pillar were first used for lane changing and blind spot detection, but now are being used for smart summon to detect close objects and free space for a better path planning. However, in the long term, for FSD functionalities, those cameras would be used at intersections or roundabouts to see vehicles coming from the sides to yield, then making a 90 degree turn or maneuvering in those tight road geometries.

AP HW 1.0 Mobileye EyeQ3 SoC-based Mono-cam Perception System



AP HW 2.0 Nvidia SoC-based ADAS Domain Controller (Source: VSI Labs)





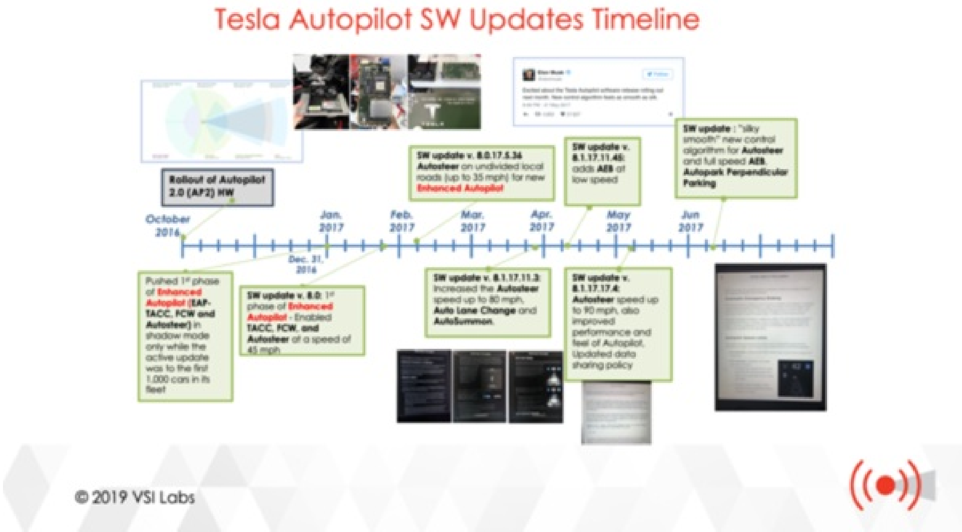
AP HW 2.5 ADAS Computer (above) vs. AP HW 3.0 FSD Computer (below): Details on this Tesla's proprietary computer were revealed at the 2019 Tesla Autonomy Day, which was summarized by VSI Labs in this Tech Brief.

Tesla OTA Autopilot Feature/Functionality Improvements

One of Tesla's biggest advantages over most other automakers is the ability to significantly improve the ownership experience, even a long time after delivery through software updates. This is especially true with non-Autopilot features that are fully utilizing OTA SW updates.

The most unique thing about Tesla is its ability to constantly activate new ADAS features and improve existing Autopilot functions, leveraging the same set of sensor suites.

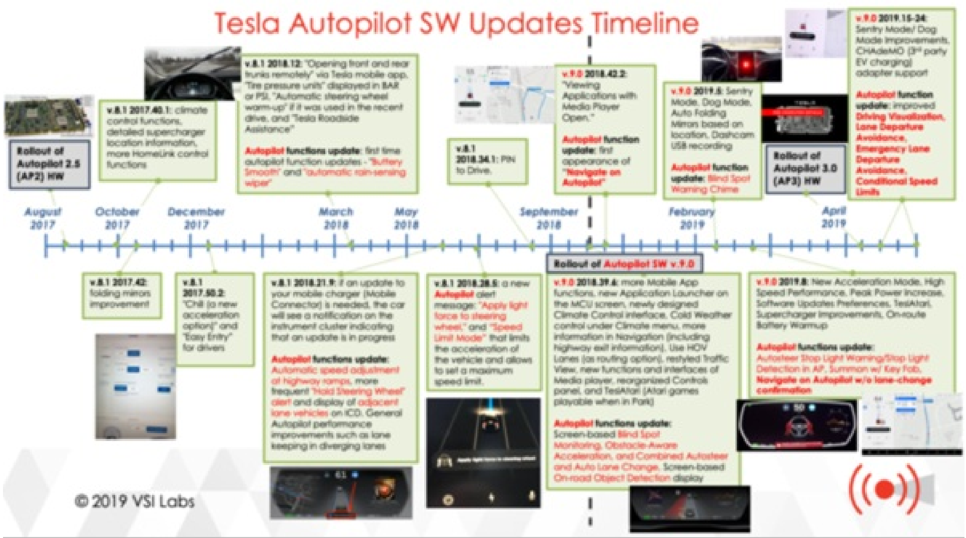
Back in September 2017, VSI Labs added the MY2017 Model S with the new hardware Autopilot 2.0 as one of our research vehicles in the Lab. This Tech Brief shows the early stage of Tesla's in-house Autopilot SW work (departing from AP1.0, powered by Mobileye EyeQ3-based mono-cam system and Mobileye's perception algorithms). Tesla enters in the long process of gradually updating "Enhanced Autopilot" features via OTA software updates utilizing a very small set of HW components initially. The Tech Brief shows the progress from the roll-out of AP2.0 HW up to when they enabled Autosteer and full speed AEB, almost a year later.



(Tesla Autopilot SW Updates Timeline - Oct '16 ~ Jul '17, Source: VSI Labs)

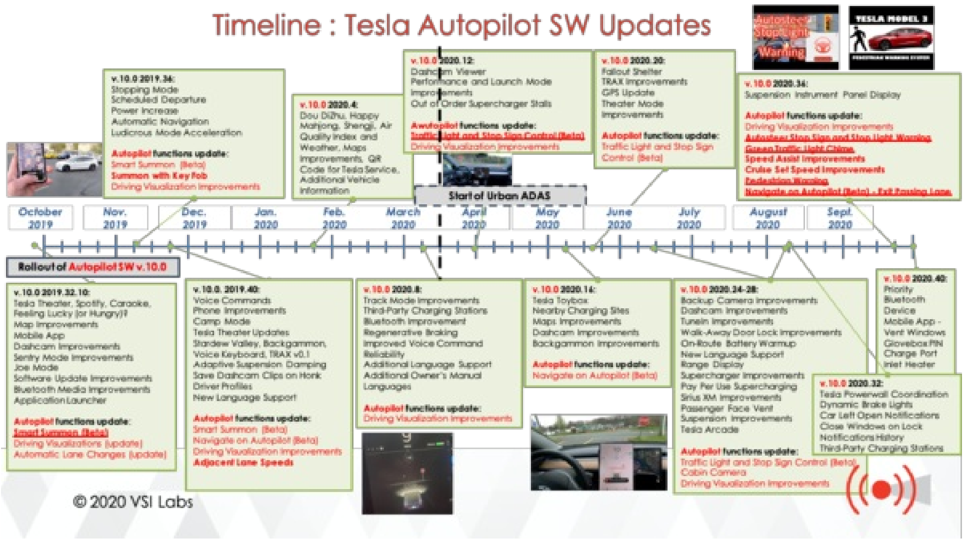
After a 3-month, Tesla OTA data study, VSI Labs discovered some very interesting activities under the vehicle's hood and documented them in this Tech Brief: Tesla was collecting a variety of snapshot information for shadow-mode feature testing and validation such as autopilot trip logs, AP disengagement logs, camera self-calibration logs, etc. Tesla was also sending labeled images as inputs for neural network training, such as automatic rain-sensing wiper algorithms based on fisheye camera inputs.

Since October 2016 when Tesla started shipping the AP 2.0 hardware suite on new MY17 Model S vehicles, Tesla sent out a total of around 170 major and minor OTA SW firmware updates until August 2019 to Model 3, S and X vehicles combined. The Tesla Autopilot SW updates progress until shortly after the rollout of AP 3.0 hardware can be found in this Tech Brief. This is when Tesla was experiencing growing concern over its long-term viability as an automotive OEM. But the software updates continued to enhance the ownership experience. Tesla vehicles have received fairly competitive active safety features via over the air updates.



(Tesla Autopilot SW Updates Timeline - Aug '17 ~ Jul '19, Source: VSI Labs)

In the 2H 2019, Tesla started rolling out Autopilot SW v.10.0 builds, with constantly improving performance and reliability of active safety features and semi-autonomous features such as Navigate on Autopilot, Auto Lane Change, Autopark and Summon.



(Tesla Autopilot SW Updates Timeline – Aug '19 ~ Present, Source: VSI Labs)

In April 2020, Tesla released a new feature called Traffic Light & Stop Sign Control. It is designed to slowdown and "automatically" stop for visible traffic lights or stop signs that are detected when the Traffic-Aware Cruise Control (TACC) or Autosteer is engaged. This feature is the start of enabling Tesla's urban ADAS functionalities, aiming to improve to autosteer on city streets. This Tech Brief detailed the underlying technologies enabling the new feature, compared it to the industry norm, and assessed what it means to Tesla's Autopilot product roadmap.

It is already known that most OEMs' strategies are to increase the reliability and driver experience of highway pilots. However, a smaller group of OEMS' including Tesla's strategy is to enable and create urban ADAS. Tesla has a very strong head start in urban ADAS and will benefit from their fleet already in place.

However, from the driving experience, the urban ADAS / high capability features may only appeal to a more niche crowd of tech enthusiasts, and the average audience may not use features like this often.

Tesla Software Architecture Evolution with Data Management Infrastructure

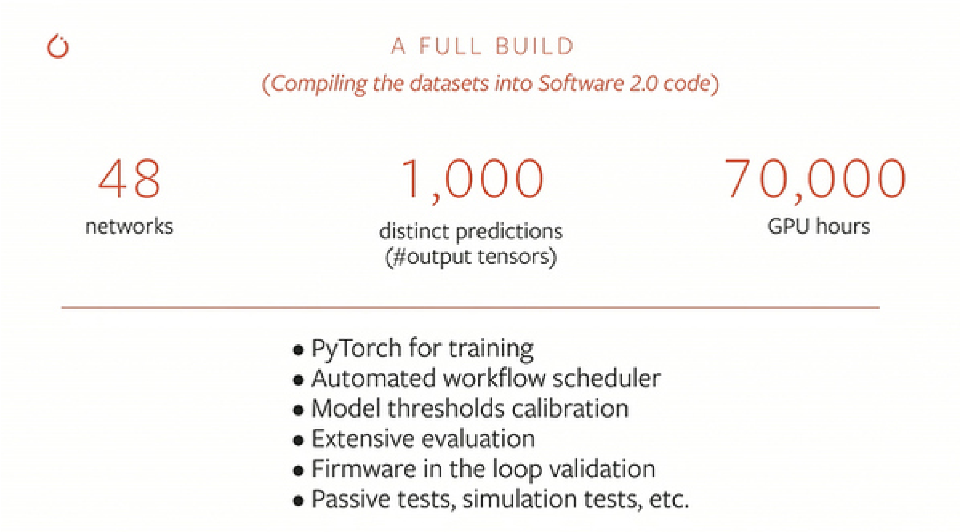
In October 2018, VSI Labs published thisTech Brief on the Tesla Vision Software vision processing pipeline where DNNs are heavily used. The Tesla Vision software has a group of advanced CNNs processing the output from each of the seven cameras (excluding the backup camera) followed by a second set of post-processing networks for scene understanding.

The DNNs are being constantly trained and have been re-written a couple of times to enable more functions of Enhanced Autopilot (EAP) and Full Self-Driving (FSD) features.

Tesla's AI head, Andrej Karpathy, has presented and explained many details of Tesla Autopilot software stack, in particular the neural network stack. He explained how their neural network inferencing happens in two stages. The first stage being a collection of several CNNs that process data from the 8 cameras. The second state being a collection of non-convolutional recurrent neural networks that process the output from stage 1 for variety of higher-level processing tasks in world space. This architecture though will be updated to all 8 camera images being ingested together into one single neural network as a result of a SW rewrite to be described in the next section.

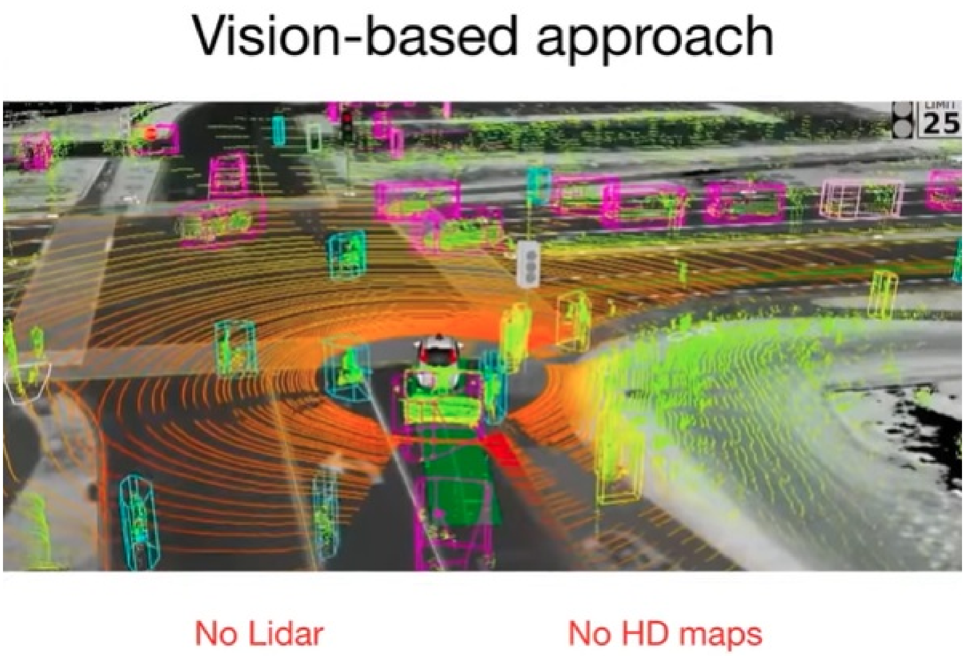
Tesla designed what they call the Hydra networks. When training neural networks to process image data for many tasks, there is a trade-off between training several discrete neural networks for each task and a very large complex neural network to handle many tasks. He explains that their approach is to leverage the benefits of both while minimizing the drawbacks. He also explained a variety of other details about training, inferencing, and the applications in autopilot.

- Currently Tesla has 48 separate neural networks in Tesla stack.
- They process camera images at 1280x960
- In total, the team is currently maintaining 48 networks that make 1000 distinct predictions (# of output tensors which can have multiple predictions in them), which takes 70,000 GPU hours to train all the neural nets. (i.e., if Tesla puts 1,000 of their GPUs on a training task, it would be done in 70 hours.)



Tesla AI Full Build (Source: PyTorch at Tesla - Andrej Karpathy)

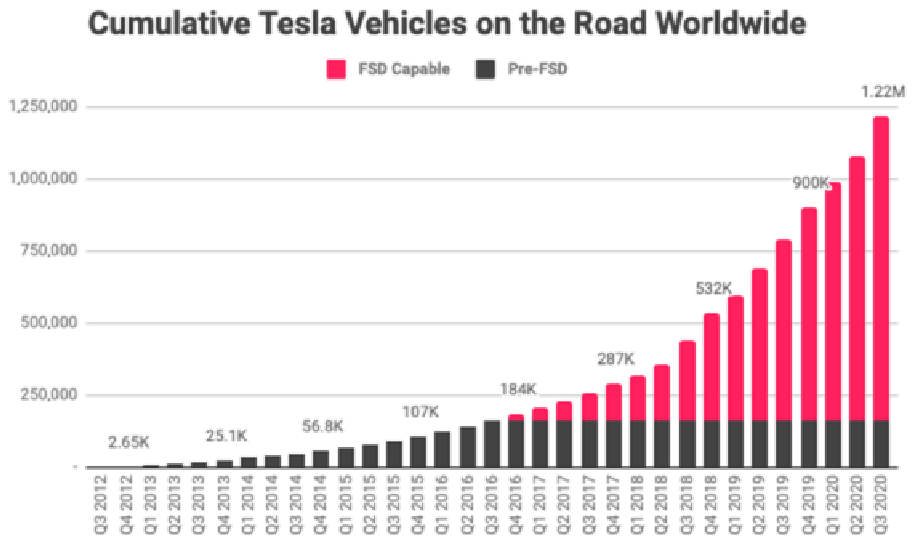
Andrej Karpathy explained how they use a prediction neural network that processes the output from multiple networks from different cameras in order to predict and understand the road layout. Traditionally, autonomous vehicles use an HD map for this. Well-known to the industry, Tesla is relying on computer vision instead of LIDAR and HD maps, which they believe are not scalable.



(Source: Scalability in Autonomus Driving Workshop | CVPR'20 Keynote | Andrej Karpathy | Tesla)

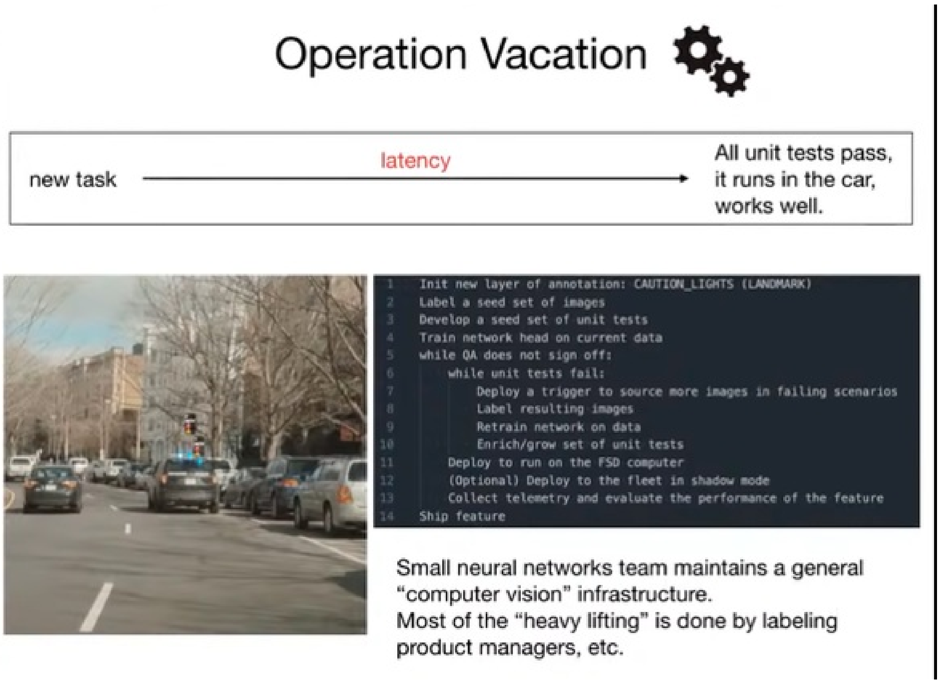
The competitive advantage Tesla has is the unmatched scale of data collection. Even Google's Waymo recently announced it has collected 20 Million miles since its inception in 2009. Tesla is currently leading by at least a factor 100, as boasted by Andrej in his recent presentations.

- 367,500 cars delivered in 2019
- ~1M total fleet globally
- 3B miles driven on the Autopilot
- 1B miles on NoA
- 200K Automated lane changes
- NoA on 50+ countries
- 1,200,000 sessions Smart Summon



Cumulative Tesl Vehicles on the Road (Source: Real-time view - Here)

In what Andrej defined as "Operation Vacation," he pushes his engineering team to focus on setting up the generic AI infrastructure to efficiently collect data, label it, train and reliably test models, so that the task of updating models to detect new objects can be handled by separate product managers and a labeling team. This keeps the AI team at Tesla nimble and efficient - and jokingly at some point the team could be on vacation and the system would improve without any more of the effort.



Operation Vacation: Tesla is mostly developing the automation infrastructure and then it's easy to develop any new task. (Source: Scalability in Autonomus Driving Workshop | CVPR'20 Keynote | Andrej Karpathy | Tesla)

One of the fundamental requirements for this approach to work is the concept of data unit tests for the machine learning models: a set of examples on which models previously failed which need to be successfully passed. Performance on unit tests can never regress, only improvements are accepted for a new model to be released into production.

At the core of Operation Vacation is what Andrej calls the Data Engine, shown below again from Andrej's presentation at Tesla Autonomy Day. The principle at the core of the Data Engine is not unique to Tesla: it is inspired by Active Learning and has been an hot research topic for years.

The goal of the Data Engine is to ensure data can be collected in the most efficient manner in order to cover the extremely long tails of examples required for models to reliably perform in real unconstrained world. The core principle of the data engine is very simple:

1. label initial dataset with new object classes

2. train model to detect new objects
3. evaluate performance
4. find cases in which performance is low
5. add those to data unit test
6. deploy models to car fleet in shadow mode to fetch similar edge cases
7. retrieve cases from car fleet
8. review and label collected data
9. retrain model
10. repeat steps 6-9 until model performance is acceptable

For example, just for stop sign recognition Tesla is going through the long tails of various examples. They have built an infrastructure for sourcing all these additional examples. Tesla iteratively applies active leaning to source examples in cases where the detector is misbehaving. Then Tesla source examples in those, labels them and incorporates them into a part of training set. Tesla has an approximate detector for stop signs based on an initial seed set of data. They run the model and deploy to cars in shadow mode and then you can detect a lack of health of that detector at test time.

Tesla Autopilot SW Rewrite and the Future of FSD

After the 2020 CES Mobileye press conference where Mobileye showcased 3D object detection and computer vision engines, VSI published this Tech Brief to compare the approaches between Tesla and Mobileye. In the article we pointed out that one of the Autopilot platform's greatest weaknesses seems to still be in estimating the depth of uncommon road users. A recent accident in which a Tesla Autopilot system accelerated into a carrier style of vehicle seems to be attributed to the Autopilot system improperly estimating the size and depth of a carrier vehicle.

During Tesla's annual shareholder and Battery Day event, Elon Musk said "We had to do a fundamental rewrite of the entire Autopilot software stack. We're now labeling 3D video, which is hugely different from when we were previously labeling single 2D images," admitting its development of Full Self Driving has reached a "local maximum."

Currently Tesla takes the stream from all 8 cameras, runs an image recognition algorithm on them individually, then passes its findings to another process to stitch all the data together as mentioned in the previous section. It does this frame by frame on each camera and then when stitched together it can kind of have things persist in time. The new update will take the data from all the cameras, fuse it together in 3D and then run an image recognition algorithm on top. Due to this it can also persist things in time better as well as get a much better idea of what it is seeing.

Elon Musk also calls the software rewrite "4D" in the sense that it's three dimensions with time added into the mix. Tesla is now labeling entire video segments, taking all cameras simultaneously and labeling those images with timestamps, in order to make 3D object tracking more accurate. He added, "The sophistication of the neural net of the car and the overall logic of the car is improved dramatically."

Similarly, a former Tesla employee at a podcast revealed the Autopilot rewrite helped Tesla combine the video feeds from its car's eight cameras into one 3D layout, which made it easier for data to be processed. The Autopilot rewrite started with 3D labeling, which improved the accuracy of labeling each frame. He also shared that Tesla's Autopilot HW 3.0 FSD computer was instrumental in the Autopilot rewrite and that Hardware 1.0 or 2.0 didn't have the capabilities to process that much data.

Elon Musk's Tweet on Autopilot SW Rewrite (Source: Twitter @elonmusk)

Elon Musk hopes that this means a beta version of the autonomous functionality can be released to private testers in October or November. VSI will keep tracking whether such a SW rewrite would solve previous problems of the computer vision-centric Autopilot platform and perform more reliably.

Conclusion

As we have said for many years, Tesla is a proxy for future vehicle architecture. This vehicle platform is truly a software defined machine with a long history of enhancements and modifications which we have documented in this brief.

It is very clear that Tesla has a bright future. But more importantly Tesla is a catalyst for change and is pushing this industry like no other OEM ever has. Tesla is also pushing the regulators who must face the fact that automated driving is here to stay.

We still think that Tesla is overly optimistic when it comes to full self-driving and we don't think they can get there with the current platform. But Tesla certainly has the capacity to leverage all its IP all the way to full driverless mobility. Meanwhile, Autopilot remains the benchmark for series production Level 2+ automation. Tesla is truly state-of-the-art when it comes to series production ADAS and autonomous driving!