Guanzheng Sun, research notes for Week Nov. 4, reporting to AJ on Nov. 13, 2024

This research analysis has contributed to MacroPolo's eventual policy brief on the tech component of autonomous driving, as found in the following link.

Part 1: https://archivemacropolo.org/analysis/autonomous-driving-the-future-is-getting-closer-part-i/?rp=e
Part 2: https://archivemacropolo.org/analysis/autonomous-driving-the-anatomy-of-autonomy-part-ii/?rp=e
Part 3: https://archivemacropolo.org/analysis/autonomous-driving-bifurcated-markets-part-iii/?rp=m

Trace the academic origin of end-to-end autonomous driving models, specifically the roots of the BEVFormer.

End-to-end autonomous driving involves training a **neural network model** to perform the entire task of vehicle control based on **raw sensor data**. This development contrasts with traditional modular approaches, which segment tasks into *detection, prediction, and planning*, each with its own dedicated components. The end-to-end approach aims to unify and jointly optimize these tasks, thereby reducing errors accumulated across separate modules and improving overall efficiency.

A timeline on the development of end-to-end autonomous driving models:

1. **Initial Development**: The concept began with ALVINN (1988), which used simple sensor inputs to generate steering outputs. This system marked the first notable end-to-end approach, taking raw input data and directly mapping it to control actions.
2. **Deep Learning Era**: With the rise of GPU computing, NVIDIA introduced an end-to-end convolutional neural network system, reigniting interest in this paradigm. Since then, deep neural networks have powered significant advances in imitation and reinforcement learning-based methods.
3. **Imitation and Reinforcement Learning**: Two main categories emerged for training these systems:

    - **Imitation Learning (IL)**: Agents learn by mimicking human driving behavior, using a dataset of driving demonstrations.

    - **Reinforcement Learning (RL)**: Agents learn by trial and error, adjusting behaviors based on reward functions. However, IL has generally outperformed RL for end-to-end driving due to RL's high data requirements and the complexity of learning effective driving policies.
4. **Policy Distillation and Privileged Information**: Techniques like policy distillation have been introduced to transfer knowledge from privileged (more informed) agents to the

end-to-end driving models, enhancing their robustness by using richer information during training.

5. **Challenges**:
    - **Interpretability**: End-to-end models are often seen as "black boxes." Recent works have tried to make these models more interpretable by incorporating intermediate predictions such as semantic segmentation or using attention mechanisms to visualize the focus areas during decision-making.
    - **Causal Confusion and Covariate Shift**: These are common issues in IL, where the model can become dependent on non-causal factors or fail to generalize beyond its training data.
    - **Robustness**: The field continues to grapple with achieving robustness across varied environments and long-tailed scenarios, which are often underrepresented in training data.
6. **Recent Innovations**: The field has benefited from innovations like Transformer-based architectures, multi-modal sensor fusion, and the use of foundation models for more powerful generalization. World model-based learning, which attempts to predict future states of the environment, is also being explored for improving the decision-making capabilities of autonomous vehicles.

Comparison between Conventional Multi-module Solutions and End-to-end Solution (Part)

Solution type	Modular autonomous driving	End-to-end autonomous driving
Drive type	Rule-based, coding for making rules.	Data-driven, using massive data to train the system.
Task mode	Multi-task learning	Single-task learning
Model	There are several modules, each adopting an independent model.	Use an end-to-end integrated foundation model
Generalization	Poor	Good

Source: ResearchInChina

Specific Stepping Stones: End-to-End Learning for Autonomous Driving

1989: ALVINN (Autonomous Land Vehicle in a Neural Network)

Researchers: Dean Pomerleau at Carnegie Mellon University.

Contribution: One of the earliest implementations of an end-to-end neural network for steering a vehicle. ALVINN used a single camera image to predict steering directions, demonstrating the feasibility of mapping sensory inputs directly to driving actions.

ALVINN (Autonomous Land Vehicle In a Neural Network) is a neural network-based system

Some OEMs' Planning for End-to-end Solution Implementation and Mass Production

OEM	Application Time	Status Quo of Implementation	Solution Features
NIO	H1 2024	R&D started in H2 2023, and mass production is expected in 2024.	-
Xpeng	2024	The plan to introduce the solution on vehicles was announced in January 2024.	Build a 600 PFLOPS GPU cluster for training.
Li Auto	H1 2024	The foundation model was launched in the first half of the year, and the end-to-end solution is planned to reach L3.	Full process modeling
Xiaomi	2024	In late 2023, an end-to-end perception and decision model was announced. In March 2024, Xiaomi SU7 was equipped with the model.	Generate road topology in real time; recognize static agents in real time
Geely	2024	Cooperation with PhiGent Robotics; expected SOP in 2024	Use the dynamic scene graph to predict possible collisions of agents
Jiyue	2024	Iterate the VTA foundation model, and develop and train the BEV end-to-end perception model	Realize coverage of all road elements; generate road topology in real time

Source: ResearchInChina

designed for autonomous road following. It is a three-layer back-propagation network developed by Dean Pomerleau at Carnegie Mellon University. ALVINN takes input from a camera and a laser range finder to produce the direction in which a vehicle (NAVLAB) should travel to follow a road.

How ALVINN Works:

1. **Network Architecture**: ALVINN has a single hidden-layer architecture with a video input "retina" (30x32 units) and a laser range finder input retina (8x32 units). These sensory inputs feed into a hidden layer of 29 units, which then connects to 46 output units responsible for determining turn curvature.
2. **Output**: The output consists of 45 units representing turn curvature and one road intensity feedback unit. The output specifies the curvature required for the vehicle to remain centered on the road.
3. **Training**: ALVINN is trained using simulated road images with different lighting and road conditions. Back-propagation is used to optimize the output of the network, ensuring it predicts the direction needed to stay on the road.
4. **Adaptation**: ALVINN develops different internal representations based on the specific characteristics of roads, such as varying widths. This allows it to tailor its processing to different environments.

Technologies ALVINN Depends On:

Artificial Neural Networks (ANN): The core of ALVINN's ability to learn and adapt to road-following tasks is based on a back-propagation ANN.

Simulated Training Data: To train effectively without the logistical difficulties of real-world data collection, ALVINN uses simulated road images.

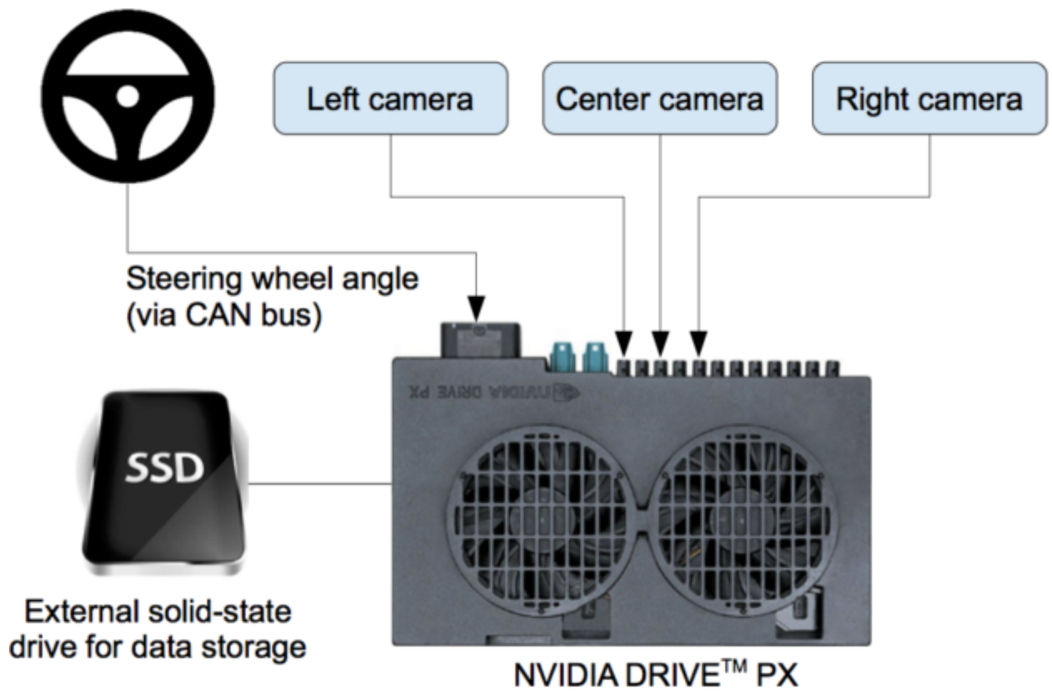
Sensors: A video camera and laser range finder provide real-time data for navigating.

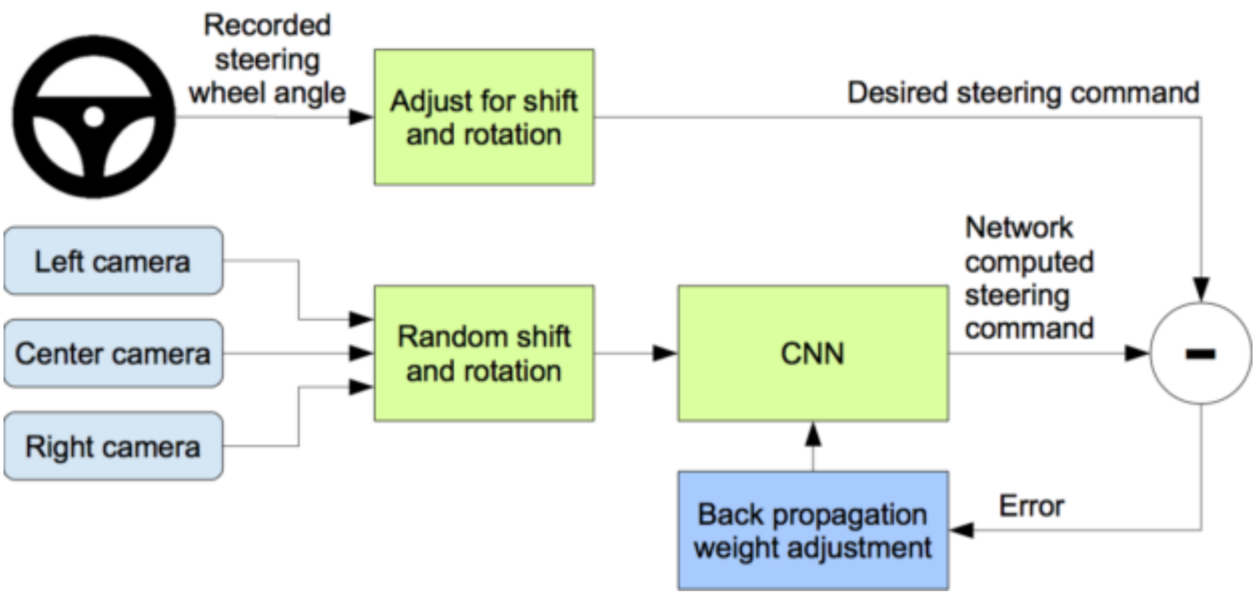
Back-propagation: The learning algorithm allows ALVINN to adjust weights and improve its road-following capability over time.

2016: NVIDIA's End-to-End Learning for Self-Driving Cars

Researchers: Mariusz Bojarski et al.

Contribution: Introduced a convolutional neural network (CNN) that maps raw pixels from a front-facing camera directly to steering commands. This work revitalized interest in end-to-end approaches using deep learning, showing impressive performance without explicit modularization.





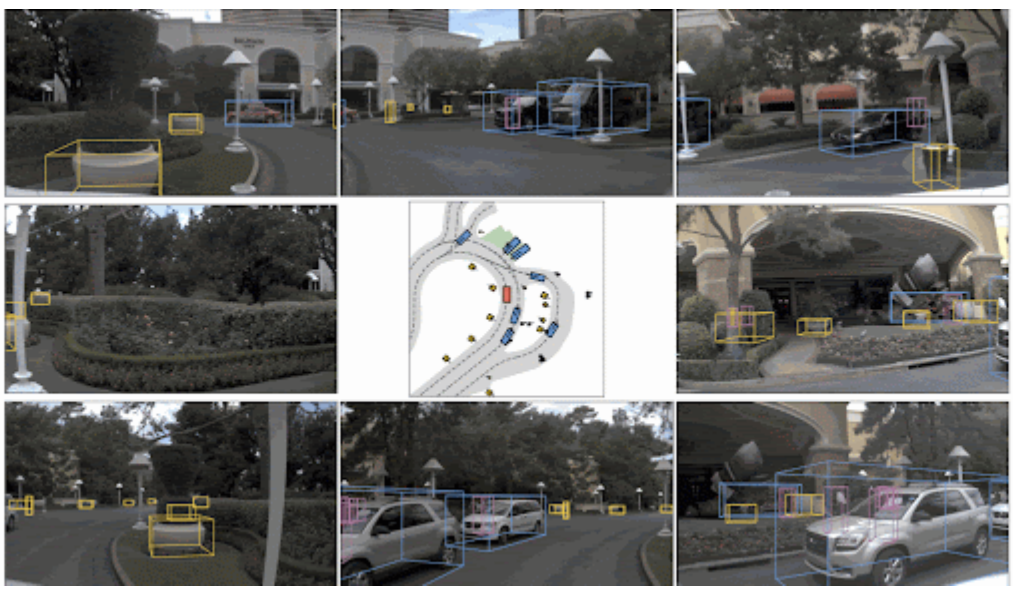
[2024： NVIDIA's Hydra-MDP]()

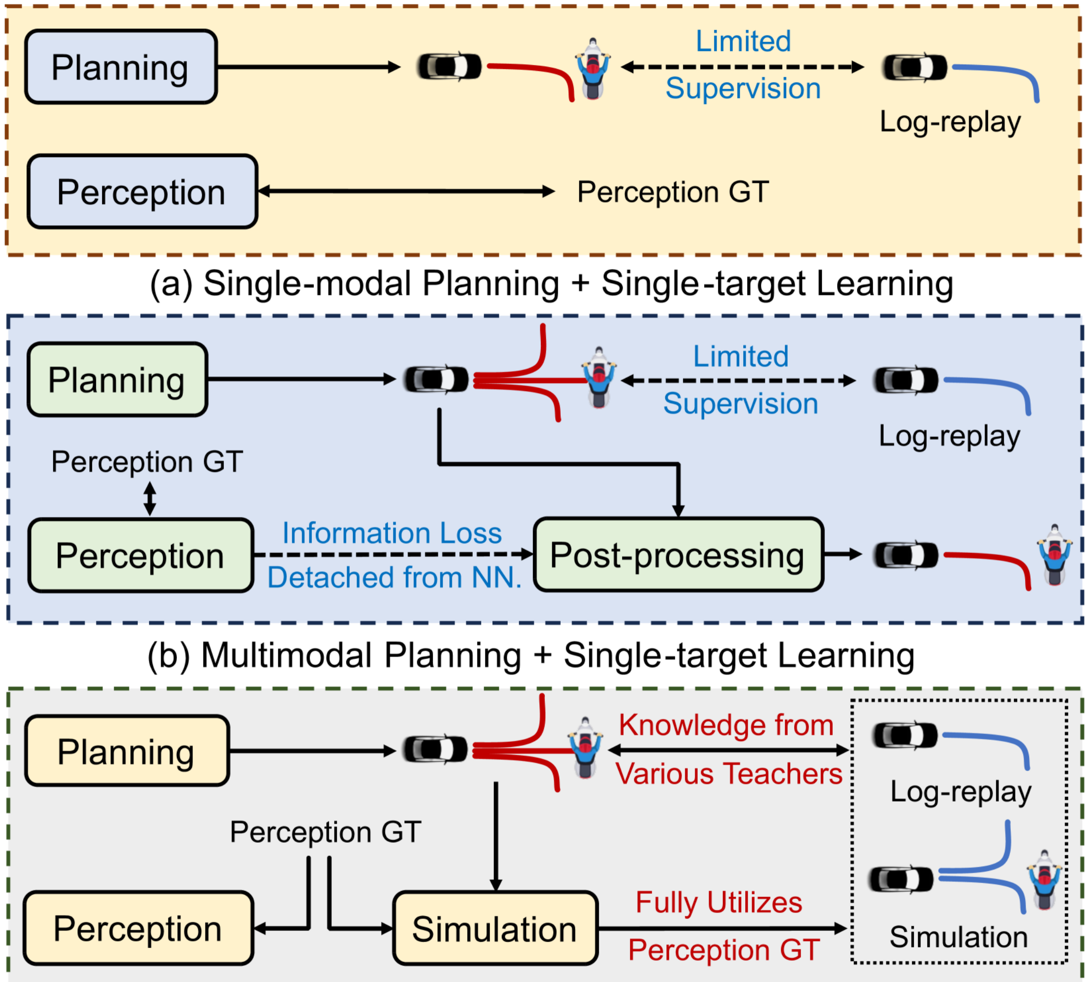
Hydra-MDP: Advancing End-to-End Driving

Building upon earlier work, NVIDIA introduced Hydra-MDP in 2024, an advanced framework that enhances end-to-end autonomous driving through a multi-teacher, student-teacher knowledge distillation architecture. Hydra-MDP integrates insights from both human drivers and rule-based planners, allowing the model to learn diverse trajectories and improve generalization across various driving environments. This approach addresses limitations of traditional imitation learning by ensuring adherence to traffic rules and safety standards. Hydra-MDP's scalability is demonstrated through its data-driven scaling laws, showcasing robustness and adaptability. Notably, Hydra-MDP secured first place and the innovation award in the E2E Driving at Scale Challenge at CVPR 2024, outperforming state-of-the-art planners on the nuPlan benchmark.

Key Features of Hydra-MDP

- **Multimodal and Multi-Target Planning**: Hydra-MDP embraces the complexity of planning by integrating diverse trajectories tailored to multiple metrics, including safety, efficiency, and comfort. This ensures adaptability to complex driving environments beyond merely mimicking human drivers.
- **Multi-Target Hydra-Distillation**: Employing a teacher-student framework, Hydra-MDP learns from multiple specialized teachers—both human and rule-based—enabling the model to predict trajectories aligning with various simulation-based metrics.
- **Explicit Safety Modeling**: The framework introduces novel approaches to modeling safety-related driving scores, addressing limitations of previous end-to-end systems that primarily relied on imitation learning without explicit safety considerations.

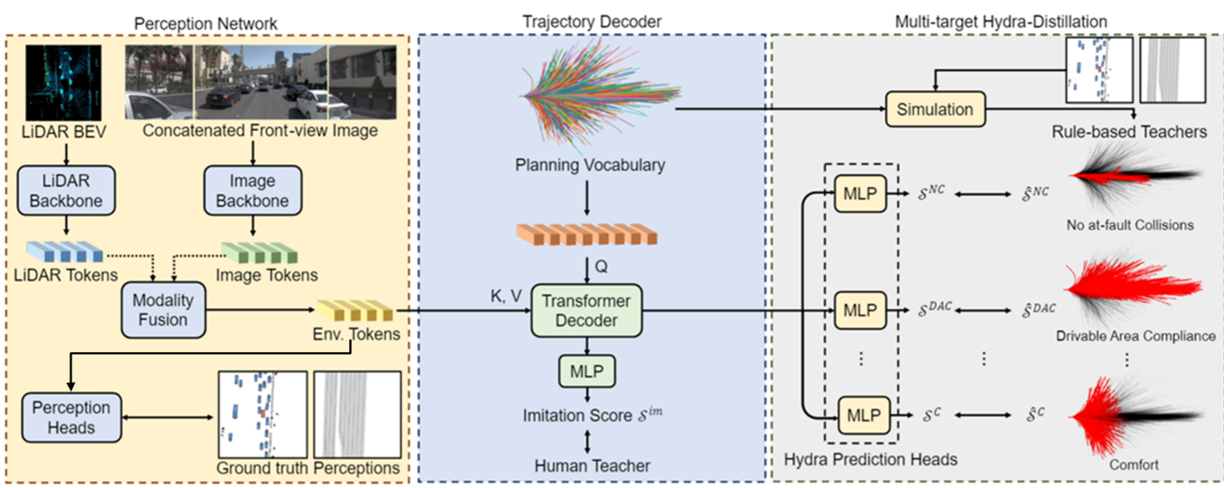




(a) Single-modal Planning + Single-target Learning

(b) Multimodal Planning + Single-target Learning

(c) Multimodal Planning + Multi-target Learning (Ours)



Youtube illustration: https://youtu.be/06BXs-R-fQ8

Development of Bird's-Eye-View (BEV) Representations

- **2018: Pseudo-LiDAR from Visual Depth Estimation**
  - *Researchers*: Yan Wang et al.
  - *Contribution*: Proposed generating point clouds from stereo images to mimic LiDAR data, bridging the gap between image-based and LiDAR-based methods for 3D object detection.
- **2019: MonoDepth and Depth Estimation Techniques**
  - *Researchers*: Clément Godard et al.
  - *Contribution*: Advanced monocular depth estimation, enabling the extraction of depth information from single images, which is crucial for generating BEV representations from cameras.

Integration of BEV in End-to-End Models

- **2020: Lift, Splat, Shoot**
  - *Researchers*: Travis Philion and Sanja Fidler.
  - *Contribution*: Introduced a method to project images into a 3D space (lifting) and then onto a BEV plane (splatting), facilitating BEV semantic segmentation from monocular images.
- **2021: BEVDet (Bird's-Eye-View Object Detection)**
  - *Researchers*: Huang Junjie et al.
  - *Contribution*: Proposed a framework for object detection in BEV space using multi-view images, improving performance by leveraging spatial relationships better represented in BEV.

Transformers in Computer Vision

- **2020: DETR (Detection Transformer)**
  - *Researchers*: Nicolas Carion et al.
  - *Contribution*: Applied transformer architectures to object detection, eliminating the need for hand-crafted components like anchor generation and non-maximum suppression.
- **2021: Vision Transformer (ViT)**
  - *Researchers*: Alexey Dosovitskiy et al.
  - *Contribution*: Demonstrated that pure transformer architectures could achieve state-of-the-art results on image classification tasks, paving the way for their application in more complex vision problems.

Culmination in BEVFormer

- **2022: BEVFormer**
  - *Researchers*: Zhijian Liu et al.
  - *Contribution*: Introduced a transformer-based framework that generates BEV representations from multi-view camera inputs. BEVFormer integrates spatial

and temporal information using transformers, enhancing 3D perception and planning in autonomous driving systems.

Key Innovations Leading to BEVFormer

1. **End-to-End Learning**: Early successes in mapping raw sensor data directly to control commands established the viability of end-to-end models.
2. **BEV Representations from Images**: Advancements in depth estimation and lifting techniques enabled the transformation of camera images into BEV space, which is more suitable for planning and navigation.
3. **Transformer Architectures**: The ability of transformers to model long-range dependencies and handle sequential data made them ideal for integrating spatial and temporal information in autonomous driving.

Features and Applications of BEVFormer

BEVFormer is a neural network architecture designed to generate Bird's-Eye-View (BEV) representations from multi-camera images, primarily for applications in autonomous driving. The name "BEVFormer" stands for **Bird's-Eye-View Transformer**, highlighting its use of transformer networks to process visual data.

Key Features:

- **Multi-Camera Input**: BEVFormer takes images from multiple cameras mounted around a vehicle, covering different angles to capture a comprehensive view of the surroundings.
- **Transformer Architecture**: It employs transformer models to effectively aggregate spatial and temporal information from the input images. Transformers are adept at handling sequences and capturing long-range dependencies, which is crucial for understanding complex environments.
- **BEV Representation**: The model projects 2D image features into a 3D space and then onto a BEV plane. This top-down view is particularly useful for tasks like object detection, tracking, and motion prediction in autonomous driving.
- **Spatiotemporal Fusion**: BEVFormer integrates both spatial (across different camera views) and temporal (over consecutive time frames) data, enhancing its ability to detect dynamic objects and understand motion patterns.

Applications:

- **3D Object Detection**: Identifying and localizing objects such as vehicles, pedestrians, and obstacles in three-dimensional space.
- **Semantic Segmentation**: Classifying each element in the BEV map to understand the types of objects or terrain present.

- **Motion Prediction**: Anticipating the future positions of moving objects, which is critical for safe navigation and planning.

Advantages:

- **Enhanced Perception**: By fusing data from multiple sources, BEVFormer provides a richer and more accurate understanding of the environment.
- **End-to-End Learning**: The transformer-based approach allows the model to be trained in an end-to-end fashion, potentially reducing the need for manual feature engineering.
- **Versatility**: While designed for autonomous driving, the principles behind BEVFormer can be applied to other domains requiring spatial-temporal analysis from multi-view data.

Significance in Autonomous Driving:

BEVFormer represents a significant advancement in the field of autonomous driving perception systems. Traditional methods often struggle with occlusions and limited fields of view. By leveraging transformer architectures and BEV representations, BEVFormer addresses these challenges by:

- **Improving Detection Accuracy**: Enhanced ability to detect and classify objects accurately, even in complex urban environments.
- **Facilitating Better Planning**: Providing detailed environmental maps that assist in path planning and decision-making processes.
- **Reducing Computational Complexity**: Streamlining the perception pipeline by unifying multiple processing steps into a single model.

In summary, BEVFormer is a cutting-edge model that enhances the capabilities of autonomous vehicles by generating detailed bird's-eye-view maps from multi-camera inputs using transformer networks. Its development marks a step forward in creating more reliable and efficient perception systems for self-driving cars.

Data on Robotaxi business models

1. Robotaxi Business Models and Cost per Mile

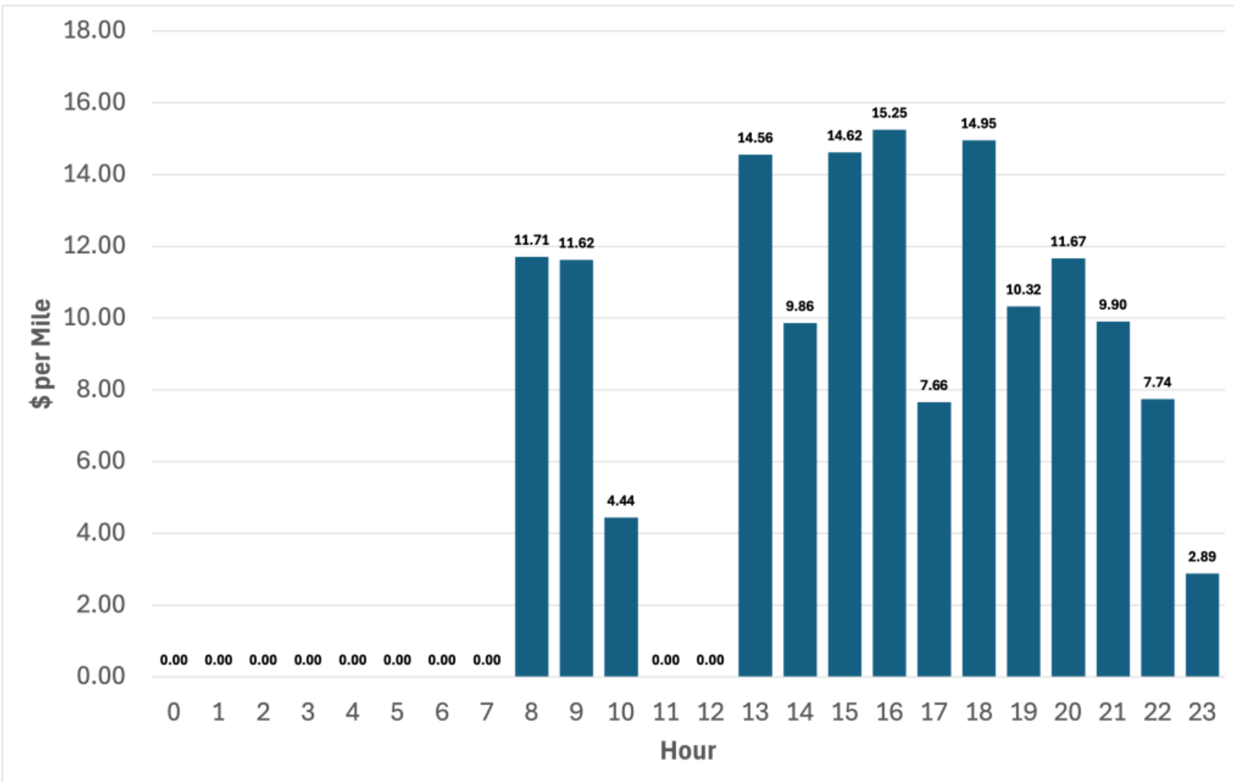
United States:

Waymo: In San Francisco, Waymo charges fares comparable to traditional ride-hailing services. For instance, a sample ride was priced between $11 and $14, aligning with Uber and

Lyft rates. However, Waymo incorporates surge pricing during peak times, potentially increasing costs.
Electrek

- First one-fifth mile of flag rate is $4.15.
- Each additional one-fifth mile or fraction thereof is $0.65.
- Each minute of waiting or traffic time delay is $0.65.

https://thelastdriverlicenseholder.com/2024/08/01/costs-of-waymo-rides/



Cruise:

Cruise's pricing structure includes a $5 base fare, plus $0.90 per mile and $0.40 per minute, without surge pricing. This results in a cost per mile of approximately $1.30, excluding time-based charges.
San Francisco Standard

Tesla:

Elon Musk has projected that Tesla's robotaxi rides could cost consumers between $0.30 and $0.40 per mile at scale, significantly lower than current ride-hailing services.
Next Big Future

Guanzheng Sun, research notes for Week Nov. 4, reporting to AJ on Nov. 13, 2024

China:

Baidu's Apollo Go:

In Wuhan, a 10-kilometer ride in an Apollo Go robotaxi costs between 4 and 16 yuan ($0.60 to $2.30), whereas a regular ride-hailing service costs between 18 and 30 yuan ($2.70 to $4.50). This indicates a cost per mile ranging from approximately $0.10 to $0.37 for robotaxis, compared to $0.45 to $0.75 for traditional services. Global Times

According to the interview from Sina Finance, the Newest robotaxi cost around ¥4.5 per kilometer ($0.39 per mile), while human ride hailing cost around ¥2.8 per kilometer ($0.24 per mile). A cost comparable to the Tesla Robotaxi.

Sina Finance

Previous Apollo moon cost $70000 based on a Chrysler Pacifica

Pony AI
A startup based in Guangzhou, China; Toyota holds 13.4% of its shares. Investors include GAC, Sequoia China, Legend Capital, and IDG.

Pony AI works with Toyota for their smart-driving solutions, the company has achieved L4-level autonomous driving, its newest technology are tested on Toyota BZ4X (previously Toyota Sienna and Lexus RX).
https://pony.ai/business?lang=en

Autonomous Driving demo: Toyota & Pony Robotaxi L4 Level Autonomous Driving VideoYouTube · Vision Effect TVNov 27, 2023

Their cost per mile is estimated to be $0.25 in 2022.

Europe:

As of now, major European automakers like BMW, Ford, and Daimler have not launched large-scale commercial robotaxi services. Geely, through its subsidiary Zeekr, has partnered with Waymo to develop purpose-built autonomous vehicles, but specific cost per mile data is not yet available.

Recent changes in Robotaxi manufacturing cost (bill of materials for Baidu's Robotaxi - can we find estimates for Waymo or others?)

Tesla Robotaxi:

Around 30000 dollars, with per millage cost of around $0.28

Baidu Apollo Go:
The 5th Gen cost around ¥600000, around $90000; while the newest 6th gen (most seen on the road) cost roughly ¥200000, around $30000. Sina Finance

Waymo:
The 5th gen, based on Jaguar I-Pace, cost around $100000 (vehicle itself 40-50k, another 40-50k for equipments). New York Times
They are patterning with Zeekr for their 6th gen minivan – the car is sold around $20-$30k in China, unless Zeekr can achieve production in the U.S. at the Volvo assembly plant, the cost is expected to be around $60k.

Technology Development

Recent changes (technology leaders and unit cost) in the upstream hardware 1) lidar 2) millimeter wave 3) on-board processors

1. Lidar

Lidar (Light Detection and Ranging) is critical for autonomous vehicles (AVs) as it provides 3D perception, enabling cars to "see" their surroundings. Recent developments in lidar technology have focused on reducing unit costs, improving range, reliability, and scalability.

A review of its development in the last 5-10 years:

1. Shift from Mechanical to Solid-State LiDAR (2015-2024)

- **Solid-State Innovation**: Around 2015-2017, the LiDAR industry began a major transition from traditional mechanical scanning LiDAR to solid-state LiDAR. Solid-state designs have fewer moving parts, improving reliability, reducing cost, and allowing for miniaturization.
- **Companies like Innoviz, Luminar, and Ouster** led this change, developing solid-state LiDARs suitable for automotive production.

2. Cost Reduction and Scalability (2018-Present)

- **Cost Focus**: One of the key advancements has been the drastic reduction in cost. In the past decade, the price of LiDAR sensors has dropped from tens of thousands of dollars to under $1,000. This drop was crucial for enabling the use of LiDAR in consumer vehicles.

- **Mass Production**: Partnerships with automotive suppliers (e.g., Luminar with Volvo, Velodyne with Ford) have led to more scalable manufacturing processes, helping meet the stringent cost requirements for mass production.

3. Range, Resolution, and Performance Improvements (2018-Present)

- **Improved Range**: Companies like Luminar have developed LiDAR sensors capable of detecting objects at distances of up to 250-300 meters with high accuracy. Long-range capabilities are essential for highway driving.
- **Higher Resolution**: Advances in resolution have also been significant, allowing LiDAR systems to identify small and distant objects, like animals or debris on the road. Higher resolution aids in more precise object classification, enhancing the safety and decision-making capabilities of autonomous driving systems.

4. Multi-LiDAR System Integration and Sensor Fusion (2019-2024)

- **Multi-LiDAR Setups**: Many automotive manufacturers have opted for multiple LiDAR sensors positioned at different locations around the vehicle to achieve a 360-degree field of view. Companies like Waymo and Cruise have used such setups to enhance their autonomous driving capabilities.
- **Sensor Fusion**: Advances in sensor fusion algorithms have enabled the integration of LiDAR with radar, cameras, and ultrasonic sensors. This combination improves the robustness of perception systems by mitigating weaknesses that individual sensors might have, such as poor visibility in rain or fog for cameras.

5. Partnerships and Adoption by Automakers (2020-Present)

- **OEM Partnerships**: Major automakers have partnered with LiDAR companies to bring autonomous driving features to market. In 2021, **Luminar partnered with Volvo** to include its LiDAR units in Volvo's flagship SUVs. Similarly, **Mercedes-Benz** and **BMW** formed alliances with companies like Valeo and Innoviz.
- **Launch in Consumer Vehicles**: LiDAR has slowly moved from experimental use cases to consumer vehicles. For example, **Honda's Legend** became the first production car with SAE Level 3 capabilities (conditional hands-off driving) using LiDAR in 2021. **Mercedes-Benz** also introduced Level 3 driving in 2023.

6. Emergence of Frequency-Modulated Continuous Wave (FMCW) LiDAR (2021-Present)

- **FMCW Technology**: Newer technologies like FMCW LiDAR, which provides velocity data in addition to distance measurements, have emerged. Companies like Aeva and Aurora have been pushing this technology, which provides a significant advantage by measuring the speed of objects directly, potentially improving perception and reducing processing requirements.

7. Commercial Viability and Safety Certifications (2020-2024)

- **Automotive-Grade Certification**: Automotive-grade certifications (e.g., ISO 26262 for functional safety) have become crucial milestones for LiDAR manufacturers. Companies like Velodyne, Innoviz, and Valeo worked towards getting these certifications to meet the rigorous safety standards of the automotive industry.
- **Robustness Improvements**: LiDAR systems have undergone significant improvements to make them robust against adverse weather conditions, such as heavy rain or snow, with better algorithms for data processing and improved sensor coatings to minimize interference.

8. Software and Machine Learning Integration (2021-Present)

- **Enhanced Perception**: LiDAR companies have increasingly been focusing on software as much as hardware, integrating **machine learning** to enhance object detection, classification, and tracking capabilities.
- **End-to-End Solutions**: Companies like Velodyne and Ouster started offering end-to-end solutions, providing not only LiDAR hardware but also the software stack for perception, which helps automotive companies integrate LiDAR data more effectively.

9. SPACs and Investment Surge (2020-2022)

- Around 2020-2021, many LiDAR companies, including **Velodyne, Luminar, and Aeva**, went public through Special Purpose Acquisition Companies (SPACs). This period saw a surge in investment, leading to increased R&D spending and accelerated technological progress.

10. Automotive OEM-LiDAR Company Consolidation (2023-Present)

- **Strategic Acquisitions**: In recent years, consolidation in the LiDAR space has taken place, with some automakers acquiring LiDAR startups to secure their supply chains. In 2023, **Mercedes-Benz** acquired a stake in Luminar, highlighting the strategic importance of LiDAR for autonomous driving and advanced driver-assistance systems (ADAS).

Technology Leaders:

Velodyne (U.S.): Velodyne remains a significant player with a focus on reducing production costs. They have introduced affordable solid-state lidar solutions, such as the Velarray H800, aimed at mass-market AVs. They pioneered 3D LiDAR sensors and transitioned towards solid-state technology, and merged with Ouster in 2023 to strengthen its position in the automotive LiDAR market.
Luminar (U.S.): Luminar has gained considerable traction through partnerships with major automakers like Volvo and Mercedes-Benz. Their Iris lidar is known for its extended range, and they have focused on scalability to reduce unit costs for integration in consumer vehicles.

Seyond (China): Seyond (previously Innovusion) is well-known for its involvement with NIO's autonomous driving projects. The company's Falcon lidar sensor boasts a range of up to 500 meters and leverages fiber laser technology for better reliability and performance.

RoboSense (China): RoboSense has been focused on making lidar cost-effective for mass adoption. Their RS-LiDAR-M1 is a MEMS-based solid-state lidar, which has seen adoption by carmakers like Geely. The M1 sensor offers significant improvements in cost reduction and robustness.

Valeo (France): Valeo has released their Scala 3 lidar, aiming at scalability for the consumer market, with partnerships involving manufacturers like Mercedes-Benz. Valeo focuses on balancing performance with affordability, aiming for €1,000 per unit in the coming years.

Hesai Technology (China): Hesai has been making strides with a focus on high-performance hybrid solid-state lidar. Their Pandar128 lidar has been adopted for both robotaxis and Level 3 consumer vehicles. They have also collaborated with partners like Xiaomi to reduce costs for mass adoption.

Innoviz Technologies (Israel): Offers solid-state LiDAR solutions and partnered with BMW to supply LiDAR for their autonomous vehicles; and selected by BMW in 2021 to provide LiDAR sensors for its Level 3 autonomous vehicles.

Aeva: Developed FMCW LiDAR technology capable of measuring instant velocity. And they partnered with TuSimple in 2021 to supply LiDAR sensors for autonomous trucking.

Unit Cost Trends:

Lidar prices have significantly dropped in recent years due to increased competition, new production methods, and improvements in manufacturing scalability. A few years ago, a high-end mechanical lidar like the Velodyne HDL-64 was priced around $75,000. Today, solid-state and MEMS lidars from companies like Luminar, Innovusion, and RoboSense are approaching a few hundred dollars per unit in high-volume production. This decline is essential for making lidar integration feasible for consumer vehicles.

2. Millimeter Wave Radar

Millimeter wave (mmWave) radar is another crucial sensor technology for autonomous driving, providing range, speed, and angle information under different environmental conditions (rain, fog, etc.).

A review of its development in the last 5-10 years:

1. Adoption of Higher Frequency Bands (2015-2024)

- **Shift from 24 GHz to 77 GHz/79 GHz**: Over the last decade, automotive radar systems have transitioned to higher frequency bands—mainly 77 GHz to 79 GHz. These higher frequencies offer improved resolution and range, allowing for better detection of smaller objects and enhanced performance in cluttered environments.
- **Improvement in Object Classification**: Moving to these higher frequency bands has improved radar systems' ability to differentiate between different types of objects, which is critical for advanced driver-assistance systems (ADAS).

2. Development of 4D Imaging Radar (2018-Present)

- **4D Imaging Technology**: Traditional radar systems provided 2D (range and velocity) or 3D (adding azimuth angle) data. 4D imaging radar, introduced over the past few years, adds elevation data, giving a complete 3D representation of objects, along with velocity.
- **Enhanced Perception**: This technology allows the radar to not only detect objects but also understand their height, providing richer environmental data, which helps in making better decisions for autonomous systems, especially in differentiating between objects like cars, pedestrians, and overpasses.

3. Advanced Signal Processing and Digital Beamforming (2018-2024)

- **Digital Beamforming**: The adoption of digital beamforming in mmWave radar has allowed the radar system to create multiple beams for simultaneous detection of several objects, improving angular resolution and accuracy.
- **MIMO (Multiple-Input Multiple-Output) Technology**: The use of MIMO radar arrays has also improved resolution and helped in achieving a wider field of view, which is essential for full 360-degree sensing in advanced autonomous vehicles.

4. Sensor Fusion and Integration (2019-Present)

- **Multi-Sensor Fusion**: Radar sensors are increasingly being used alongside LiDAR, ultrasonic, and camera systems for comprehensive environmental sensing. Fusion of these sensors has allowed autonomous driving systems to combine the robustness of radar (e.g., performance in adverse weather) with the visual detail provided by cameras and LiDAR.
- **Smaller Footprint Sensors**: Radar systems have also become smaller and more integrated, making them easier to embed into vehicle designs for 360-degree sensing.

5. AI and Machine Learning Integration (2020-2024)

- **Enhanced Radar Signal Interpretation**: Machine learning and AI techniques have been integrated to help radar systems better interpret reflections, reducing false positives and improving the classification of different types of obstacles.

- **Object Detection and Prediction**: AI-enhanced radar can now predict the movement of objects more accurately, helping to improve decision-making in complex driving situations, such as distinguishing between moving and stationary objects or detecting vulnerable road users like cyclists and pedestrians.

6. Emergence of Short-Range and Long-Range Radar Applications (2018-2024)

- **Short-Range Radar (SRR)**: Used for features like parking assistance, blind-spot monitoring, and rear cross-traffic alerts. The recent advancements have made SRR more precise, allowing for enhanced capabilities in crowded parking environments.
- **Long-Range Radar (LRR)**: Key for adaptive cruise control (ACC) and forward collision warning (FCW) systems. Modern LRR systems offer detection ranges of up to 300 meters, with significant improvements in resolution and accuracy, making them suitable for autonomous driving on highways.

7. Cost Reduction and Automotive-Grade Certifications (2020-Present)

- **Lower Production Costs**: Advances in semiconductor technology have led to more affordable radar sensors, which has contributed to the wider adoption of radar technology in mid-range and economy vehicles, rather than just luxury models.
- **Automotive-Grade Radar**: Companies like Bosch and Continental have worked on developing radar units that meet the high standards of the automotive industry, achieving certifications like ISO 26262 for functional safety, which is crucial for integrating radar in safety-critical systems.

8. 4D Radar Solutions in Commercial Vehicles (2022-Present)

- **Deployment in Production Vehicles**: Several car manufacturers have started incorporating 4D radar in production vehicles for both ADAS and higher-level autonomous driving. In 2022, companies like Arbe Robotics and ZF Friedrichshafen introduced advanced 4D radar units, which improved the quality of perception data available to the vehicle.
- **Enhanced Safety and Redundancy**: The use of 4D radar in commercial vehicles has helped achieve better redundancy, improving safety in urban and highway environments by ensuring the vehicle understands and predicts the behavior of surrounding vehicles and pedestrians accurately.

Technology Leaders:

Bosch (Germany): Bosch is a long-time leader in automotive radar. Their recent radar units, like the 6th generation long-range radar, provide enhanced object recognition and low-speed maneuvering capabilities, aimed at Level 3/4 driving. In 2023, Bosch introduced their new "Mid-Range Radar" sensors to support SAE Level 3 automated driving, enabling vehicles to handle more challenging road scenarios autonomously.

Continental (Germany): Continental continues to innovate with their ARS540, a high-resolution 4D imaging radar designed for use in autonomous applications. Their focus is on improving spatial accuracy and target separation. In 2021, Continental launched the "ARSM" (Advanced Radar Sensor Module) series to provide a 360-degree view of the vehicle environment.

Aptiv (U.S.): Aptiv is focused on the development of 77 GHz radar units, offering a balance of cost-effectiveness and performance. Partnered with Hyundai in 2019 to form Motional, a joint venture focusing on developing fully autonomous driving systems, including using radar as a key sensor for safety. Their latest generation radars are optimized for use in multiple driving scenarios.

Huawei (China): Huawei has invested heavily in automotive radar technology. Their 77 GHz mmWave radar integrates with their broader smart mobility solutions, focusing on cost optimization for production scalability.

Zongmu Technology (China): Zongmu has developed a series of radar solutions aimed at enhancing ADAS and autonomous driving capabilities, partnering with domestic automakers to provide affordable mmWave radar units.

NXP Semiconductors (Netherlands): NXP provides radar chipsets that have enabled the automotive industry to develop high-resolution radar systems, advancing ADAS capabilities. In 2022, NXP introduced a new 4D imaging radar platform capable of generating detailed images for driver assistance applications.

Texas Instruments (US): Texas Instruments is a leader in the production of millimeter-wave radar chips used for automotive sensing. In 2021, TI introduced the AWR2944 radar sensor that provides longer range and increased accuracy for ADAS and automated driving.

Hella (German-French): Hella, now part of Faurecia, is a well-known automotive radar supplier, especially for blind-spot detection and rear cross-traffic alert systems. In 2022, Hella launched an advanced radar for detecting objects up to 300 meters, suitable for highway driving assistance and vehicle automation.

Zendar (US): Zendar focuses on merging the capabilities of radar with imaging technologies to create radar sensors with higher resolution. Their unique radar system, introduced in 2023, aims to close the gap between radar and LiDAR/camera technologies in terms of image quality and detail. https://www.zendar.io

Unit Cost Trends:

The cost of millimeter wave radar has been reduced significantly over the last few years, primarily driven by increased production volume and design efficiency. The typical cost for an automotive-grade radar has dropped from several hundred dollars to roughly \$50-\$100 per unit, particularly for front and rear short- and medium-range radars. This price drop has been driven by advancements in CMOS-based radar chips, allowing for more integration and scalability in production.

3. On-Board Processors

On-board processors are the "brain" of autonomous vehicles, responsible for processing vast amounts of data from sensors to make real-time decisions.

Qualcomm Snapdragon is now taking the lead, previously the head was Intel Tegra.

Technology Leaders:

NVIDIA (U.S.): NVIDIA remains a leading force with its DRIVE platform. Their Orin SoC (System-on-Chip) is capable of handling up to 254 TOPS (Trillions of Operations Per Second), providing sufficient power for Level 4/5 autonomy. NVIDIA focuses on partnerships with automakers like Mercedes-Benz and NIO to bring cost-effective high-performance solutions to market.

Qualcomm (U.S.): Qualcomm has expanded its Snapdragon Ride platform, offering a scalable architecture that targets everything from ADAS to fully autonomous driving. Snapdragon Ride is valued for its power efficiency, which also helps keep costs lower for deployment in consumer vehicles.

Mobileye (Israel, subsidiary of Intel): Mobileye's EyeQ5 is designed for high-level ADAS and autonomous vehicles. The company has partnerships with several major automakers, including BMW and Geely, focusing on affordability through improved silicon efficiency and integration.
Huawei (China): Huawei is investing heavily in automotive-grade chipsets. Their Ascend and MDC platforms are designed for high-performance autonomous applications. Huawei focuses on optimizing processing power per dollar, making it a significant player in the Chinese market.

NXP Semiconductors (Netherlands): NXP offers a range of automotive processors, including their S32G vehicle network processors. They focus on providing a balance between performance and cost, particularly for Level 2/3 automation.

Renesas (Japan): Renesas has been a key supplier of automotive processors, particularly targeting the ADAS market. Their R-Car V4H is aimed at improving cost efficiency for Level 2+ ADAS systems.

Unit Cost Trends:

Recent developments in on-board processors for autonomous driving have primarily focused on increasing the performance-per-watt ratio and making the processors more affordable. Companies like Qualcomm and Mobileye are actively pursuing efficiency improvements that enable powerful processing without an exorbitant cost increase. For instance, Qualcomm's Snapdragon Ride chips are designed to be more affordable for consumer vehicles, bringing high-performance AI capabilities at a reasonable price. Unit costs for high-end processors can vary, with some ranging between $500 to $1,500 depending on the configuration and application. However, the trend is moving toward lower cost solutions as manufacturing scales up and competition intensifies.

Of course, Autonomous vehicles (AVs) rely on a array of specialized chips to process data from various sensors. The primary categories of these chips include:

Central Processing Units (CPUs): These general-purpose processors handle a wide range of tasks, including running the vehicle's operating system and managing communication between different components.

Graphics Processing Units (GPUs): GPUs are essential for handling the massive parallel computations required for processing visual data and running machine learning algorithms.

Application-Specific Integrated Circuits (ASICs): These are custom-designed chips optimized for specific tasks, such as accelerating neural network computations.

Microcontroller Units (MCUs): MCUs manage real-time control tasks, including sensor interfacing and executing safety-critical functions.

Field-Programmable Gate Arrays (FPGAs): FPGAs offer flexibility by allowing hardware reconfiguration to optimize performance for specific applications.

Leading Companies and Their Contributions:

NVIDIA: A dominant player in the AV chip market, NVIDIA's DRIVE platform integrates high-performance GPUs and CPUs to handle complex computations required for autonomous driving. Their DRIVE Orin system-on-a-chip (SoC) is capable of delivering up to 254 trillion operations per second, supporting advanced driver-assistance systems (ADAS) and full autonomy.

Intel's Mobileye: Specializing in vision-based systems, Mobileye develops ASICs tailored for autonomous driving. Their EyeQ series chips are widely adopted for processing visual data and making driving decisions.

- Mobileeye has been critizied for stealing Chinese critical data by the Chinese government, and also criticized by Geely as severely delaying co-efforts on autonomous driving

Qualcomm: Through its Snapdragon Ride platform, Qualcomm offers scalable solutions combining CPUs, GPUs, and AI accelerators to support various levels of vehicle autonomy.

Tesla: Tesla has developed its own Full Self-Driving (FSD) computer, featuring custom-designed chips optimized for neural network processing, reducing reliance on external suppliers.

Horizon Robotics: A Chinese company focusing on AI chips for autonomous driving, Horizon Robotics offers processors like the Journey series, designed for efficient processing of sensor data and decision-making in AVs.

Renesas Electronics: A Japanese semiconductor manufacturer, Renesas provides MCUs and SoCs for automotive applications, including autonomous driving, emphasizing safety and reliability.

NXP Semiconductors: Based in the Netherlands, NXP offers a range of automotive processors and MCUs, such as the S32G vehicle network processors, supporting real-time data processing and vehicle networking.

Precision Mapping

Cost of **precision mapping** (some Robotaxi operates need HD maps, while some don't. What's the **added cost of mapping each city** you operate in, how does this slow/hinder scaling?)

In China’s case, a HD map with 10cm precision cost roughly 10 yuan per kilometer, while 1cm precision cost 1000 yuan per mile. So Chinese auto companies have managed to develop technologies that allow them to achieve smart driving based on V2X networks and other advanced technologies using different levels of mapping.
https://cn.nikkei.com/china/ccompany/52205-2023-04-26-10-54-48.html

Mapping Challenges: Collecting data for HD maps is much more demanding than for traditional maps. Factors like static points (intersections, traffic signs), lines (roads, bridges), areas (land use types), and dynamic elements (traffic light status, vehicle flow) are included. The level of detail is much higher, making data collection significantly challenging.

High Costs of Real-time Updates: It is challenging to gather real-time data from multiple lanes in one direction simultaneously. Data collection often requires individual lane collection and frequent updates, which significantly raises the costs.

Efficiency of Traditional vs. High Precision Mapping: According to a 2020 report, using traditional survey vehicles for centimeter-level HD mapping can collect around 500 km of data daily at a cost of 10 yuan per kilometer. In comparison, achieving the same precision with millimeter-level mapping can only cover around 100 km per day, with costs potentially reaching 1,000 yuan per kilometer—100 times the cost of traditional mapping.

Cost of Specialized Survey Vehicles: Specialized surveying vehicles cost between 5-8 million yuan each. Building a mapping team with around 20 vehicles results in total costs exceeding 100 million yuan, illustrating the high financial barrier for precision mapping.

A professional HD-map capable surveying vehicle cost around $400,000-1,000,000, and a fleet that contains 20 cars mean it would cost around $20,000,000.

High Precision Requirements: Compared to traditional maps, high-definition (HD) maps require more precise data, richer content, and higher demands for freshness and update frequency. Traditional maps have an accuracy of within 10 meters, while HD maps need a precision of 0.5 meters or better.

Technology for precision mapping: https://arxiv.org/pdf/2206.05400v1 (Best source on how it works, translating roads to images to actual data), as well as the article below: https://www.cambridge.org/core/journals/journal-of-navigation/article/high-definition-map-for-automated-driving-overview-and-analysis/7FFB4F68B9C27F4312AF8DCD553205FE

Huawei claims “The survey cost for a map with 10-cm accuracy is 10 yuan ($1.44) per kilometer, but for accuracy to 1 cm costs up to 1,000 yuan”. https://asia.nikkei.com/Spotlight/Electric-cars-in-China/Huawei-scraps-expensive-precision-maps-in-self-driving-cars

The HD Map for Autonomous Vehicles Market, by value, is estimated to be USD 1.4 billion in 2021 and is projected to reach USD 16.9 billion by 2030. Markets and Markets

Why don’t companies just buy from Google and Apple? Apparently – buying from existing companies is more expensive than doing it yourself – DeepMap, a U.S. startup in HD mapping, charges $5000 per kilometer for mapping service in the U.S.

Below is a table that contrasts buying v. building HD Maps. Source

Basis	Buy HD Maps	Build HD Maps
Expertise	Can leverage vendor's expertise	Requires internal expertise or hiring experts
Cost	Less expensive upfront but would need regular updates as maps are constantly changing	High upfront costs and ongoing maintenance expenses
Scalability	Can scale with vendor's support	Can customize and scale to meet specific needs
Customization	Limited ability to customize	Greater control over features and customization
Accuracy	Mostly rely on AI-assisted annotation tools, which are not always accurate	Better judgment in edge cases with highly accurate annotations
Time-to-market	Faster deployment with a turnkey solution	It may take longer to develop in-house

Key considerations for companies to decide buy or build:

Data Availability: Geospatial data necessary for HD maps is often proprietary, making it difficult for AV companies to collect high-quality data independently.

Regulatory Compliance: Different countries have unique regulations governing the collection and distribution of geospatial information, complicating efforts for companies operating in multiple regions.

Standardization Issues: The lack of standardized data specifications for HD mapping leads to variations among manufacturers and mapping companies, affecting interoperability and consistency.

When conducting precision mapping for autonomous vehicles, companies often need to capture detailed imagery and data of urban environments. This process can involve filming or photographing public spaces, which may require permits or permissions, depending on the city's regulations.

Permit Requirements:

Public Property: Filming or photographing on public streets, sidewalks, or other city-owned properties typically necessitates a permit. For instance, in Chicago, the City of Chicago issues permits for filming on public ways, with fees of $250 per day per location. Student films and independent projects may qualify for a reduced fee of $25 per day per location upon verification.
https://www.chicago.gov/city/en/depts/dca/supp_info/permits.html

City-Specific Regulations: The specific requirements vary between municipalities. Some cities are more permissive, while others may require fees or special permissions. For example:
San Francisco, California: Mapping data collection often requires a temporary encroachment permit, as vehicles may need to operate in unique ways (such as frequent stops or utilizing advanced sensor equipment that interacts with public infrastructure).

New York City, New York: There may be requirements to register the activity with local transportation or public works departments, particularly for vehicle fleets operating extensively in dense urban environments.

Drone Use for Mapping: If drones are involved in the geographic surveying, there will typically be additional costs and requirements related to aviation. The Federal Aviation Administration (FAA) in the U.S., for instance, requires special permits to fly drones for commercial purposes over urban areas.

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1. What is Self-Driving?

According to the definition found in this article by McKinsey & Company[1], at its most basic level, a self-driving (autonomous vehicle, AV) is one that uses advanced software, hardware, and services to operate itself, with minimal human intervention. University of Michigan Center for Sustainable Systems[2] further defines AV as vehicles that use technology to partially or entirely replace the human driver in navigating a vehicle.

2. What purposes was this technology created to serve?

AV was created not only to revolutionize transportation (although a main purpose), but also to address various societal needs. One fundamental purpose of AV is to reduce human error, prevent traffic accidents, and improve road safety. Google, in their 2010 blog, disclosed to the public that the goal of their automated vehicle research is "to help prevent traffic accidents, free up people's time and reduce carbon emissions by fundamentally changing car use"[3]. AV can be programmed not to break traffic laws and not drink and drive, their reaction times are quicker than humans, and they can be optimized for safer driving[4]. Of course, technology, like human, are not entirely reliable, hardware and software can malfunction, and existing technology cannot fully recognize

[1] McKinsey & Company. 2025. "What Is a Self-Driving Car? | McKinsey." March 5, 2025. https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-a-self-driving-car.
[2] Center for Sustainable Systems, University of Michigan. 2024. *Autonomous Vehicles Factsheet.* Pub. No. CSS16-18. Ann Arbor, MI: University of Michigan.
[3] Thrun, Sebastian. 2010. "What We're Driving at." *Official Google Blog* (blog). Accessed April 18, 2025. https://googleblog.blogspot.com/2010/10/what-were-driving-at.html.
[4] Fagnant, Daniel J., and Kara Kockelman. 2015. "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations." *Transportation Research Part A: Policy and Practice* 77 (July):167–81. https://doi.org/10.1016/j.tra.2015.04.003. p. 169.

everything on the road, just as humans do. But AI can do better at obeying stated speed limit and never DUI.

Aside from making automobiles safer, researchers are also developing AV to reduce road congestions and fuel consumption. AV can break and accelerate smoothly and programmatically, leading to fuel savings and less break wear; they may also be less willing to change lanes.[5] Advanced AV technology relies on vehicle to everything (V2X), which include vehicle to vehicle (V2V) and vehicle to infrastructure (V2I).[6] This network includes reception and transmission of information from vehicle to road and other transportation infrastructure and other vehicles on the road to lively report road information, which can avoid congestion by informing Avs to utilize less congested local roads and creating optimized routes counting the stop signs and traffic lights.

Multiple studies have explored the potential of autonomous vehicles (AVs) to alleviate congestion. At different levels of AV adoption, congestion reduction through adaptive cruise control (ACC) and traffic monitoring systems could facilitate smoother traffic flows by minimizing unnecessary acceleration and braking on freeways. According to Atiyeh (2012)[7], these measures could enhance fuel economy by approximately 23–39% and increase traffic speeds during congestion by about 8–13% for all vehicles, depending on the effectiveness of vehicle-to-vehicle (V2V) communication and the implementation of traffic-smoothing algorithms. Furthermore, if AVs are able to safely travel closer together, additional savings in fuel consumption and congestion are expected, potentially significantly boosting the capacity of

[5] Fagnant and Kockelman 2015, p. 170.
[6] Fagnant and Kockelman 2015, p. 170.
[7] Atiyeh, Clifford, 2012. Predicting Traffic Patterns, One Honda at a Time. MSN Auto, June 25.

existing highway lanes (Tientrakool, Ho, and Nicholas F. 2011)[8]. Shladover et al. (2012)[9] estimate that the implementation of cooperative adaptive cruise control (CACC) at market penetration levels of 10%, 50%, and 90% could increase lane capacity by approximately 1%, 21%, and 80%, respectively.

AV can deliver freight and unlicensed travelers to their destinations[10]. Subsequently increasing access and mobility across a range of populations currently unable or not permitted to operate conventional automobiles, such as the blind and the elderly[11] (Anderson et al. 2014, p. 17). Admittedly, the blind and elderly may utilize ride-sharing services like Uber, Lyft, or taxis; but those services may get delayed, cancelled, or not inclusive for these marginalized peoples. Having a car in your garage that can take you to where you need to go is always a better guarantee than relying on someone else.

Of course, one of the most praised and applauded purpose of self-driving is the opportunity for multi-tasking and leisure during a trip. Avs enable drivers to engage in other productive or enjoyable activities—such as working, reading, watching movies, or even sleeping—during trips, thereby significantly reducing the opportunity cost associated with time spent traveling by car[12].

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[8] Tientrakool, Patcharinee, Ya-Chi Ho, and Maxemchuk Nicholas F. 2011. "Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance | IEEE Conference Publication | IEEE Xplore." Accessed April 18, 2025. https://ieeexplore.ieee.org/document/6093130.
[9] Shladover, Steven E., Dongyan Su and Xiao-Yun Lu. "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow." *Transportation Research Record* 2324 (2012): 63 - 70.
[10] Fagnant and Kockelman 2015, p. 169.
[11] Anderson, James M., Kalra Nidhi, Karlyn D. Stanley, Paul Sorensen, and Constantine Samaras. 2014. *Autonomous Vehicle Technology: A Guide for Policymakers*. RAND Corporation research report series, RR-443-1-RC. Erscheinungsort nicht ermittelbar: RAND Corporation.
[12] Anderson et al (2014). p. 18.

Lastly, rather than just contributing to regular civil usage, AVs can also empower logistics (self-driving trucks), military operations, mining, and agricultural production through programmed routes.

3. What purposes was it adopted to use?

First of all, no system has achieved level 5 – fully autonomous vehicles that require no human intervention, as developed by The Society of Automative Engineers (SAE)[13]. I have attached two graphs outlining the SAE definitions for autonomous driving levels. The first graph provides a concise overview of each level, while the second details the specific capabilities and responsibilities associated with each category.

Levels	Description
Level 0	Vehicles equipped with no automated features, requiring the driver to be in complete control of the vehicle.
Level 1	Vehicles equipped with one or more primary automated features such as cruise control, but requiring the driver to perform all other tasks.
Level 2	Vehicles equipped with two or more primary features, such as adaptive cruise control and lane-keeping, that work together to relieve the driver from controlling those functions.
Level 3	Vehicles equipped with features that allow the driver to relinquish control of the vehicle's safety-critical functions depending on traffic and environmental conditions. The driver is expected to take over control of the vehicle given the constraints of the automated features after an appropriately timed transition period.
Level 4	Vehicles equipped with features that allow the driver to relinquish control of the vehicle's safety-critical functions. The vehicle can perform all aspects of driving even if the driver does not respond to a request to intervene.
Level 5	Fully autonomous vehicles that monitor roadway conditions and perform safety-critical tasks throughout the duration of the trip with or without a driver present. This level of autonomy is appropriate for occupied and unoccupied trips.

Figure 1. SAE Levels of Automation: Summary of Definitions

[13] On-Road Automated Driving (ORAD) committee. 2021. "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles." SAE International. Accessed April 18, 2025. https://doi.org/10.4271/J3016_202104.

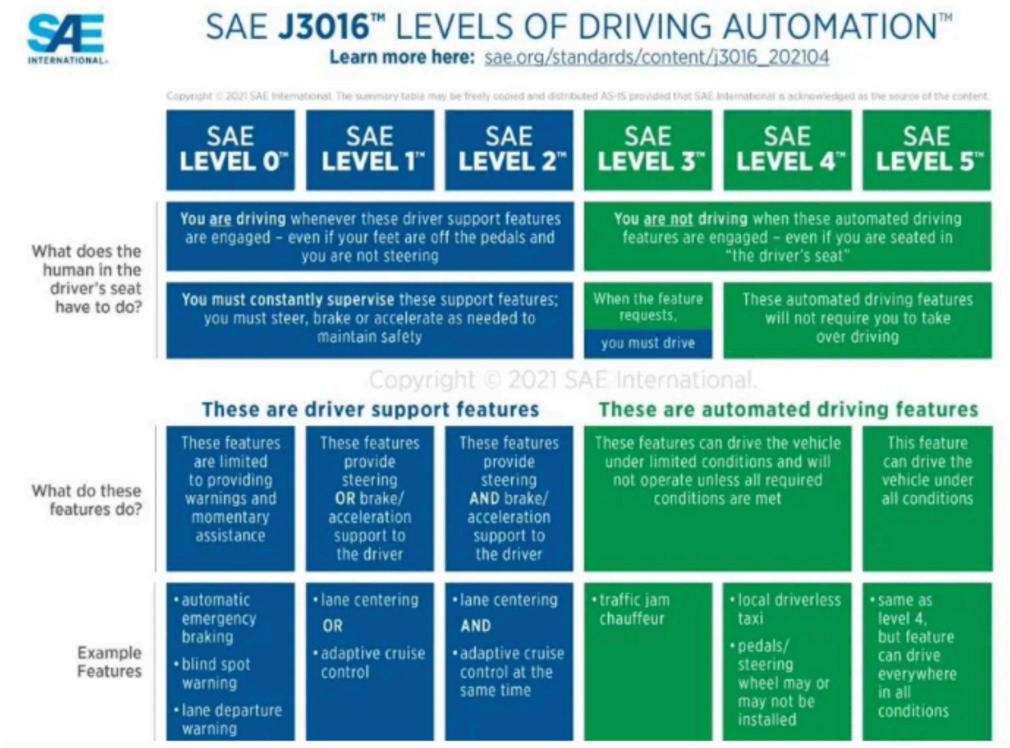

Figure 2. SAE Levels of Driving Automation: Detailed Capabilities

Nevertheless, existing autonomous vehicles, mostly operate on L2 (exemplified by post 2015 vehicles equipped with ACC with lane centering), L3 (Tesla AP and similar technologies), L4 (Tesla FSD, Waymo, other Chinese AV tech companies), can provide services including but not limited to:

- Highway Assistant Driving
- City Assistant Driving
- Robotaxi (such as Waymo)
- Self-driving delivery cars (such as Nuro, they are very cute)
- Amazon Self-Driving Rivians.

4. What's the nature of its politics?

There are no national standards or guidelines for Avs, allowing states to determine their own. The AV START Act (S.1885), introduced in 2017 to establish a federal framework for AV testing and deployment, failed to pass both chambers of Congress and has not been reintroduced. Consequently, regulatory authority over AVs continues to reside predominantly with individual states. [14]By November 2024[15], 35 states have enacted laws regulating various aspects of AV operation, including testing protocols, deployment guidelines, and liability considerations. These laws vary widely, creating a complex and fragmented regulatory environment across the country. The NHTSA's recent AV STEP program represents an effort to provide a degree of federal oversight, but comprehensive regulation remains underdeveloped.

Stakeholders have expressed concerns that a "patchwork of conflicting state laws could hamper deployment of Avs" (Anderson et al. 2014, p. 53). The federal government need to expand research and create a standardized national framework, or at least negotiatory and conciliatory structures that determine standards for security, data privacy, and liability.

Current technologies are not able to react completely to all the events happening on the road, such as in low visibility settings[16] or noticing people are crossing the road[17]. The security risks as related to hurting pedestrians are not the only security concerns as relating to road security,

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[14] All Info - S.1885 - 115th Congress (2017-2018): AV START Act. (2017, November 28). https://www.congress.gov/bill/115th-congress/senate-bill/1885/all-info

[15] Dunn, James, Trey Grayson, and Heather McMutry. 2024. "AV Compliance Is Still a State-by-State Slog —…." Frost Brown Todd. December 17, 2024. https://frostbrowntodd.com/av-compliance-is-still-a-state-by-state-slog-for-now/.

[16] Shepardson, David, Akash Sriram, and Akash Sriram. 2024. "US Probes Tesla's Full Self-Driving Software in 2.4 Mln Cars after Fatal Crash." *Reuters*, October 18, 2024, sec. Autos & Transportation. https://www.reuters.com/business/autos-transportation/nhtsa-opens-probe-into-24-mln-tesla-vehicles-over-full-self-driving-collisions-2024-10-18/.

[17] Rose, Andy, Veronica Miracle, and Jeffery Kopp. 2023. "A Woman Was Found Trapped under a Driverless Car. It Wasn't the First Car to Hit Her | CNN Business." CNN. October 3, 2023. https://www.cnn.com/2023/10/03/tech/driverless-car-pedestrian-injury/index.html.

technological limitations of all existing solutions to self-driving (including lidar, radar, and image) could all make mistakes when reaction times toward sudden accidents on the road[18].

Road security, moreover, isn't the sole concern as related to governing this technology. Self-driving technology collects extensive amount of road and image data[19], as well as personal data [20](generational, name, geolocational, behavioral, and information from connected services). These data could be used to conduct analyses and pose severe privacy concerns.

Self-driving's reliance on live data and connected services, also expose them to cyberattacks. Although this has primarily only taken place within sci-fi movies, this concern could still become a reality. Although some solutions have been proposed[21], the danger of your car being controlled by someone else during a tiring road trip or city street could be very terrifying.

Moreover, several accidents regarding self-driving in China has brought concerns over the liability of accidents [22]in self-driving: who should take responsibility? Should it be the driver, the car, the vehicle company, or the self-driving solution companies? This concern has been echoed in multiple sources I reviewed on self-driving: coming from either manufacturers[23], legislators[24],

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[18] Thadani, Trisha, Rachel Lerman, Imogen Piper, Faiz Siddiqui, and Irfan Uraizee. 2023. "The Final 11 Seconds of a Fatal Tesla Autopilot Crash." Washington Post. Accessed April 13, 2025. https://www.washingtonpost.com/technology/interactive/2023/tesla-autopilot-crash-analysis/.

[19] Guariglia, Matthew. 2023. "The Impending Privacy Threat of Self-Driving Cars." Electronic Frontier Foundation. August 4, 2023. https://www.eff.org/deeplinks/2023/08/impending-privacy-threat-self-driving-cars.

[20] Kessler, David, and Alexis Wilpon. 2021. "Tech & Telecom, Professional Perspective - Privacy Implications of Autonomous Vehicles." Accessed April 13, 2025. https://www.bloomberglaw.com/external/document/XB0JL88000000/tech-telecom-professional-perspective-privacy-implications-of-au.

[21] Danby, Charlotte, and Jack Weatherston. 2025. "Protecting Autonomous Vehicle Drivers from Cyberattacks." Waterloo News. April 7, 2025. https://uwaterloo.ca/news/eweal-protecting-autonomous-vehicle-drivers-cyberattacks.

[22] Villasenor, John. 2014. "Products Liability and Driverless Cars: Issues and Guiding Principles for Legislation." Brookings. April 24, 2014. https://www.brookings.edu/articles/products-liability-and-driverless-cars-issues-and-guiding-principles-for-legislation/.

[23] Anderson et al (2014). p. 152.

[24] Mosquet, Xavier, Thomas Dauner, Nikolaus Lang, Michael Rüßmann, Rakshita Agrawal, Florian Schmieg, and Antonella Mei-Pochtler. 2021. "Revolution in the Driver's Seat: The Road to Autonomous Vehicles." BCG Global.

and drivers themselves. Current liability system and its applicability to Avs are being debated, with uncertainty about who would be at fault in case of a crash involving a self-driving vehicle.

Moreover, the transition to AVs will become politically complicate as well. Negatively affected groups, such as taxi, ride-share, and truck drivers may exert pressure on policymakers to protect their interests[25]. The automotive industry, those with advanced tech may seek less control on self-driving tests and innovations, and those with less advanced tech hoping to limit their competitor's progress by exerting more stringent control.

5. Assumptions and Biases

One common assumption is that autonomous vehicles (AVs) are inherently safer than human drivers. However, as I previously noted, current technological limitations prevent AVs from reliably detecting and responding to all road conditions and incidents. Moreover, machines remain susceptible to malfunctions. Taken together, these factors suggest that, at present, AVs should serve primarily as driving assistance tools rather than as fully autonomous replacements for human drivers.

Algorithm-based calculation may provide less coverage and service in marginalized communities, both due to risk calculation and lack of necessary infrastructures. This is similar to insurance companies declining to offer new coverage in California[26]. Highly advanced network coverage and precision mapping, necessary for self-driving, could be lacked in these

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January 8, 2021. https://www.bcg.com/publications/2015/automotive-consumer-insight-revolution-drivers-seat-road-autonomous-vehicles. p. 4.

[25] Mosequet et al (2021), p. 5.

[26] Isidore, Chris. 2025. "California's Insurance Is in Crisis. The Solution Will Cost Homeowners a Ton | CNN Business." CNN. January 9, 2025. https://www.cnn.com/2025/01/09/business/california-wildfires-homeowners-insurance/index.html.

communities, or the companies fear if their vehicles might be damaged. This makes administrative policies enforcing non-discrimination particularly important.

Lastly, some (like Elon Musk) may argue that Self-driving and robotaxis drive prices down. But AVs are costly, evidenced by the equipment and tech-innovation costs. If self-driving dominates the road, those costs might become burden for all customers. Driving the cost up for everyone.

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Guanzheng Sun Memo, OBOR

President Xi should proceed with announcing and implementing the OBOR plan, as it offers significant economic, political, and geopolitical benefits. In the following sections, I will present the benefits of OBOR, focusing on economic growth, domestic political stability, and geopolitical influence. Subsequently, I will address the concerns related to the plan, demonstrating how the benefits ultimately surpass the potential drawbacks.

Benefits of OBOR

Economic Benefits

Industrial Overcapacity

A key concern regarding the OBOR initiative is that it may obstruct China's overall economic efficiency due to heavy participation from state-owned enterprises (SOEs) and central planning—an issue I will explore further in the risks section. However, ratifying the project could potentially enhance China's economic efficiency by addressing industrial overcapacity. This would be achieved by redirecting surplus steel and cement production to infrastructure projects abroad, such as the construction of railways, pipelines, power stations, and ports in OBOR's participating countries.

Markets and Resources

OBOR's infrastructural development also facilitates greater and more direct access to resources and markets for Chinese enterprises. With reduced transportation costs and a larger pool of suppliers, production inputs are expected to become cheaper. Additionally, the FDI from OBOR will likely lead to expanded markets for China and its producers, particularly in an era where FDI increasingly complements trade (Pandya, 2016). This is further supported by evidence in the

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memo, indicating that Central Asian states are actively seeking to diversify their exports, sources of technical and financial support, and their economies as a whole.

Potential Reliance and Dependence

The projects funded by OBOR are very likely to adhere to Chinese infrastructural standards. For instance, the Nairobi-Mombasa railway—one of the flagship projects of OBOR—uses Chinese railway standards, rolling stock, and a Chinese IT system for operations. Completed projects will require ongoing maintenance and repair, but since the recipient countries may lack the necessary technology and personnel, they are likely to develop a dependency on China for these services. This dependency, in turn, creates additional employment opportunities for Chinese companies abroad, ensuring a consistent demand for their services.

Political Benefits

Stability and Prosperity of Xinjiang

A key threat to China’s internal stability has been the separatism, terrorism, and religious extremism in Xinjiang. Political and religious turmoil has constrained Xinjiang's development since the early 2000s, limiting external connections and industrial investment. Moreover, Han Chinese hold higher political and economic positions, with better access to information and networks, further contributing to regional disparities. As a crucial node on the "Belt" portion of OBOR (shown in Exhibit 1) and due to its geographical proximity to Central Asian states, Xinjiang is positioned as the entry point for pipelines, highways, and railways, as well as a major trade hub for China’s transactions with countries from the west. Combined with its vast reserves of solar and wind power and its comparative advantage in textiles, Xinjiang stands to benefit

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significantly from OBOR. Increased investments and the creation of new jobs are expected to bring economic prosperity and higher employment to the region.

Exhibit 1
Map of "One Belt One Road"

While concerns exist, that Han Chinese may benefit more than ethnic minorities, such development is still preferable to no development at all. Without OBOR, manufacturers from coastal China would likely avoid investing in Xinjiang, given its inland location and political uncertainties, and would instead seek alternative production bases in cheaper coastal provinces. Overall, OBOR will greatly benefit Xinjiang, and the resulting economic prosperity and job creation are likely to promote greater stability in Xinjiang and western China as a whole.

Maintaining Elitist Political Influence

Milner and Kubota (2005) argue that trade liberalization reduces the political influence of vested interests that have benefited most from state interventionism, thereby creating new cleavages

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that weaken the political power of business associations. Xi’s elitist faction, which represents the interests of business elites and SOEs while advocating for state intervention, is one such group that would be threatened by trade liberalization.

OBOR, through its preferential treatment of SOEs and affiliated enterprises in major infrastructure projects, provides substantial support to Xi's faction, strengthening its defense against Premier Li’s populist faction. While it is true that these companies may suffer losses from global investments and infrastructure project failures, doing nothing would result in increased influence for Li's faction, promoting economic policy reforms toward a more market-oriented economy. This shift could ultimately undermine the elitist faction's economic base and popularity, threatening the faction’s political power and continued administration.

Geopolitical Benefits

Expansion in Central Asia

China’s investment in Central Asia through OBOR may help it earn greater support from these countries to eradicate the roots of religious extremism and terrorism in Xinjiang. Central Asian states welcome this involvement, as it aligns with their shared objective of maintaining regional stability. Moreover, China’s expansion into Central Asia enables these countries to diversify their export markets and counterbalance Russia's political and economic dominance. Given the region's insufficient government institutions, security issues, and geographic challenges, few Western investors have been willing to engage economically. Consequently, China's financial investments are crucial for Central Asian states as they seek to balance Russian influence while preserving their independence.

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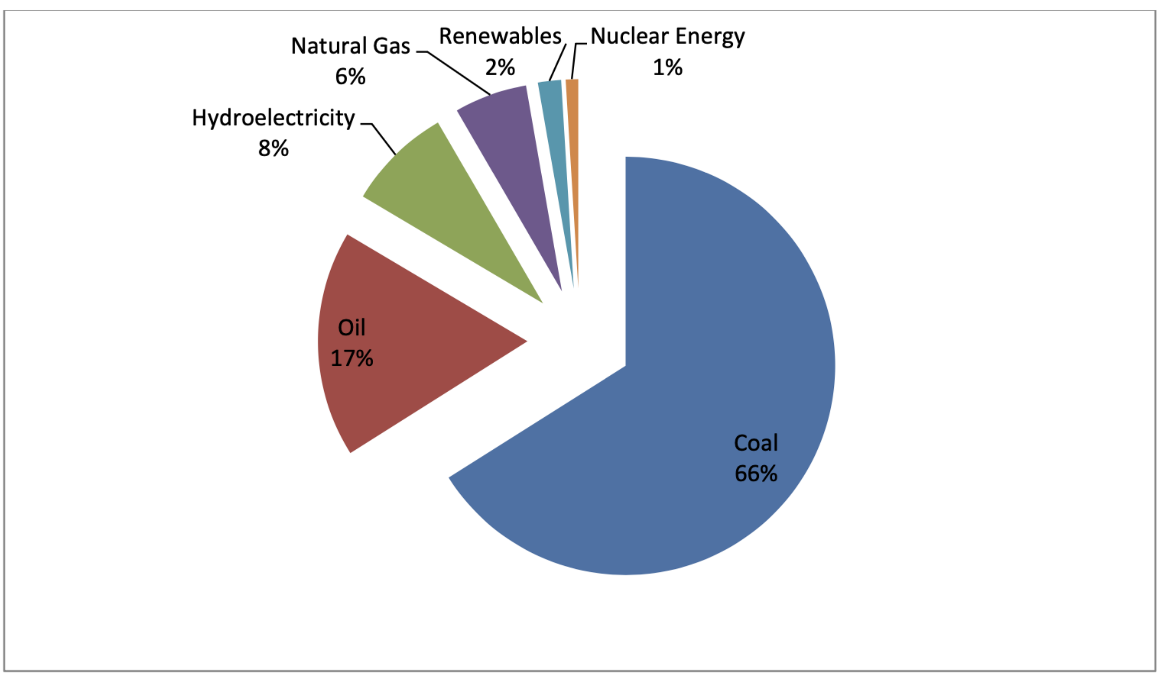
Energy Security

OBOR also plays a significant role in enhancing China's energy security. Before OBOR, 85% of China's oil and natural gas was transported via the Indian Ocean and the Malacca Strait—vulnerable to disruptions. Furthermore, China's dependence on oil imports from the Middle East exposed it to risks from regional conflicts and civil wars. With OBOR's construction of pipelines in Russia and Central Asia, China can reduce its dependence on Middle Eastern energy supplies by sourcing natural gas from Central Asia and oil from Russia, extending as far as the Caspian Sea. These imports, which accounted for 25% of China's energy consumption in 2015 (as shown in Exhibit 2), are essential for sustaining the country's rapidly growing industrial economy. By diversifying its energy imports, China can enhance energy security even amid global conflicts—an increasingly critical concern in today's deteriorating international order.

Exhibit 2

Primary Energy Consumption in China by Fuel Type: 2014



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Response to Concerns and Alternatives

Profitability and Returns

The long-term sustainability and profitability of China's OBOR projects have faced criticism, with nearly 40% of past investments classified as troubled transactions (as shown in Exhibit 3). However, profitability is not the only driving force behind these projects; they are also selected for their strategic geopolitical value. Moreover, since many of the OBOR participating companies are state-affiliated and investing on behalf of the government, the primary focus is on achieving long-term geopolitical influence for the state, rather than immediate financial returns considered by typical private-owned companies.

Exhibit 3

Troubled Transactions of Chinese ODI by Sector since 2005 ($ billion)

Sector	Investment	Engineering Contracts	Troubled Transactions
Energy and power	274.6	236.8	95.0
Metal	121.5	20.4	68.9
Real estate and construction	69.3	51.4	11.7
Finance	56.8	N/A	29.7
Transport	49.7	164.8	33.1
Agriculture	28.6	13.0	9.7
Technology	33.9	14.5	15.0
Chemicals	8.2	7.7	1.9
Tourism	11.8	3.5	5.6
Utilities	8.2	9.2	0
Other	26.3	5.0	2.5
Total	**683.0**	**529.9**	**273.1**

Source: Derek Scissors et al., China Global Investment Tracker, "China's investment in the world increasing, not soaring," American Enterprise Institute and the Heritage Foundation, Ongoing, in this case January 2016, http://www.aei.org/china-global-investment-tracker/ and https://www.aei.org/publication/the-double-edged-sword-of-chinas-global-investment-success/.

Invest elsewhere

Some critics argue that, rather than investing in OBOR, China should redirect its efforts toward developed democracies, where government institutions are more stable and secure. However, such investments may be impossible in the first place due to factors like ethnocentrism, organized labor opposition, and strategic sensitivities often present in developed economies.

Andrews, Leblang, and Pandya (2018) find that ethnocentrism fosters citizen distrust of foreign entities, which directly influences FDI decisions. This challenges the assumption that advanced economies are immune to domestic biases when attracting foreign investment. Similarly, Owen (2015) demonstrates that concentrated and strong labor power often translates into more restrictive FDI policies, contradicting the belief that labor groups necessarily favor liberal FDI practices. Additionally, Chen and Munier (2022) find that European nations receiving Chinese investments in strategic sectors, such as technology and infrastructure, are more inclined to support FDI screening due to national security concerns. As a result, developed economies may not welcome Chinese investments, leaving riskier developing nations as China’s only investment destinations.

Russian Relations

Lastly, the memo identifies that China’s ongoing investments and involvement in Central Asia may conflict with Russia's interests and regional ambitions. However, the 2015 declaration outlined in the memo, which delineates the responsibilities of the two countries in Central Asia, demonstrates China's efforts to mitigate potential conflicts. Furthermore, as shown in Exhibit 1, Russia is also a major participant and beneficiary of the OBOR project, with planned infrastructure investments in the transportation and energy sectors. As indicated in Exhibit 4, Russia already accounted for 9% of China’s crude oil imports in 2013, and this figure is likely to increase significantly with the construction of new pipelines and the potential development of the Caspian Sea oil reserve. Given these substantial benefits, Russia may be more inclined to make concessions to China after evaluating the advantages of collaboration.

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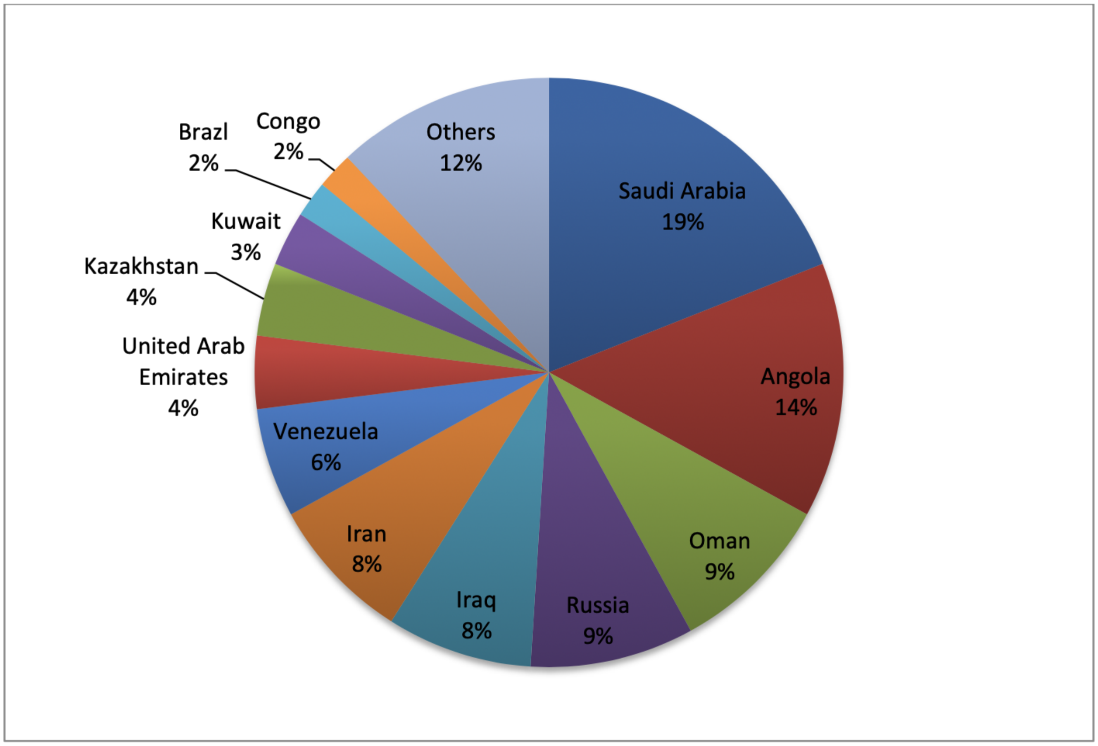
Exhibit 4

China's Crude Oil Imports by Source: 2013



Conclusion:

In summary, OBOR offers a comprehensive strategy that not only addresses China's industrial overcapacity and energy security concerns but also promotes domestic stability in Xinjiang and expands influence in Central Asia. Although critics have highlighted the potential profitability challenges and possible conflicts with Russia's regional ambitions, these risks are balanced by substantial economic, political, and strategic benefits. Moreover, alternative investment options, such as in developed democracies, face significant barriers including ethnocentrism, labor opposition, and security concerns, leaving OBOR as the optimal choice for China.

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Works Cited

Andrews, Sarah, David Leblang, and Sonal S. Pandya. 2018. “Ethnocentrism Reduces Foreign Direct Investment.” *The Journal of Politics* 80(2): 697–700.

Chan, Zenobia T., and Sophie Meunier. 2022. “Behind the Screen: Understanding National Support for a Foreign Investment Screening Mechanism in the European Union. *The Review of International Organizations* 17: 513–541.

Milner, Helen, and Keiko Kubota. 2005. “Why the Move to Free Trade? Democracy and Trade Policy in the Developing Countries.” *International Organization* 59 (1): 707–743.

Owen, Erica. 2015. “The Political Power of Organized Labor and the Politics of Foreign Direct Investment in Developed Democracies.” *Comparative Political Studies* 48(13): 1746–1780.

Pandya, Sonal. 2016. “Political Economy of Foreign Direct Investment: Globalized Production in the Twenty-First Century.” *Annual Review of Political Science* 19: 455–475.