SUPPLY CHAIN COMPLEXITIES IN DEVELOPING ELECTRIC AUTONOMOUS VEHICLES: A COMPARATIVE ANALYSIS OF TESLA AND WAYMO

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Examiner: Junior Researcher, America Rocio Quinteros Condoretty

ABSTRACT

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Supply chain complexities in developing electric autonomous vehicles: a comparative analysis of Tesla and Waymo

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This thesis examines the supply chain complexities associated with electric autonomous vehicles (AVs). This study focused on the two leading U.S. companies on the field: Tesla and Waymo. The companies employ fundamentally different supply chain and autonomous strategies and the study focuses on what effects chosen strategies have on ability to scale and what kind of risks are associated with each strategy.

Tesla has a vertically integrated strategy which gives it control of its supply chain from its beginning to its end. This strategy results in greater cost efficiency, reduced supply chain risks, and better scalability opportunities compared to Waymo's outsourcing strategy. Waymo's strategy allows it to focus on software development; however, it also brings high costs and a vulnerable supply chain.

The study highlights the significant difference the employed supply chain strategy makes to a company's cost structures and scalability potential. Vertical integration allows for substantial cost savings and rapid scaling possibilities. Waymo's sensor-heavy approach and high dependence on third-party suppliers result in significantly higher costs and reduced scaling opportunities. The findings emphasize the critical influence that chosen supply chain strategies have on operational efficiency and market competitiveness in the emerging AV sector.

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Kauppatieteet

Otto Paakko

Hankintaketjun haastavuudet sähköisten itsestään ajavien autojen valmistuksessa: vertaileva analyysi Teslasta ja Waymosta

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Tämä kandityö tutkii hankintaketjun vaikutuksia sähköisten itsestään ajavien autojen valmistamiseen. Työn kohteena ovat Yhdysvaltojen alan johtavat yritykset Tesla ja Waymo. Kyseisillä yrityksillä on erilaiset strategiat sekä hankinnoissa, että itsestään ajavien autojen valmistuksessa. Työ tutkii, kuinka nämä strategiset valinnat vaikuttavat yritysten kykyyn laajentaa toimintojaan ja minkälaisia riskejä liittyy valittuihin strategioihin.

Tesla käyttää hankintastrategiana vertikaalista integraatiota, jonka avulla se pystyy kontrolloimaan hankintaketjua lähes täysin alusta loppuun. Tämä strategia tuo Teslalle paremman tehokkuuden tuotantoon ja laajentamiseen sekä vähentää hankintaketjuun liittyviä riskejä. Waymon hankintojen ulkoistaminen antaa yritykselle mahdollisuuden keskittyä erityisesti heidän ydinosaamiseensa eli itsestään ajavan ohjelmiston kehittämiseen. Ulkoistaminen kuitenkin tuo mukanaan useita negatiivisia puolia, kuten korkeat valmistuskustannukset, sekä haavoittuvaisen hankintaketjun.

Tämä työ korosti erityisesti sitä kuinka suuri merkitys yrityksen valitsemalla hankintastrategialla on yrityksen kuluihin sekä laajentumispotentiaaliin itsestään ajavien autojen alalla. Vertikaalinen integraatio tuo mukanaan suuria kustannus säästöjä sekä mahdollistaa nopean toiminnan laajentamisen. Waymo puolestaan tarvitsi useita antureita autoilleen sekä oli vahvasti riippuvainen kolmansista osapuolista hankinnoissaan, mikä lopulta johti suuriin kuluihin sekä vähempiin laajentumismahdollisuuksiin.

ABBREVIATIONS

AI	Artificial Intelligence
AV	Autonomous Vehicle
COGS	Cost of Goods Sold
EV	Electric Vehicle
FSD	Full Self-Driving
ICE	Internal Combustion Engine
LFP	Lithium-Iron-Phosphate
LIDAR	Light Detection and Ranging
OEM	Original Equipment Manufacturer
SAE	Society of Automotive Engineers
SCRM	Supply Chain Risk Management

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1 Introduction

With improvements in manufacturing processes and economies of scale, electric vehicles (EVs) are becoming increasingly cost-effective to manufacture. Governments worldwide actively support EV manufacturing due to their greater sustainability than internal combustion engine vehicles (ICEs) (IEA, 2024). Autonomous vehicles (AVs) have gained relevance due to recent advancements in Artificial Intelligence (AI) and semiconductor technology. The combination of these two sectors, AI-specific chips, is essential for the development of AVs (Insemitech, 2024).

However, supply chains for both AI-specific chips and batteries needed for EVs have posed significant challenges for companies in recent years. The COVID-19 pandemic caused a global semiconductor shortage, and with the increasing manufacturing of EVs, the price of raw materials required for batteries has increased drastically (IEA, 2023a). Another critical concern lies at the end of the battery supply chain. If batteries cannot be effectively recycled, it becomes more difficult to argue that EVs are environmentally friendly (Morse, 2021). Fortunately, recent developments in battery recycling show promise. For example, Redwood Materials has developed methods to reuse and recycle over 95% of a battery's materials (Redwood Materials, 2024). These advancements are expected to greatly benefit the supply chain by reducing the future demand for raw materials, as recycled components could eventually supply a significant portion of the inputs needed for battery production.

Addressing the challenges of AVs and the EV supply chain would benefit humanity significantly. AVs have the potential to drastically reduce the number of road accidents, enhancing safety and saving lives (MacCarthy, 2024). AVs could make transport more affordable for everyone (Simply Fleet, 2024a). Additionally, AVs could save people a lot of time by allowing them to engage in other activities instead of focusing on driving, especially in situations such as traffic. Electric AVs could significantly reduce pollution in cities with high vehicle density and decrease global emissions (Simply Fleet, 2024b). However, this impact would depend on ensuring that the whole supply chain is sustainable, from mining raw materials to recycling and reusing the batteries.

Therefore, this thesis explores the challenges of building electric AVs from a supply chain perspective, focusing mainly on the two leading companies in the field, Waymo and Tesla, and the critical bottlenecks that they face in sourcing and scaling essential components such as batteries, chips and sensors required for AVs. As the automotive industry moves towards EVs (Reuters, 2024a) and autonomous technology (Goldman Sacks, 2024), understanding the complexities of supply chain issues becomes increasingly important. This topic is highly relevant due to the recent advancements in AI and semiconductor technology, the global push for sustainability, and the rising demand for the materials needed to build electric AVs (Argus, 2023; IEA, 2023b). Solving these challenges could accelerate the mass adoption of AVs, reducing road accidents, lowering emissions, and revolutionizing the transportation industry by saving people time and money (Simply Fleet, 2024c).

Currently, companies like Waymo and Tesla are leading the development of electric AVs in the U.S., especially after one of the most prominent players, General Motors (GM), recently announced that they are ending their robotaxi project due to high scaling costs and increased competition (Wong, 2024). Both Tesla and Waymo face different challenges in their supply chains. While Tesla has a vertically integrated strategy, building its cars, batteries, and chips, Waymo relies more on third-party manufacturers for its vehicles and sensors. Despite their different approaches, both companies also face similar supply chain challenges, such as the scarcity of raw materials, global semiconductor shortage, and the need to source advanced sensors (Dimerco, 2024a). Addressing these supply chain difficulties is crucial for scaling production and achieving fully autonomous driving.

While the technical challenges of building AVs are well documented in studies such as "Deep learning for object detection and scene perception in self-driving cars: Survey, challenges, and open issues"(Gupta et al.,2021) and "A Review of Autonomous Vehicles: Progress, Methods and Challenges"(Parekh et al., 2022), there is comparatively less research on the impact of supply chain bottlenecks on the industry. This thesis aims to fill this gap by exploring how supply chain issues affect manufacturing and scaling progress.
To provide a comprehensive analysis, it is essential to understand why EVs are a more suitable platform for AVs than ICEs. For instance, EVs offer significant advantages over ICE vehicles, including higher energy efficiency, lower operating costs, and reduced

emissions; these benefits make EVs a more suitable platform for autonomous cars (EV Magazine, 2024). Additionally, understanding the different levels of autonomous technology is crucial for contextualizing the findings of this research.

To better understand autonomy and the requirements of a fully autonomous vehicle, the Society of Automobile Engineers (SAE) has created international levels of driving automation from L0-L5 (SAE, 2021a). Waymo currently operates at L4 and Tesla at L2; the main difference between these levels is driver responsibility: in L2, the driver is responsible and must constantly supervise and take over if the system requires it; in L4, the driver does not touch the wheel and is not responsible for any possible accidents. It is good to note that Tesla does not have a self-driving car at the time of writing this, whereas Waymo does. However, after GM quit its robotaxi efforts, Tesla is the only American automaker that still has an active robotaxi project (Mathews, 2024) (Waymo does not manufacture cars and thus is not seen as an automaker). Chapter 3 will provide a more detailed discussion of this.

EVs are a newer and less established technology than ICE vehicles, meaning that the supply chain is less mature, and the scarcity of raw materials needed for the large batteries makes it complicated (Dimerco, 2024b). When you add the different sensors and chips required for building AVs, it becomes even more complex. Many companies such as Pony.ai, Zoox, Baidu, Tesla, Motional, and Waymo are trying to develop electric AVs currently (Law, 2023), and to narrow the research, this thesis will mainly focus on two of the leaders in the U.S., Waymo by Google and Tesla.

Waymo is a company owned by Alphabet (Google’s parent company). They buy their cars from different automotive manufacturers and then install the required sensors needed for AVs. Tesla, however, manufactures its vehicles and batteries and designs its chips in-house. Tesla has a vertically integrated supply chain, which provides them many benefits when scaling production. However, they still face similar supply chain challenges that every EV and AV maker faces, such as the scarcity of materials and the global semiconductor shortage. At the time of conducting this study, full autonomy has yet to be achieved. Waymo cars are currently closest to this since they already operate driverless taxi services in certain American cities (Waymo, 2024a). Tesla's automation systems, however, still require that the driver pay attention to the road while the system is active, and the driver needs to be ready to take over when the system requires it (Tesla, 2024a).

This topic is highly relevant at the moment. At the time of writing, Tesla has just announced its new potential robotaxi. While Waymo has revealed plans for a new city expansion, and GM, once considered one of the leaders in the field, has just dropped out of the robotaxi race (Tesla, 2024b; Waymo, 2024b). One of the reasons GM cited for discontinuing its efforts was the high cost of scaling, a key issue addressed in this research. Additionally, GM stated that the increasing competition in the market contributed to its decision to exit the race (Shepardoson and Eckert, 2024).

The existing studies on AVs tend to focus heavily on technical challenges such as algorithm development, data collection, and sensor fusion. For instance, Lim and Taeihagh (2019) examined ethical and technical concerns in algorithmic decision-making for autonomous vehicles, highlighting issues in perception, decision-making, and control algorithms (Lim and Taeihagh, 2019). Similarly, Marko et al. (2021) discuss the engineering challenges in ensuring the safety and security of highly automated vehicles, focusing on continuous system improvement and handling uncertainties (Marko et al., 2021). Additionally, Yeong et al. (2021) provide a comprehensive review of sensor fusion technologies and their applications, addressing the integration of multiple sensors such as Lidar, Radar, Cameras, and ultrasonic sensors. However, fewer studies focus on the supply chain issues that arise from combining electric powertrains with self-driving technology. While the technical difficulties of building EVs are well documented, less attention has been paid to how sourcing and scaling for critical components like batteries, AI chips, and sensors directly affect the ability to mass-produce autonomous EVs. Additionally, while Tesla's vertically integrated supply chain (for designing their chips and producing their batteries) has received some attention, such as Cooke's (2020) study focusing on Tesla's Gigafactory logistics (Cooke, 2020), there is no comparative analysis on how it contrasts with Waymo's reliance on multiple external suppliers. These supply chain challenges are crucial to scaling production but are often overshadowed by more technical discussions.

The primary objective of this thesis is *to explore the supply chain complexities that companies like Tesla and Waymo face in developing electric AVs*. It aims to analyze how both companies handle challenges like semiconductor shortages, material supply chains (batteries, vehicles), and sensor sourcing and how these supply chain bottlenecks affect their ability to scale. The central problem this thesis addresses is how supply chain issues, such as the scarcity of raw materials for batteries, the global chip shortage, and the production and sourcing of advanced sensors, are slowing down the progress of building and scaling electric AVs. Therefore, this study explores the following research questions:

- RQ1: What are the key supply chain bottlenecks that electric autonomous vehicle manufacturers face?
- RQ2: How do the supply chain strategies of Tesla and Waymo differ, and how does this impact their ability to scale?
- RQ3: What role does the cost of the vehicle play in determining the scalability of Tesla's and Waymo's electric AV production?

This study focuses primarily on Tesla and Waymo as the leading examples of AV manufacturers. However, the rapidly evolving nature of both technology and the global supply chain means that the findings may quickly become outdated as new innovations or disruptions occur. Additionally, while Tesla and Waymo have different approaches, the analysis may not fully represent the strategies of other AV makers in this space.

The thesis is structured as follows. Chapter 2 provides a review of the literature. Chapter 3 outlines the differences between EVs, ICEs, and AV driving levels. Chapter 4 presents the methodology. Chapter 5 details the results, organized by key supply chain bottlenecks, supply chain strategies and scalability, and the role of vehicle cost in scalability. Chapter 6 discusses the findings, and finally, Chapter 7 provides a summary and conclusions.

2 Review of Literature

In the literature review section, key theories and existing literature on supply chain management strategies are examined. Focusing on supply chain risk management (SCRM), vertical integration, and outsourcing and analyzing their implications for resilience, scalability, and operational efficiency. Additionally gaps in the current literature are identified, particularly the comparative studies of the mentioned strategies in the AV industry.

2.1 Supply Chain Risk Management

SCRM is essential for minimizing disruptions and ensuring a stable supply chain. Literature reviews like "Improving Supply Chain Resilience through Industry 4.0: A Systematic Literature Review under the Impressions of the COVID-19 pandemic" (Spieske & Birkel 2021a) highlights the growing need for SCRM due to recent global disruptions, including the COVID-19 pandemic, which challenged supply chain resilience and highlighted vulnerabilities. SCRM consists of strategies to identify, assess, and mitigate risks associated with supply chains (Spieske & Birkel 2021b).

These key risks in the AV supply chain are raw material shortages, such as lithium and cobalt for batteries, semiconductor availability, and the sensors needed for autonomous capabilities. Effective SCRM involves identifying, assessing, and mitigating these risks. For instance, digitalization and automation, core aspects of Industry 4.0 (4^{th} Industrial revolution), have been shown to enhance supply chain resilience by enabling real-time monitoring and rapid responses to distruptions (Spieske & Birkel, 2021c). Tesla's integration of these technologies within its vertically integrated operations demonstrates the effectiveness of combining SCRM with advanced technological solutions.

Battery sustainability also plays a crucial role in SCRM for AV manufacturers. Tesla's investments in battery recycling and innovations like the 4680-battery cell align with SCRM goals by reducing dependence on newly mined resources (Gaines, 2014).

2.2 Vertical integration

Vertical integration involves a company controlling multiple stages of its production process, from raw material procurement to final assembly. This strategy can enhance supply chain resilience by reducing dependency on external suppliers and providing greater control over critical components (Hayes, 2024a).

Tesla's vertically integrated model is a prime example of this approach. Its Gigafactories produce significant portions of its battery cells in-house, reducing dependency on third-party suppliers (Tesla, 2023a). Tesla's decision to design its own AI chips further illustrates the benefits of vertical integration. By controlling this critical aspect of its supply chain, Tesla can mitigate risks associated with semiconductor shortages, as demonstrated during recent global supply disruptions (Lambert, 2021).

Vertical integration also enables the implementation of Industry 4.0 practices, such as digitalized production and real-time monitoring, which improve resilience and operational efficiency. Studies highlight the strategic advantages of this approach, including faster innovation and reduced costs through streamlined operations (Tabim et al., 2024).

However, vertical integration presents challenges. High capital investments and increased operational complexity can strain resources. Companies must excel in diverse fields, from manufacturing to technology development, which, if not managed effectively, may lead to inefficiencies. Furthermore, vertically integrated companies may struggle with reduced flexibility in adapting to external market changes or sourcing opportunities (Hayes, 2024b).

2.3 Outsourcing

Outsourcing involves delegating specific production processes or components to external suppliers. This strategy allows companies to focus on core competencies but introduces risks related to dependency and coordination (Twin, 2024a).

Waymo's outsourcing strategy highlights the potential and challenges of this approach. The company collaborates with original equipment manufacturers (OEMs) like Jaguar and Zeekr to procure vehicles, integrating its autonomous systems into these platforms (Zhao et al., 2020). This model enables Waymo to focus on its core strength—autonomous software development—while leveraging the manufacturing expertise of its partners.

However, outsourcing also creates vulnerabilities. Waymo relies on external suppliers for critical components such as cameras and radar, which could increase its exposure to supply chain disruptions. Additionally, outsourcing can restrict scalability due to the high costs and coordination challenges associated with managing multiple suppliers. Despite these drawbacks, outsourcing provides certain advantages. It allows companies to enter markets quickly, leveraging established expertise without significant upfront investments (Twin, 2024b). This flexibility is particularly beneficial in rapidly evolving industries like AVs. However, the literature lacks a detailed analysis of how outsourcing strategies can address long-term challenges, such as supply chain risks and scalability, especially in the autonomous industry.

While existing studies provide valuable insights into the individual components of SCRM, vertical integration, and outsourcing, there is a lack of comparative analysis on how these strategies impact AV manufacturers' resilience and scalability. Most research focuses on isolated aspects, such as vertical integration in Tesla or the advantages of outsourcing in general, without examining their combined effects within the AV industry.

This thesis addresses these gaps by exploring Tesla's and Waymo's distinct supply chain strategies. By analyzing their approaches to managing risks, integrating advanced technologies, and addressing material constraints, this study contributes to a deeper understanding of the operational challenges and opportunities in scaling electric AV production.

3 Understanding the Superiority of EVs and the Levels of Driving Automation

3.1 Why EVs are Superior to ICEs in the Context of AVs

EVs have a long list of benefits compared to ICEs, which become even more relevant when building AVs on a scale. EVs are significantly more energy-efficient compared to ICE vehicles, they convert 73% of the electrical energy from the battery into power at the wheels, while ICE vehicles convert only 13% of the energy stored in gasoline (Kane, 2017). EVs generally have lower operating costs than ICE vehicles because electricity is cheaper than gasoline or diesel, and electric motors require less maintenance. EVs don't need oil changes, fuel filters, spark plugs, or other standard maintenance required by ICE vehicles, reducing long-term operating expenses (Lindwall, 2024). They produce zero tailpipe emissions, significantly reducing air pollution in urban areas. Even when accounting for the emissions from electricity generation, EVs typically have a lower carbon footprint than ICE vehicles, especially in regions where renewable energy sources power the grid (Green, 2024). EVs have fewer moving parts than ICE vehicles. While ICE vehicles have complex engines with many moving parts that wear out over time, EVs have simple electric motors. This results in greater durability and less likelihood of breakdowns (Hughes, 2023). EVs provide instant torque due to the nature of electric power, which leads to faster acceleration that could potentially help AVs prevent accidents. They can run on renewable energy, making them an essential component of a sustainable energy system. As more renewable energy sources like solar and wind are integrated into power grids, EVs can further reduce their environmental impact by being charged using clean energy. They are also much quieter than ICE vehicles since they do not have an internal combustion engine. This contributes to lower noise pollution in cities and urban environments, making for a more pleasant and less stressful environment. EVs also have lower central gravity due to the heavy battery on the floor of the vehicles, reducing the risks of a rollover in case of an accident. All these benefits make it quite clear why building AVs on an electric powertrain is beneficial. The fleet will be cheaper, easier to maintain, safer, and more environmentally friendly (Sherman, 2022; Sisodia, 2024).

3.2 SAE Levels of Driving Automation – Comparing Tesla and Waymo

To better understand AVs and the requirements of a fully autonomous vehicle, the Society of Automobile Engineers (SAE) has created international levels of driving automation from 0-5, as seen in Figure 1 below (SAE, 2021b). Additionally, understanding the fundamentally different approaches of Tesla and Waymo toward autonomous technology is crucial for gaining insights into the industry's current state, potential future advancements, and the ways their different strategic approaches impact their respective supply chains.

SAE J3016 Levels of Driving Automation						
SAE Levels	SEA Level 0	SEA Level 1	SEA Level 2	SEA Level 3	SEA Level 4	SEA Level 5
What does the human in the driver's seat have to do?	You are driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not streeting			You are not driving when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests. **You must drive**	These automated driving features will not require you to take over driving	
Features	**These are driver support features**			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example features	Automatic emergency braking, Blind spot warning, Lane departure warning	Lane centering **OR** adaptive cruise control	Lane centering **AND** adaptive cruise control at the same time	Traffic jam chauffeur	Local driverless taxi, Pedals/steering wheel may or may not be installed	Same as level 4, but feature can drive everywhere in all conditions

Figure 1. SAE Levels of Driving Automation (L0-L5)

Examples of Different Manufacturers and their SAE Levels			
Manufacturer	SAE Level	Description	Details
Tesla	L2	Partial Automation	Tesla FSD provides advanced driving features in many scenarios, requires active human supervision.
Mercedes-Benz	L3	Conditional Automation	Mercedes' DRIVE PILOT allows autonomous driving in very specific conditions, with the driver ready to take over. Approved on some German highways.
Waymo	L4	High Automation	Waymo's autonomous ride-hailing operates in select U.S. cities without human intervention but only within pre-defined zones.
Cruise (GM)	L4	High Automation	Cruise operated autonomous taxis in urban areas like San Francisco, with vehicles driving without a human operator. (No longer operational)
Baidu Apollo	L4	High Automation	Baidu's Apollo trials offer autonomous ride-hailing in specific areas in China, with no drivers in designated zones.
Nuro	L4	High Automation	Nuro specializes in autonomous delivery vehicles designed for goods transportation within certain local areas, operating without passengers.

Figure 2. Examples of Different Manufacturers and their SAE Levels

As illustrated in Figure 2, Tesla's Full Self-Driving (FSD) system operates at L2 based on the SAE levels. However, Tesla currently fulfills all other L3 requirements except for driving supervision. When Tesla's FSD system is enabled, the driver does not need to touch the pedals or the steering wheel for it to operate. Still, they must pay constant attention and be ready to take control immediately, classifying the system as L2.

The SAE driving automation levels can be misleading, especially at Levels 2-4, since the L3 system doesn't necessarily mean that it's better in everything than the L2, and L2 can even be better at something than L4. For example, Mercedes-Benz has gotten approval for the L3 system on certain German highways (Mercedes-Benz, 2024). However, the car can only operate on certain highways, unlike Tesla's FSD system, which can operate outside highways but needs constant driver supervision. As for the L4 that Waymo has, Tesla's L2 system can operate in more areas, whereas Waymo can only operate in some mapped regions. However, even though Tesla's FSD can do some things that Waymo's L4 system can’t, Waymo still has a better system overall, especially in the areas it operates since it already operates a driverless robotaxi. Other L4 companies include Baidu, based in China, and Nuro, which makes deliveries but does not operate with passengers. In addition, Cruise by GM had a robotaxi network until very recently but decided to stop their efforts due to high costs and competition (Hamlin, 2024; PRNewswire, 2024; Krishner, 2024).

Although Waymo currently has a robotaxi fleet, while Tesla doesn’t, this research chose to compare Tesla to Waymo due to their fundamentally different approaches and explore the scalability challenges they face if they achieve L4 or L5 automation. Additionally, Tesla and Waymo were chosen since many industry experts see the AV race as being between them. Although Waymo already has a robotaxi network, some experts think that Tesla’s approach is better in the long run. Some very recent statements include Google’s (Waymo’s parent company) CEO Sundar Pichai, who said in December 2024: “I think obviously Tesla is a leader in the space. It looks to me like Tesla and Waymo are the top two” (Ashraf, 2024a). Waymo’s co-founder Anthony Levandowski, who has left Waymo, believes that Tesla has an advantage in the AV race and stated in October 2024: “I would rather be in Tesla’s shoes than in Waymo’s shoes.” (Ashraf, 2024b). Additionally, Tesla’s former head of AI said in a recent podcast appearance on September 2024: “I personally think Tesla is ahead of Waymo. I know it doesn’t look like that, but I’m still very bullish on Tesla and its self-driving program.” (No-Priors, 2024).

Achieving L5 autonomy remains the ultimate goal and would surpass both L2 and L4. However, reaching L5 requires solving many technical and regulatory challenges. Tesla and Waymo have fundamentally different approaches to achieving this goal, resulting in slightly different technical challenges for each company. Tesla relies exclusively on a camera-based system called Tesla Vision. This approach, theoretically simple, constantly collects data from over one million cars equipped with a 360-degree view. Tesla’s CEO Elon Musk argues, "Humans drive with eyes & biological neural nets, so makes sense that cameras & silicon neural nets are only way to achieve generalized solution to self-driving.”(Engineering, 2024). However, using only cameras could pose some technical difficulties, including the resolution of cameras, measuring the depth without Lidar, weather, and environmental road conditions such as heavy snow, rain, or mud blocking the cameras. During Tesla’s latest tech event on 9.10.2024 called We Robot, Musk predicted that they would have unsupervised AVs in certain American cities as early as 2025, which would elevate Tesla's systems to L4 like Waymo's or possibly even L5 (Tesla, 2024b).

Waymo's approach, however, is fundamentally different from Tesla's, as it relies on multiple sensors and high-definition mapping to operate its vehicles. Waymo has sensors like Lidar and Radar, as well as cameras. Lidar (Light Detection and Ranging) uses laser beams to measure distances by bouncing light off objects, creating detailed 3D maps of the environment, and detecting obstacles, pedestrians, and other vehicles, even in low light or at night. Radar uses radio waves to detect objects' speed and distance, even in poor weather conditions like rain or fog. It is particularly useful for tracking moving objects (like other cars) and providing real-time data on the surrounding traffic. However, these sensors are not enough to create the high-definition maps that Waymo cars use for navigation, and the maps need to be manually updated, especially when there are significant changes to the environment, such as construction, road closures, or modifications to traffic patterns (Waymo, 2024c).

Regulatory approval is also a big challenge for companies seeking L5. Waymo has been approved for L4 in certain cities since 2016 (Butzel, 2017), whereas Tesla has not yet been approved for unsupervised autonomy. It is unclear if a camera-only approach can get regulatory approval, and only time will tell if that's possible. However, based on its newest tech event, Tesla aims to get approval in certain cities in 2025 (CNET, 2024).

4 Methodology

This section presents the methodology used to gather and analyze empirical data collected from various sources to examine Tesla and Waymo's supply chain strategies, scalability challenges, and operational approaches in the electric AV industry. The data includes details on component sourcing, production costs, profitability, and insights into hardware and software strategies. Additionally, this section describes the data collection method, data analysis techniques, and the rationale for the chosen approach.

4.1 Description of Empirical Data

Tesla's Supply Chain and Scalability

Tesla is known for its vertically integrated supply chain, which manages multiple stages of the production process in-house. This strategy can be seen in their very detailed 2023 Impact Report (Tesla, 2023b). This strategy includes battery production, chip design, and software development to minimize the reliance on external suppliers. Tesla, however, does not yet produce all the components needed for its electric vehicles, and for example, sources its cameras from Samsung and LG. Cameras are a crucial part of the autonomous capability in Tesla's cars, and they recently made a long-term supply agreement with Samsung and LG, where 70% of the cameras come from Samsung and the rest from LG (ArenaEV, 2024). This deal ensures supply chain stability for the vision-based driving automation system.

These data sources were chosen because they provide detailed information for this thesis. The Impact Report 2023 is packed with crucial information about Tesla's supply chain, and investor reports include important External sources, which are also needed since Tesla still relies on external suppliers to make its cars.

Waymo's Supply Chain and Scalability

In contrast to Tesla's vertical integration, Waymo relies more heavily on an outsourcing strategy. Waymo has partnered with original equipment manufacturers (OEMs) for vehicle production. They have, for instance, recently collaborated with Hyundai for the Ioniq 5 EV and Zeekr, a Chinese EV manufacturer, for its 6th generation robotaxis (Reuters, 2024b; CNBC, 2024). Waymo outsources all its vehicles and most of the sensors. However, it recently developed its own Lidar sensors—Waymo's Honeycomb Lidar, which costs approximately $7,500 per unit (Waymo, 2019). The information on where Waymo sources their other sensors, such as cameras and radar, remains undisclosed. Waymo does not even state whether they outsource their sensor, but it can be assumed due to their low production volume and high equipment costs. This lack of transparency in the supply chain could be attributed to the highly competitive space of AVs.

Comparative Cost Analysis

The cost structure of building AVs further differentiates Tesla and Waymo. The cost data from both companies is limited, especially in the case of Waymo. However, credible cost sources were found for both companies. The data includes Waymo's and Tesla's current and future model cost ranges. These ranges will be used to calculate the estimated cost per vehicle in the results. The data from Waymo's cost is minimal. There are only a few mentions about their current 5th Generation and the upcoming 6th Generation. However, these sources are highly credible since they come directly from Waymo's CEO, Co-CEO, Waymo's website, and public information on the cost of the vehicles they use. The data from the CEOs come from interviews and podcast appearances, one from 2021 and the other from this year (2024). Both are talking about the 5th Generation model that was revealed in 2020. Additionally, the cost of the Jaguar I-Pace is used as a data point since that is the model used in 5th Generation vehicles. 6th Generation cost estimates only use Waymo's website, and the costs of Zeekr vehicles used in 6th Generation as a data point since it is the only credible source that can be found.

Tesla's cost data comes directly from the company's website, statements from key figures, such as the CEO, and external cost analyses about the Model 3 vehicle. The data is much more detailed particularly due to its long history of being a public company. However, exact manufacturing costs have never been mentioned to the public. The key data point here is the cost of goods sold (COGS) from their quarterly financial filings. The data on Tesla's upcoming model is minimal since it was made public only a few months ago, and the only statement from it is from their tech event in October 2024. (Tesla, 2024b)

This study suffers from minimal availability of data, which can result from the industry and technology being very new in addition to the competitive landscape of the business. Thus, companies do not want to give any information to the public that they do not have to. Academic papers on this topic were minimal, and most of the academic papers used were about supply chain theories in general and Tesla’s vertical integration. There were not any relevant academic papers on Waymo’s supply chain, most likely since there is not enough publicly available information to write that. The data relating to the two companies was collected from public releases and statements by Tesla, Waymo, and their key figures. In addition, news articles were used as a data point as well.

4.2 Data Analysis

This study uses a mixed methods approach, combining qualitative and quantitative methods to analyze Tesla’s and Waymo’s supply chain strategies. Mixed methods research provides a robust framework to address complex phenomena by integrating qualitative insights and quantitative evidence, offering a deeper and more nuanced understanding of the research problems. According to Cresswell and Plano Clark (2017), such an approach enables researchers to harness the strengths of both methodologies, thereby maximizing findings and guiding informed decision-making. In this study, this methodological choice ensures a comprehensive evaluation of the operational and financial aspects of scaling electric AVs.

4.2.1 Qualitative Analysis

The qualitative analysis section uses a comparative case study method to compare Tesla’s vertically integrated supply chain and Waymo’s outsourcing model. It uses sources such as Tesla’s 2023 Impact Report, Waymo's press releases, and various industry reports. The analysis is guided by the SCRM framework, which evaluates how each company addresses critical risks such as supply chain disruptions, component shortages, and scalability challenges.

The key areas that the analysis focuses on are these companies' different supply chain strategies. Tesla’s vertically integrated strategy includes producing batteries, chips, and software in-house. However, Tesla is not fully vertically integrated and relies on some external suppliers for components, such as the cameras they use for the autonomous capabilities. Waymo is more reliant on external manufacturers and uses an outsourcing strategy. They source vehicles, chips, and necessary sensors from third-party manufacturers and OEMs. Waymo only focuses on developing autonomous software and equipping cars with necessary sensors. Recently, they started to manufacture the Lidar sensor in-house to reduce manufacturing costs.

4.2.2 Quantitative Analysis

The quantitative analysis uses these data points to assess how each company’s supply chain strategy affects its scalability and profitability. For example, Tesla’s decision to exclude the costly Lidar and Radar sensors contrasts Waymo’s reliance on high-cost hardware.

The quantitative analysis focuses on the numerical cost comparison between the cheapest current models and potential upcoming models that have already been announced but are not yet in use. The data is gathered from Tesla’s own sources, such as the average manufacturing costs of their current vehicle lineup. Then, an estimate is given for the manufacturing costs of their most affordable model, Model 3. Additionally, external sources of the Model 3 manufacturing costs are used. Tesla’s upcoming robotaxi manufacturing costs are based on their presentation about the vehicle. Waymo’s data is much less limited, and the cost analysis is based on the statements made by the Co-CEO of the company in interviews and podcasts and the estimated costs of the vehicles that they use, such as the Jaguar I-Pace and Zeekr. Waymo’s vehicle costs are also given in estimates, and in this case, the manufacturing cost range is wider due to the limited availability of publicly disclosed statements and data.

The quantitative analysis uses these data points to assess how each company’s supply chain strategy affects its scalability and profitability. For example, Tesla’s decision to exclude the costly Lidar and Radar sensors contrasts Waymo’s reliance on high-cost hardware.

4.2.3 Justifications for Methods

The mixed methods approach was pivotal to answering the research questions effectively. The qualitative analysis captures strategic differences between Tesla and Waymo, particularly regarding supply chain bottlenecks and their implications for scalability. The quantitative analysis offers crucial numerical insights into the financial feasibility of their strategies, focusing on cost structures and implications for scaling.

As highlighted by Golicic and Davis (2012), mixed methods research is especially beneficial in supply chain studies, where traditional quantitative or qualitative methods alone may be insufficient to unravel multifaceted issues. Combining these methods provides a balanced understanding of Tesla's and Waymo's operational and financial challenges.

Limitations of this study include the availability of empirical data, particularly for Waymo, which is not publicly traded and thus has fewer disclosures. Nevertheless, this mixed methods framework ensures that key insights and conclusions can be drawn despite these constraints.

5 Results

This section presents the findings related to the research questions, focusing on three critical areas: supply chain bottlenecks, supply chain strategies, and vehicle manufacturing costs concerning scalability. Key bottlenecks are assessed based on their current impact and scalability implications, ranked from high to low vulnerability. The comparison of Tesla's vertical integration and Waymo's outsourcing strategies highlights the strengths, risks, and implications of each approach for supply chain risk management (SCRM) and scalability. Finally, an analysis of manufacturing cost estimates for current and future models sheds light on the cost efficiency of these strategies and their impact on scalability. This section will review the findings, which are discussed in more detail in the discussion section.

5.1 Key Supply Chain Bottlenecks

This section covers the key supply chain bottlenecks in the electric AV industry by focusing on the two companies researched in this thesis, Tesla and Waymo. Three of the most critical bottleneck areas are rated based on their impacts on the supply chains. Current impact and scalability are considered in each area, and they are rated from low to high based on how significant risks each area carries, as Table 1 shows.

Table 1. Comparison of supply chain bottlenecks' impact on Tesla and Waymo

■ Low ■ Medium ■ High

Supply Chain Bottleneck	Aspect	Tesla	Waymo
Material Shortage (Lithium, Cobalt)	Current Impact	Battery innovations, direct parterships	Dependend on OEMs, less control over sourcing
	Scalability Impact	Scaling battery tech still in progress	Limited by supply constraints
Semiconductor Shortages	Current Impact	In-house chip design	Reliant on external suppliers
	Scalability Impact	Still reliant on manufacturers	Relience on manufacturers
Sensor Supply Shortages	Current Impact	Camera only approach	Lidar, Radar and Cameras
	Scalability Impact	Cameras are cheap to scale	Multiple sensors increase sourcing risks

Tesla can combat supply chain risks noticeably better than Waymo, mainly due to vertical integration, a more established supply chain, and fewer sensors. Material shortages are a much lower risk for Tesla since they have an established supply chain and existing contracts with mining companies. However, scalability might introduce risks due to the scarcity of battery materials globally. Waymo's risks are higher due to solely depending on OEMs, thus having no direct control over the battery supply chain. The risks increase when considering a more significant scale since a suitable EV manufacturer might not be found.

Semiconductor supply chains are very similar in both; the main difference is that Tesla designs its chips while Waymo does not. However, both are reliant on external manufacturers. The most significant difference in the supply chain risks is in the sensors. The sensors that Waymo uses are costly compared to just cameras, and there are not many manufacturers for Lidar and Radar sensors that Waymo can use since the tech is new and Waymo needs very specific types of sensors. Tesla's camera approach does not introduce bottlenecks since cameras are cheap, and there are many existing manufacturers.

5.2 Supply Chain Strategies and Scalability

Tesla and Waymo employ two vastly different strategies for managing supply chains and mitigating risks. Tesla follows a vertically integrated strategy, controlling multiple stages of production within the company, whereas Waymo relies heavily on outsourcing key components from third-party suppliers. Both approaches have significant implications for SCRM, influencing each company's ability to respond to disruptions, scale production, and manage costs. As seen in Tbale 2 This analysis compares the two different strategies used by Tesla and Waymo and analyze their effects on SCRM.

Table 2. Tesla vs Waymo Supply Chain Strategies

Aspect	**Tesla**	**Waymo**
Supply Chain Strategy	Vertical Integration	Outsourcing
Control Over Supply Chain	High (batteries, chips, vehicle assembly in-house)	Low (Relience on external suppliers for vehicles and sensors)
Key Strengths	Resilience to distruptions, innovation speed, cost control	Focus on core technology (autonomous software), flexibility in parterships
Key Risks	High upfront investment, operational complexity	Dependency on suppliers, vulnerability to distruptions.
Scalability	Strong due to efficiency and control	Limited due to high cost and external dependencies
SCRM	Reduced risk through internal control and partnerships	Increased risks due to supplier dependency
Cost Efficiency	Lower cost per vehicle due to economies of scale	Higher cost per vehicle due to reliance on costly components and low scale

The analysis found that Tesla's vertical integration strategy is superior to Waymo's outsourcing strategy in multiple aspects. Vertical integration gives Tesla more control over the supply chain, which reduces risks. Vertical integration's key benefit over outsourcing is scalability and cost efficiency. Vertical integration allows for grander scale and reduced cost per vehicle. The risks of vertical integration are mainly the high upfront investments and operational complexity. The benefits of outsourcing are a higher focus on the core competence, which for Waymo is the autonomous software. However, in terms of SCRM and scalability, vertical integration is superior.

5.3 Role of Vehicle Cost in Scalability

The cost per vehicle in building electric AVs is one of the most critical metrics for potential scalability. This section analyzes the manufacturing costs per vehicle for Tesla and Waymo. The costs, as shown in Figure 3, are estimated based on the publicly available data of Tesla, Waymo, and some of Waymo's suppliers. The exact manufacturing costs are not public knowledge, but based on the data points gathered, an accurate estimate can be formed for this research.

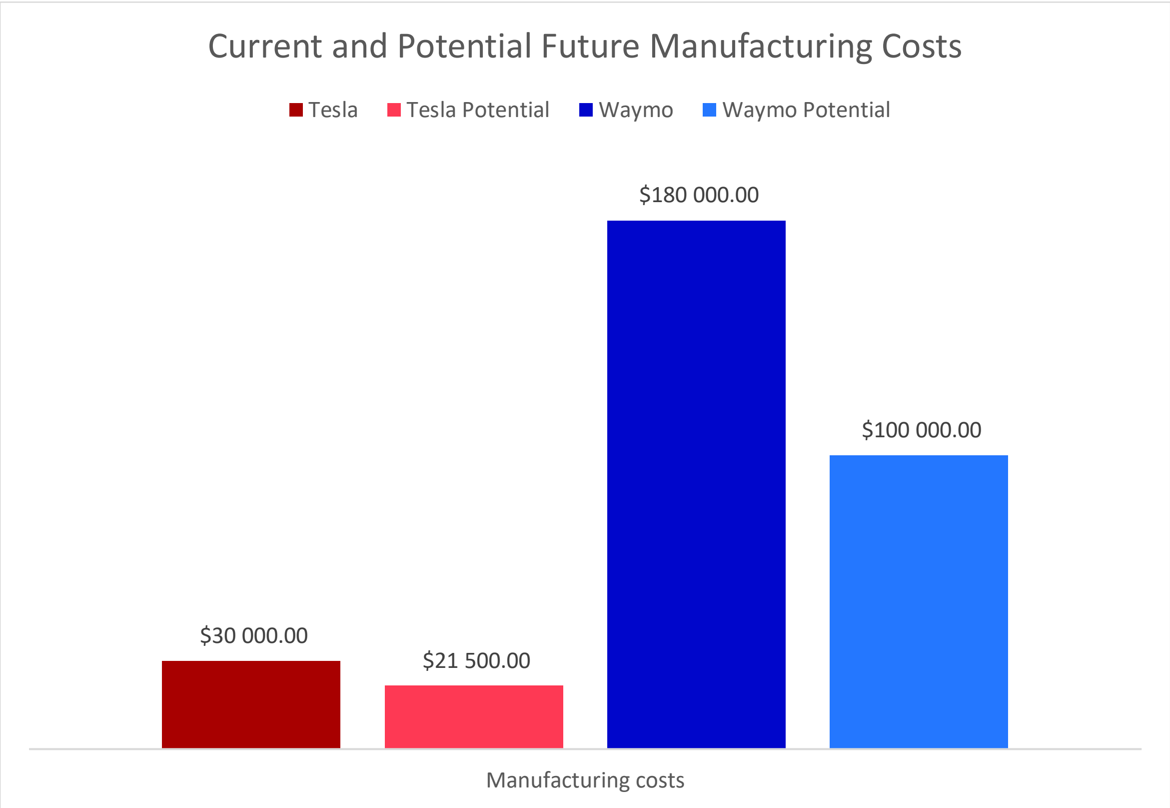

Figure 3. Comparative Cost Analysis of Tesla and Waymo Vehicles

5.3.1 Tesla's Cost Efficiency

The estimated manufacturing costs can be seen in the table. The current cheapest possible vehicles and already announced future vehicles were used for the analysis. The future models were included since both already announced a model and discussed potential cost savings. Tesla's cheapest model is the Model 3, and Waymo's is the 5th Generation vehicle. The future models are Robotaxi for Tesla and 6th Generation for Waymo. The cost analysis can be seen more clearly in the discussion section. The analysis showed that Tesla has a significant cost advantage over Waymo, mainly due to vertical integration and economies of scale. In the near future, Waymo doesn't seem able to come close to Tesla's manufacturing costs. Regarding scalability, Tesla has a clear advantage due to much lower cost per vehicle.

5.4 Interpretation of Results

The findings of this thesis provide critical insights into the supply chain bottlenecks, strategic approaches, and scalability challenges faced by the electric AV industry, especially the researched companies Tesla and Waymo. By comparing Tesla's vertical integration model with Waymo's outsourcing strategy, the results highlight the significant impact of these supply chain strategies on scalability, cost efficiency, and operational resilience. In this section, I connect the results to my research questions by offering a broader interpretation of their implications for the AV industry.

5.4.1 Addressing the Supply Chain Bottlenecks

The analysis revealed that Tesla and Waymo face similar challenges, including raw material shortages, semiconductor supply disruptions, and the complexity of sourcing advanced sensors. However, Tesla's vertically integrated model, coupled with the lack of some sensors, positions it far better to manage these bottlenecks. For example, Tesla can mitigate raw material risks through their direct partnerships with mining companies and innovations in battery technology (e.g., cobalt-free 4680 cells). At the same time, Waymo relies on OEMs to address these challenges. In addition, Tesla's in-house chip design reduces the supply risks in semiconductor shortages. In contrast, Waymo must rely solely on external suppliers, giving them less flexibility and greater exposure to possible supply chain disruptions. These findings show the importance of innovation and control in reducing vulnerabilities in the global supply chain. The findings also emphasize how the vertical innovation model can help manufacturers navigate the complex bottlenecks in the EV and AV sectors while scaling their production.

5.4.2 Evaluating Supply Chain Strategies and Scalability

Regarding scaling AVs, Tesla’s vertically integrated model provides a competitive advantage. It can produce critical components like batteries and chips in-house, reducing costs and enhancing resilience to possible disruptions. In addition, Tesla’s simplified sensor strategy (a camera-only approach) further reduces costs and complexity and helps in rapid scaling. On the other hand, Waymo's outsourcing model gives them flexibility and focuses on autonomous software development, but it also introduces scaling challenges. The high reliability of OEMs limits production flexibility, while the sensor-heavy approach increases supply chain difficulties and costs. The high cost per vehicle and the high reliance on external suppliers reduce Waymo’s ability to scale its fleet rapidly.

These findings demonstrate how the trade-offs between vertical integration and outsourcing affect the rapid scaling of production. While Tesla’s approach requires a significant upfront investment and operational expertise, it enables them to scale rapidly while maintaining the resilience of their supply chain. Waymo’s approach, which is less capital-heavy at the beginning, introduces significant dependencies that significantly affect large-scale expansion.

5.4.3 The Role of Vehicle Costs in Scalability

Vehicle cost is one of the most important metrics when considering scalability. Companies don’t have unlimited resources, and with very high costs, it becomes questionable if the business model can ever be profitable. Tesla’s cost-efficient manufacturing, the economics of scale, vertical integration, and exclusion of the costly sensors provide it a clear advantage in scaling. Waymo’s estimated cost per vehicle is around 6 times higher than Tesla’s

($180,000 vs $30,000). Even with the anticipated cost reductions with the new generation, it’s unlikely that Waymo can come anywhere near to Tesla’s costs in the foreseeable future since Tesla’s costs are also dropping, with the new anticipated Robotaxi costing an estimated $21,500 to produce. This cost disparity emphasizes the critical role of manufacturing efficiency and scale in achieving profitability and market expansion. Tesla’s ability to produce vehicles at much lower costs positions it significantly better for scaling electric AVs for mass adoption.

5.4.4 Broader Implications

These results have broader implications for the AV industry and supply chain strategies. Regarding scalability and market leadership, Tesla’s approach shows that vertical integration can support rapid scalability, cost efficiency, and resilience. Vertical integration could be the way to go for other companies looking to compete in the AV market since these attributes are essential for achieving widespread adoption. In terms of strategic focus, Waymo’s outsourcing strategy enables them to focus heavily on autonomous software development rather than manufacturing expertise. While this allows for innovation in the software, it also highlights the importance of aligning supply chain strategies with long-term scalability goals. These findings suggest that manufacturers may increasingly prioritize cost efficiency and supply chain resilience as the AV industry matures. Companies like Waymo may need to reassess their reliance on third-party suppliers to remain competitive.

5.4.5 Conclusion of Results

In conclusion, the results of comparing Tesla's and Waymo's supply chains illustrate that supply chain strategies significantly influence the scalability and resilience of electric AV production. Tesla’s vertical integration provides a model for achieving large-scale, cost-efficient manufacturing, while Waymo’s outsourcing model demonstrates the challenges of balancing innovation while highly depending on external suppliers. These findings offer valuable insights for the AV industry, emphasizing the need for adaptable, resilient, and cost-efficient supply chain strategies to overcome complex bottlenecks and achieve sustainable growth.

6 Discussion

In the results section, key findings to the research questions were presented. This discussion section focuses on interpreting and analyzing these findings. The discussion examines wider implications for Tesla's and Waymo's supply chain strategies and provides broader into the challenges and opportunities in scaling AVs. This section aims to offer a deeper understanding of the strategic trade-offs faced by the two companies by discussing the findings in more detail

6.1 Addressing Supply Chain Bottlenecks

One of the most significant supply chain bottlenecks in electric AVs is the raw materials needed for batteries. Lithium, cobalt, and nickel are crucial for producing batteries. However, due to the recent boost in EV manufacturing due to government incentives and potentially higher profits for companies, the demand for these materials has surged, creating supply constraints.

Tesla's vertically integrated supply chain is excellent at countering these supply chain bottlenecks. By investing in battery recycling and new battery technologies, such as the cobalt-free 4680 cell, Tesla reduces its dependence on scarce materials. In addition, Tesla has partnered directly with mining companies to secure a steady supply of raw materials.
Compared to Tesla, Waymo is more vulnerable to supply chain bottlenecks since they do not control vehicle manufacturing. Waymo relies on external manufacturers like Jaguar and Zeekr, which face the same material shortages Tesla does. However, Waymo has minimal control over mitigating the challenges. This dependency could lead to production delays and higher costs for Waymo AVs. In addition, Tesla is the most established company in the EV sector due to its scale and innovations. By getting the vehicles from other manufacturers than Tesla, Waymo's risk of supply chain bottlenecks increases since different manufacturers have less established supply chains. Outsourcing could carry a particular benefit for Waymo since they theoretically could change the EV supplier if it's having manufacturing issues.

Still, due to Waymo's tiny fleet and the process it takes to design the sensors for other vehicles, it's not feasible or practical.

The global semiconductor shortage, which began in 2020, is another critical bottleneck for AV manufacturers. Semiconductors are essential for powering the advanced computing systems in AVs. Due to the recent AI boom and the increase in the manufacturing of cars with driver-assisting systems, this could be a significant supply chain bottleneck for companies, especially when trying to scale.

Tesla's supply chain for its chips is very resilient due to the fact that they are able to rewrite the software and order the chips from another manufacturer if its current supplier has shortages. Waymo, on the other hand, depends more on third-party suppliers for semiconductors, making it more vulnerable to supply disruptions, especially when trying to scale its operations.

The sensors required for autonomous driving represent a significant supply chain bottleneck for AV companies. The development and sourcing of these sensors significantly impact scalability and production costs. Tesla's camera-only approach (Tesla Vision) eliminates the need for expensive Lidar and Radar sensors, significantly reducing production costs. However, it may have limitations in specific driving environments, such as heavy snow or fog. Waymo's sensor-heavy approach, which includes cameras, Radar, and Lidar, has allowed them to make a reliable system that already functions as a robotaxi in certain cities. However, this approach introduces a significantly more expensive cost per unit. This reliance on expensive, mostly outsourced sensors introduces a significant vulnerability to Waymo's supply chain, especially when trying to scale the fleet.

6.2 Evaluating Supply Chain Strategies

SCRM in Tesla's Vertically Integrated Supply Chain

Tesla's vertically integrated supply chain gives it control over many different stages, such as battery production, chip design, and vehicle assembly. This model is a prime example of how supply chain risks can be reduced. It offers Tesla significant advantages, especially during global disruptions (Scott, 2024a).

Tesla has lately been heavily investing in battery production facilities that they refer to as "Gigafactories, which currently produce most of Tesla's batteries (Advice Scout, 2024). However, Tesla still has some battery supply contracts with companies like Panasonic due to the growing demand and production of their EVs (Global Fleet, 2024). By moving to more in-house production of batteries, Tesla has been able to reduce risks by reducing reliance on external battery suppliers. Additionally, Tesla has been working on new battery technologies that would greatly reduce or even eliminate the use of highly scarce battery materials, such as cobalt and nickel. For example, Tesla's new battery innovation revealed on Tesla Battery Day in 2020, called 4680-cell is a cobalt-free battery made entirely in-house (EV Lithium, 2024a). Another innovation is a Lithium-Iron-Phosphate (LFP) battery that does not contain cobalt or nickel (EV Lithium, 2024b). These batteries, however, are not currently built in-house but are supplied by CATL. Both batteries are currently in use on some of Tesla's new models, and when they can scale this production, they can significantly reduce supply chain risks connected to the scarcity of some raw materials (Scott, 2024b). Tesla is also actively working on battery recycling and the sourcing of raw materials, which would further secure its supply chain and make it more sustainable (Doyle, 2024).

Designing the chips in-house is also a great way to reduce SCRM. For example, during the global chip shortage, Tesla engineers were able to rewrite their software to support alternative chips, which ensured that they could keep production going even when specific chips were unavailable. By designing the chips in-house, Tesla can also partner with multiple semiconductor manufacturers, reducing reliance on single suppliers, making the supply chain more stable. In addition to chips and software, Tesla also builds their vehicles themselves. This gives them flexibility in the operations and helps them to implement innovations faster in production, reducing operational risks, such as delays caused by integrating new technologies.

Tesla’s vertically integrated strategy offers several advantages for its SCRM, mainly by reducing the exposure to external supply risks and allowing the company to respond more quickly to changes in the market (EightCeption, 2024a). Vertical integration gives Tesla a competitive edge in the highly competitive EV and AV markets. However, it also comes with some risks, such as the high capital investments needed for building it and the additional operation complexity that it brings. A vertically integrated supply chain requires Tesla to excel in various unrelated fields, such as manufacturing batteries and software development, which can create delays or inefficiencies if not managed effectively (EightCeption, 2024b).

SCRM in Waymo’s Outsourcing Model

Waymo has developed a fifth-generation hardware suite for its autonomous vehicles, which includes custom-engineered sensors such as Lidar, Radar, and cameras (Waymo, 2020a). These sensors are designed to work together as an integrated system, providing the Waymo Driver with a comprehensive view of its surroundings. For example, its lidar provides a 360-degree field of view with over 300 meters of range, while the new radar system offers high resolution and a wide field of view to detect objects in all weather conditions (Waymo, 2020b).

Although the blog highlights the engineering and design of these components, it does not explicitly specify whether Waymo manufactures these sensors internally or through external suppliers. Waymo does not seem to publicly disclose if they partner with external manufacturers in their sensors. However, it is noted that Waymo aims to make its hardware scalable and production-ready, suggesting the involvement of partners for large-scale manufacturing (Waymo, 2020c). Due to Waymo's small production volume, it can be assumed that they partner with external suppliers to manufacture their sensors. Data regarding the chips used for Waymo vehicles is also minimal. Samsung is believed to be the chip developer and manufacturer of Waymo vehicles (Reuters, 2021). This larger dependence on external suppliers, paired with the more costly sensors used, gives Waymo less control over its supply chain when compared to Tesla’s vertically integrated model. This makes Waymo's supply chain more vulnerable to external factors such as the semiconductor shortage and COVID-19.

Waymo's software and hardware supply chain is vastly different compared to Tesla's. As mentioned before, Tesla designs the software in-house, while Waymo must work closely with external partners to integrate the autonomous software with the hardware for their vehicles. This higher reliance compared to Tesla introduces operational risks, such as integration delays or incompatibility issues, which could slow down the rollout of autonomous vehicles.

As shown, Waymo has much more supply chain risk management challenges than Tesla. While Waymo benefits from being able to focus on its core technology-autonomous driving software, it is more exposed to external risks due to the outsourcing of key components. This makes them much more vulnerable to supply chain bottlenecks and their ability to scale production due to the limited availability of third-party components. This could be one of the main reasons why Waymo has not been able to scale its fleet quickly since the start of its driverless taxis in 2017 (History Timelines, 2024).

Implications for Scalability

Tesla's vertical integration provides a significant advantage in scaling production by lowering per-vehicle costs and maintaining considerable control over critical supply chain elements. However, it requires significant upfront investments and operational expertise. On the other hand, Waymo's outsourcing model allows it to focus on its core competence—autonomous software—and makes it more suited for targeted deployments, such as robotaxis in limited regions. However, the outsourcing strategy introduces dependencies on multiple suppliers that could significantly limit scalability.

6.3 Impact of Vehicle Costs,

In addition to vertical integration, one of the main reasons Tesla is more cost-efficient than Waymo is economics of scale. Tesla produces over 2 million cars a year, which helps to reduce per-vehicle costs. Because Tesla is an electric car manufacturer and not just an AV project, they can produce almost 10 times as many vehicles a day (5000) (Tesla, 2024c) than Waymo's whole fleet size (700) (Roy, 2024). In addition, Tesla does not use costly sensors like Radar and Lidar. When all these cost benefits are added together, Tesla can produce their electric cars with potential autonomous ability at a much lower cost than Waymo.
In Tesla's most recent financial statement, Q3 2024, the cost of goods sold (COGS) per vehicle was $35,100 (Tesla, 2024d). Although COGS is not exactly the same as manufacturing costs, we can assume that Tesla's cheapest model, the Model 3, costs around $30,000 to manufacture. This estimate is based on the fact that all other Tesla vehicles raise the COGS of the company and that in 2018, German engineers tore down a Tesla Model 3 and estimated that the cost would be around $28,000. In addition, the CEO of Tesla, Elon Musk, agreed that $28,000 would be possible with production of around 10,000 units a week (Lambert, 2018). Currently, the production of Tesla is at around 40,000 per week, with a significant portion being the Model 3 and Model Y (Tesla, 2024c). Due to these data points, $30,000 in manufacturing cost for the Model 3 is a fair estimate.

Regarding Tesla's potential robotaxi, the manufacturing cost estimate becomes more theoretical. Tesla announced that the robotaxi would cost consumers under $30,000 (Levin, 2024). We can get a very theoretical estimate if we look at the Model 3 selling price to the estimated manufacturing cost. The cheapest Model 3 version you can currently purchase when writing is $42,490 (Tesla, 2024e). The selling price of Model 3 is around 1,4 times higher than the estimated manufacturing cost. By applying this logic, I can get the estimated manufacturing cost by dividing the expected selling price by 1,4, which is around $21,500. Again, it is good to note that this manufacturing number is theoretical, and the actual manufacturing cost can differ significantly.

Waymo's cost structure is again an estimate since the company has not publicly stated its manufacturing costs. Two key data points are used for the current 5th Generation cost, and again, estimating the 6th Generation costs is more theoretical, similar to Tesla's robotaxi estimate. The two key data points for the current cost are the statement from 2021, where the CEO John Krafcik referred to the Generation 5 vehicle, stating that "If we equip a Chrysler Pacifica Van or a Jaguar I-Pace with our sensors and computers, it costs no more than a moderately equipped Mercedes S-Class. So for the entire package, including the car - today" Which according to the Forbes article reporting this cost around $180,000 at the time. The other data point is a more recent podcast appearance by Waymo's Co-CEO Dmitri Dolgov, who stated in early 2024 that the cost of the equipment added, meaning sensors and chips, costs under $100,000, this cost is without labor needed to add the sensors and without the cost of the actual car where the sensors are added. Waymo stopped using the Chrysler Pacifica Van in 2023, so we do not need to consider that. The Jaguar I-Pace, which Jaguar now discontinues, started at $71,000 when Waymo announced their 5th Generation (Stafford, 2020). Waymo most likely does not pay the full price since they order in large quantities however, with the cost of labor added, we can assume that the price of around $180,000 seems reasonably accurate for 5th Generation. The cost estimates for Waymo's 6th Generation are highly speculative. Waymo has stated that the new Generation is "significantly cheaper" but refused to say how much. With the new Zeekr EV Minivan from the Chinese manufacturer and fewer amount of sensors (Waymo, 2024d), the price could go as low as $100,000 per car, with the most significant cost reductions being in the vehicle and reduced sensors. Zeekr's cheapest vehicles retail for a little over $20,000 in China, so compared to the $71,000 Jaguar I-Pace, significant cost reductions can be expected here (Bobylev, 2024).

Cost effects on scalability

Although the costs in this section are estimates, we can still use them to see the benefits of vertical integration and economies of scale on the per-unit manufacturing costs over the outsourcing model. Cost is a critical part when considering scalability, and Tesla seems to be better positioned for the scaling of robotaxis if they manage to solve L4 or L5 autonomy. Waymo could struggle with scaling due to the high costs, which could be one reason why Waymo's fleet hasn't been scaling quickly since getting approved for L4 in 2016. However, it's good to note that Waymo's production volume is tiny, and the cost comes down with every generation when the production volume and technology improve. Waymo, however, stated that they do not have any plans to move into car manufacturing in the near future

(Waymo, 2024e). The results of this study indicate that even with high production volume, Waymo can’t meet Tesla's manufacturing costs anytime soon due to the cost benefits of vertical integration and the economics of scale.

7 Summary and Conclusions

This thesis explored the challenges of building EVs from a supply chain perspective, focusing on the two leading companies in the field: Tesla and Waymo. The research examined the supply chain bottlenecks faced by these two companies, their respective strategies for overcoming these challenges, and implications for scalability and cost efficiency. This section summarises the findings, answers the research questions, highlights practical implications, and provides recommendations for future research.

This study aimed to address the supply chain challenges associated with electric AVs, especially focusing on the most critical parts: sourcing batteries, chips, and sensors. Tesla and Waymo were chosen as comparative case studies due to their contrasting supply chain strategies – Tesla's vertically integrated model versus Waymo's outsourcing approach. They were also selected because they can be seen as the current leaders in the industry. The research combined qualitative and quantitative methods to analyze these strategies' operational, financial, and scalability implications.

7.1 Key Findings and Contributions

The findings underscore significant differences between Tesla and Waymo in managing supply chain risks, scaling production, and controlling costs. Both Tesla and Waymo face similar supply chain bottlenecks, including raw material shortages, semiconductor supply constraints, and sensor sourcing difficulties. However, Tesla's vertical integration approach enables much greater control and reduces risks associated with these bottlenecks, while Waymo's outsourcing strategy, in contrast, increases exposure to external disruptions. Tesla's vertically integrated approach, combined with its economics of scale, provides them a competitive advantage by reducing costs per vehicle and enhancing supply chain resilience, which helps in enabling rapid scaling. Waymo's outsourcing strategy allows it to focus on its core competency – autonomous software- but limits its flexibility and scalability due to reliance on external suppliers. Tesla's cost-efficient production model, driven by the economics of scale and simplified sensor strategies, positions it better for mass-market adoption. Waymo's high development costs per vehicle, compounded by low production volumes and sensor-heavy designs, restricts its ability to expand rapidly.

These findings align with prior research on supply chain risk management and scalability in high-tech industries but contribute novel insights by comparing two fundamentally different strategies in the emerging AV sector. This comparative analysis bridges a cap in the literature by emphasizing the supply chain implications of vertical integration versus outsourcing in AV manufacturing.

7.2 Practical Implications

The results have significant implications for stakeholders in the AV industry. For Investors, Tesla's vertically integrated model demonstrates strong potential for cost-efficient scalability, making it an attractive long-term investment. Waymo's outsourcing approach may appeal to investors prioritizing innovation in autonomous software but presents risks related to high costs and limited scalability. For Industry Leaders, the study highlights the importance of aligning supply chain strategies with long-term business goals. Companies aiming for rapid scalability should consider the benefits of vertical integration, while those prioritizing specialized innovation may opt for outsourcing but must mitigate associated risks. Governments promoting sustainable mobility can use these findings to design policies that incentivize supply chain resilience, such as supporting battery recycling initiatives and domestic chip production.

7.3 Limitations and Future Research

While this thesis provides valuable insights, it is essential to acknowledge its limitations. The AV industry evolves rapidly, with frequent technological advancements and supply chain practices. While relevant at the time of writing, the findings may become outdated as companies innovate and adapt. A relevant example of these rapid advancements is Tesla's new version 13 (V13) software update for their autonomous system. While not yet L4 or even L3, it is a huge step up from their previous V12 software.

Additionally, Tesla and Waymo represent two distinct approaches to AV manufacturing, and they are fundamentally different companies. Tesla is the largest EV manufacturer in the world, and currently, they do not have AVs. At the same time, Waymo is the first company in the U.S. to launch an autonomous driving fleet and does not sell any of its vehicles to consumers. Although they can be seen as the leaders in AV technology in the U.S., comparing their supply chain strategies might be a little misleading since the other is an established manufacturer with large manufacturing plants on many continents. In contrast, the other only has under 1000 operational vehicles. Although Waymo has a higher cost than Tesla, it is also the one with working robotaxis at the moment. It would be necessary to also look at the profitability metrics, taking the manufacturing cost into account. Still, since this data is even more limited than the manufacturing costs, it is not included in this thesis. This study could be done when/if Tesla manages to build their robotaxi fleet. It is good to note that the high manufacturing cost of 180,000 USD might not matter if it can stay profitable. Suppose the car's lifetime revenue can generate over its lifetime is around 1,000,000 USD and the maintenance, charging, etc., are around 250,000 USD. In that case, the manufacturing cost per vehicle does not seem that high anymore. Lastly, this study only focuses on two companies from the United States and does not account for the multiple advanced AV companies mainly located in China.

Future research could address these limitations by exploring additional AV manufacturers to provide a broader comparative analysis of the field. Additionally, investigating the long-term impacts of new battery technologies, recycling innovations, and semiconductor advancements on supply chain scalability would give the topic more credibility. Lastly, analyzing the role of regulatory frameworks and public-private partnerships in shaping the AV supply chain could be a valuable addition.

This thesis concluded that supply chain strategies significantly influence electric AVs' scalability, cost efficiency, and resilience. Tesla’s vertically integrated model demonstrates a clear advantage for large-scale production, while Waymo’s outsourcing approach highlights the trade-offs between innovation and dependency on external suppliers. As the AV industry evolves, companies must adopt adaptable and resilient supply chain strategies to overcome bottlenecks and achieve sustainable growth.

References

AdviceScout (2024) 'Tesla Gigafactories'. [online] Available at: https://www.advicescout.com/tesla-gigafactories/ [Accessed 28 Dec. 2024].

ArenaEV, (2024) Tesla Strikes Deal with Samsung to Secure Camera Supply. [online] Available at: https://www.arenaev.com/tesla_strikes_a_new_deal_with_samsung_to_buy_cameras_for_the_next_five_years-news-362.php [Accessed 28 Dec. 2024].

Argus, (2023) AI Boom to Drive Demand for Chip Materials. [online] Available at: https://www.argusmedia.com/en/news-and-insights/latest-market-news/2464740-ai-boom-to-drive-demand-for-chip-materials [Accessed 28 Dec. 2024].

Ashraf, A. (2024a) Alphabet CEO Sundar Pichai Names Tesla as Main Competitor. [online] Available at https://www.benzinga.com/24/12/42503675/alphabet-ceo-sundar-pichai-names-tesla-as-main-competitior-to-its-waymo-robotaxi-unit [Accessed 28 Dec. 2024].

Ashraf, A. (2024b) 'Waymo co-founder says Tesla has an advantage in race to autonomous driving: "I'd rather be in Tesla's shoes than in Waymo's shoes"', Benzinga. [online] Available at: https://www.benzinga.com/news/24/10/41355911/waymo-co-founder-says-tesla-has-an-advantage-in-race-to-autonomous-driving-id-rather-be-in-teslas-sh [Accessed 28 Dec. 2024].

Bobylev, E. (2024) 2025 Model Year Zeekr X Launched in China with a 25% Sliced Price. [online] Available at: https://carnewschina.com/2024/11/01/2025-model-year-zeekr-x-launched-in-china-with-a-25-sliced-price/ [Accessed 28 Dec. 2024].

Butzel, (2017) Waymo Begins Testing Driverless Vehicles. [online] Available at: https://www.butzel.com/alert-Waymo-Becomes-First-to-start-testing-on-public-roads-without-driver [Accessed 28 Dec. 2024].

CNBC, (2024) Waymo's 6th Generation Robotaxi with Geely Zeekr. [online] Available at: https://www.cnbc.com/amp/2024/08/19/waymo-generation-6-robotaxi-geely-zeekr.html [Accessed 28 Dec. 2024].

CNET (2024) 'Tesla's robotaxis could hit Texas and California roads by 2025'. [online] Available at: https://www.cnet.com/roadshow/news/teslas-robotaxis-could-hit-texas-and-california-roads-by-2025/ [Accessed 28 Dec. 2024].

Cooke, P. (2020) Tesla's Gigafactory Logistics: A Sustainability Perspective. [online] Available at: https://www.mdpi.com/2071-1050/12/5/2044 [Accessed 28 Dec. 2024].

Creswell, J.W. and Plano Clark, V.L. (2017) Designing and Conducting Mixed Methods Research. 3rd ed. Thousand Oaks, CA: SAGE Publications.

Dimerco, (2024) EV supply chain challenges. [online] Available at: https://dimerco.com/ev-supply-chain-challenge/ [Accessed 14 Dec. 2024].

Doyle, S. (2024) What Does Tesla Do with Old Batteries? [online] Available at: https://batteryspotlight.com/what-does-tesla-do-with-old-batteries/ [Accessed 28 Dec. 2024].

EightCeption, (2024) Vertical Integration in Tesla's Strategy. [online] Available at: https://eightception.com/vertical-integration-forward-backward-and-examples/ [Accessed 28 Dec. 2024].

Engineering.com, (2023) Now Revealed: Why Teslas Have Only Camera-Based Vision. [online] Available at: https://www.engineering.com/now-revealed-why-teslas-have-only-camera-based-vision/ [Accessed 28 Dec. 2024].

EV Lithium (2024) '4680 battery power innovation'. [online] Available at: https://www.evlithium.com/Blog/4680-battery-power-innovation.html [Accessed 28 Dec. 2024].

EV Lithium (2024) 'Tesla LFP battery'. [online] Available at: https://www.evlithium.com/Blog/tesla-lifepo4-battery.html [Accessed 28 Dec. 2024].

EV Magazine (2024) 'Top 10 advantages of EVs over ICE vehicles'. [online] Available at: https://evmagazine.com/top10/top-10-advantages-of-evs-over-ice-vehicles [Accessed 28 Dec. 2024].

Gaines, L. (2014) 'The future of automotive lithium-ion battery recycling: Charting a sustainable course', *Sustainable Materials and Technologies*, 29, pp. 1-9. [online] Available at: https://www.sciencedirect.com/science/article/pii/S2214993714000037 [Accessed 28 Dec. 2024].

Global Fleet, (2024**)** Tesla-Panasonic Alliance Thrives Through Years. [online] Available at: https://www.globalfleet.com/en/manufacturers/global/analysis/massive-production-and-price-cuts-how-did-tesla-panasonic-alliance-thrive-over-years?curl=1&t%5B0%5D=Tesla&t%5B1%5D=Electrification& [Accessed 28 Dec. 2024].

Goldman Sachs (2024) 'Partially autonomous cars forecast to comprise 10 percent of new vehicle sales by 2030'. [online] Available at: https://www.goldmansachs.com/insights/articles/partially-autonomous-cars-forecast-to-comprise-10-percent-of-new-vehicle-sales-by-2030 [Accessed 28 Dec. 2024].

Golicic, S.L. and Davis, D.F. (2012) Implementing mixed methods research in supply chain management. *International Journal of Physical Distribution & Logistics Management*, 42(8/9), pp.726–741. https://doi.org/10.1108/09600031211269721 [Accessed 28 Dec. 2024].

Green.org, (2024) Benefits of Electric Cars for the Environment. [online] Available at: https://green.org/2024/01/30/benefits-of-electric-cars-for-the-environment/ [Accessed 28 Dec. 2024].

Gupta, A., Anpalagan, A., Guan, L. and Khwaja, A.S. (2021) 'Deep learning for object detection and scene perception in self-driving cars: Survey, challenges, and open issues', *Array*, 10, p. 100057. [online] Available at: https://www.sciencedirect.com/science/article/pii/S2590005621000059 (Accessed: 28 December 2024).

Hamlin, T. (2024) Trump, Tesla Will Turbocharge Self-Driving Race. [online] Available at: https://www.reuters.com/breakingviews/trump-tesla-will-turbocharge-self-driving-race-2024-12-23/[Accessed 28 Dec. 2024].

Hayes, A. (2024) Vertical integration. [online] Available at: https://www.investopedia.com/terms/v/verticalintegration.asp#:~:text=Vertical%20integration%20is%20a%20business,bring%20production%20processes%20in%2Dhouse[Accessed 28 Dec. 2024].

History Timelines (2024) 'Waymo history timeline'. [online] Available at: https://historytimelines.co/timeline/waymo [Accessed 28 Dec. 2024].

Hughes, G. (2023) n.d. Electric Cars: Maintenance Benefits. [online] Available at: https://electriccarwiki.com/electric-cars-maintenance-benefits/ [Accessed 28 Dec. 2024].

Insemitech, (2024) The role of AI-specific chips in autonomous vehicles. [online] Available at: https://insemitech.com/blogs/the-role-of-ai-specific-chips-in-autonomous-vehicles/ [Accessed 14 Dec. 2024].

International Energy Academy (IEA), (2023) Global EV Outlook 2023: Trends in Batteries. [online] Available at: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries [Accessed 28 Dec. 2024].

International Energy Agency (IEA), (2024) Electric Vehicles. [online] Available at: https://www.iea.org/energy-system/transport/electric-vehicles [Accessed 14 Dec. 2024].

Kane, M. (2017) Efficiency Compared: Battery Electric (73%), Hydrogen (22%), ICE (13%). [online] Available at: https://insideevs.com/news/332584/efficiency-compared-battery-electric-73-hydrogen-22-ice-13/ [Accessed 28 Dec. 2024].

Yeong, J. et al. (2021) Sensor fusion technology in autonomous vehicles: A review. *Sensors*, 21(6), p.2140. [online] Available at: https://www.mdpi.com/1424-8220/21/6/2140 [Accessed 14 Dec. 2024].

Krishner, P. (2024) General Motors Halts Cruise Robotaxi Funding. [online] Available at: https://apnews.com/article/general-motors-robotaxi-cruise-stop-funding-9685bb09f8045a36cd7e19a358257565 [Accessed 28 Dec. 2024].

Lambert, F (2018) Tesla Model 3 Teardown Reveals Material and Production Cost. [online] Available at: https://electrek.co/2018/05/31/tesla-model-3-teardow-material-production-cost [Accessed 28 Dec. 2024].

Lambert, F. (2021) How Tesla Pivoted to Avoid Global Chip Shortage. [online] Available at: https://electrek.co/2021/05/03/how-tesla-pivoted-avoid-global-chip-shortage/ [Accessed 28 Dec. 2024].

Law, M. (2024) Top 10 autonomous vehicle companies. [online] Available at: https://technologymagazine.com/top10/top-10-autonomous-vehicle-companies [Accessed 14 Dec. 2024].

Levin, T. (2023) Tesla Robotaxi "Cybercab" Reveal. [online] Available at: https://insideevs.com/news/736879/tesla-robotaxi-cybercab-reveal/ [Accessed 28 Dec. 2024].

Lim, H.S.M. and Taeihagh, A. (2019). Algorithmic decision-making in autonomous vehicles: Ethical and technical challenges. [online] arXiv. Available at: https://arxiv.org/abs/1910.13122 [Accessed 14 Dec. 2024].

Lindwall, C. (2024) Electric vs. Gas Cars: Is It Cheaper to Drive an EV? [online] Available at: https://www.nrdc.org/stories/electric-vs-gas-cars-it-cheaper-drive-ev [Accessed 28 Dec. 2024].

MacCarthy, D. (2024) The Evolving Safety and Policy Challenges of Self-Driving Cars. [online] Available at: https://www.brookings.edu/articles/the-evolving-safety-and-policy-challenges-of-self-driving-cars/ [Accessed 28 Dec. 2024].

Marko, N., Möhlmann, E., Ničković, D., Niehaus, J. and Priller, P. (2021) Challenges of engineering safe and secure highly automated vehicles. [online] arXiv. Available at: https://arxiv.org/abs/2103.03544 [Accessed 14 Dec. 2024].

Mathews, J. (2024). General Motors pulling the plug on Cruise robotaxi. [online] Available at: https://finance.yahoo.com/news/general-motors-pulling-plug-cruise-010517177.html?guccounter=1 [Accessed 14 Dec. 2024].

Mercedes-Benz Group, (2024) DRIVE PILOT: Autonomous Driving Innovation. [online] Available at: https://group.mercedes-benz.com/innovations/product-innovation/autonomous-driving/drive-pilot-95-kmh.html [Accessed 28 Dec. 2024].

Morse, R. (2021) Addressing Environmental Impacts of EV Batteries. [online] Available at: https://www.science.org/doi/pdf/10.1126/science.372.6544.780 [Accessed 28 Dec. 2024].

No-Priors, (2024) The Road to Autonomous Intelligence with Andrej Karpathy. [podcast] Available at: https://podcasts.apple.com/fi/podcast/the-road-to-autonomous-intelligence-with-andrej-karpathy/id1668002688?i=1000668455289 [Accessed 28 Dec. 2024].

Parekh, et al., (2022) 'A review on autonomous vehicles: Progress, methods and challenges', *Electronics*, 11(14), p. 2162. [online] Available at: https://www.mdpi.com/2079-9292/11/14/2162 (Accessed: 28 December 2024).

PRNewswire, (2024) Nuro Goes Fully Driverless in Three States. [online] Available at: https://finance.yahoo.com/news/nuro-goes-fully-driverless-three-140000903.html [Accessed 28 Dec. 2024].

Redwood Materials (2024) ‘Recycle with us’. [online] Available at: https://www.redwoodmaterials.com/recycle-with-us/ [Accessed 28 Dec. 2024].

Reuters, (2021) Samsung to Develop Autonomous Driving Chips for Waymo. [online] Available at: https://www.reuters.com/article/technology/samsung-to-develop-autonomous-driving-chip-for-googles-waymo-media-idUSKBN2B71A2/ [Accessed 28 Dec. 2024].

Reuters, (2024) ‘Shift to electric vehicles will have far-reaching impact, IMF says’. [online] Available at: https://www.reuters.com/business/autos-transportation/shift-electric-vehicles-will-have-far-reaching-impact-imf-says-2024-10-

22/#:~:text=%22The%20rising%20adoption%20of%20electric,help%20countries%20achieve%20climate%20goals [Accessed 28 Dec. 2024].

Roy, A. (2024) Alphabet's Waymo to Expand Robotaxi Fleet with Hyundai EVs. [online] Available at: https://www.reuters.com/business/autos-transportation/alphabets-waymo-expand-robotaxi-fleet-with-hyundai-evs-2024-10-04/#:~:text=Waymo%20has%20about%20700%20vehicles,uncrewed%20robotaxis%20that%20collect%20fares[Accessed 28 Dec. 2024].

SAE International (2024) 'SAE J3016 update'. [online] Available at: https://www.sae.org/blog/sae-j3016-update [Accessed 28 Dec. 2024].

Scott, A. (2024) 'Tesla's vertical integration revolutionizes supply chains'. [online] Available at: https://supplychain360.io/teslas-vertical-integration-revolutionizes-supply-chains/ [Accessed 28 Dec. 2024].

Shepardson, D. & Eckert, N. (2024) General Motors to drop development of Cruise robotaxi. [online] Available at: https://www.reuters.com/business/autos-transportation/general-motors-drop-development-cruise-robotaxi-2024-12-10/ [Accessed 14 Dec. 2024].

Sherman, D. (2022.)Why EVs Are Safer Due to Low Center of Gravity. [online] Available at: https://www.motorbiscuit.com/safe-evs-they-dont-want-to-roll-over/ [Accessed 28 Dec. 2024].

Simply Fleet, (2024) 7 benefits of self-driving cars. [online] Available at: https://www.simplyfleet.app/blog/7-benefits-of-self-driving-cars [Accessed 14 Dec. 2024].

Sisodia, R. (2024) Top 8 Benefits of Electric Vehicles. [online] Available at: https://www.evmechanica.com/top-8-benefits-of-electric-vehicles/ [Accessed 28 Dec. 2024].

Spieske, A. and Birkel, H. (2021) 'Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic', *Computers & Industrial Engineering*, 158, p. 107452. [online] Available at: https://doi.org/10.1016/j.cie.2021.107452. [Accessed 28 Dec. 2024].

Stafford, E, (2020) Jaguar I-Pace 2020 Review. [online] Available at: https://www.caranddriver.com/jaguar/i-pace-2020 [Accessed 28 Dec. 2024].

Tabim, K., Singh, R. and Brooks, J. (2024) Digital Transformation in the Automotive Industry. [online] Available at: https://link.springer.com/article/10.1007/s10796-021-10220-x [Accessed 28 Dec. 2024].

Tesla, (2023) 2023 Tesla Impact Report. [online] Available at: https://www.tesla.com/ns_videos/2023-tesla-impact-report.pdf [Accessed 28 Dec. 2024].

Tesla, (2024e) Tesla Model 3 Design Overview. [online] Available at: https://www.tesla.com/model3/design#overview [Accessed 28 Dec. 2024].

Tesla, (2024b) We Robot. [online] Available at: https://www.tesla.com/we-robot [Accessed 14 Dec. 2024].

Tesla, (2024a) 'Support: Autopilot'. [online] Available at: https://www.tesla.com/support/autopilot [Accessed 28 Dec. 2024].

Tesla, (2024c). Tesla Third Quarter 2024 Production, Deliveries, and Deployments. [online] Available at: https://ir.tesla.com/press-release/tesla-third-quarter-2024-production-deliveries-and-deployments [Accessed 28 Dec. 2024].

Tesla, (2024d). Q3 2024 Update. [online] Available at: https://digitalassets.tesla.com/tesla-contents/image/upload/IR/TSLA-Q3-2024-Update.pdf [Accessed 28 Dec. 2024].

Twin, A. (2024) 'Outsourcing'. [online] Available at: https://www.investopedia.com/terms/o/outsourcing.asp [Accessed 9 Jan. 2025].

Waymo, (2019) Bringing 3D Perimeter Lidar to Partners. [online] Available at: https://waymo.com/blog/2019/03/bringing-3d-perimeter-lidar-to-partners/ [Accessed 28 Dec. 2024].

Waymo, (2020) Introducing the 5th Generation Waymo Driver. [online] Available at: https://waymo.com/blog/2020/03/introducing-5th-generation-waymo-driver [Accessed 28 Dec. 2024].

Waymo, (2024b) Next stop Miami. [online] Available at: https://waymo.com/blog/2024/12/next-stop-miami [Accessed 14 Dec. 2024].

Waymo, (2024a) Waymo Official Website. [online] Available at: https://waymo.com/ [Accessed 28 Dec. 2024].

Waymo, (2024d) Meet the 6th Generation Waymo Driver. [online] Available at: https://waymo.com/blog/2024/08/meet-the-6th-generation-waymo-driver [Accessed 28 Dec. 2024].

Waymo, (2024e) Waymo and Hyundai Enter Partnership. [online] Available at: https://waymo.com/blog/2024/10/waymo-and-hyundai-enter-partnership/ [Accessed 28 Dec. 2024].

Waymo, (2024c) Waymo Driver Overview. [online] Available at: https://waymo.com/waymo-driver/ [Accessed 28 Dec. 2024].

Wong, K. (2024) GM Ends Cruise Robotaxi Program After $10 Billion Investment. [online] Available at: https://www.btimesonline.com/articles/171566/20241212/gm-ends-cruise-robotaxi-program-after-10-billion-investment.htm [Accessed 28 Dec. 2024].

Zhao, X., Tan, M., and Liu, J. (2020) Waymo's Outsourcing Strategy in Autonomous Driving. [online] Available at: https://www.matec-conferences.org/articles/matecconf/abs/2020/21/matecconf_ictle2020_04002/matecconf_ictle2020_04002.html [Accessed 28 Dec. 2024].