GLOBAL SEMICONDUCTOR SHORTAGE TRIGGERING OBSTRUCTIONS AND PRODUCTION DELAYS

by

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This thesis is dedicated to my parents, Late Prof. Sudhir Ranjan Chakraborty and Late Arati Chakraborty, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. They supported me in all my pursuits and inspired me to follow my dreams. I am forever grateful for their encouragement when the times got rough.

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Abstract

Global Semiconductor Shortage Triggering Obstructions and Production Delays

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The global COVID-19 pandemic served as an enormous shock that severely disrupted the delicate supply-demand balance in semiconductor supply chains. Lockdowns and travel restrictions temporarily halted production at overseas chip fabrication facilities. This reduced supply was misaligned with a sudden spike in semiconductor demand as consumer electronics purchases surged while working and learning from home became widespread. However, the automotive industry had drastically scaled back chip orders earlier in the pandemic as car sales plunged. This mismatch resulted in acute semiconductor shortages for automakers as production rebounded quicker than anticipated amidst chip supply rigidity. The research analyzed this complex interplay through extensive literature review, data analysis, and forecast modeling.

The study synthesized perspectives from prior work examining supply chain vulnerabilities and automotive industry impacts. A thematic analysis identified key drivers including pandemic disruptions, supply-demand mismatches, manufacturing concentration risks, automotive priority gaps, and macroeconomic shifts. Financial impacts on major automakers were also reviewed. An original dataset on country-level automotive production over 22 years provided empirical insights. Descriptive analysis evidenced dramatic declines in 2020 output across all major producing economies from pandemic disruptions. China maintained production leadership despite the crisis. Sophisticated forecasting using LSTM neural networks was conducted to predict recovery timeframes and enhance preparedness.

Key implications highlighted supply chain resilience strategies and collective action as imperative for managing systemic shortages. The deepening necessity and complexity of semiconductor supply chains poses risks from over-optimization without agile buffers. For the automotive industry, rethinking innovation roadmaps, increasing visibility, strategic stockpiling, and creative engineering is needed to navigate disruptions. The research limitations around constrained forecasting, conceptual materials analysis, aggregated data usage, and geographically limited literature review were acknowledged. Recommendations included addressing these gaps through expanded techniques, proprietary data access, and globally diverse information sources. Overall, the study contributed timely perspectives to aid stakeholders across electronics supply chains seeking to enhance resilience while upholding rapid innovation. The insights generated can help the automotive and semiconductor industries be better positioned to navigate future crises.

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LIST OF ABBREVIATIONS

IC	**I**ntegrated **C**ircuit
OEM	**O**riginal **E**quipment **M**anufacturer
EV	**E**lectric **V**ehicle
HEV	**H**ybrid **E**lectric **V**ehicle
LED	**L**ight **E**mitting **D**iode
GaAs	**Ga**llium **As**enide
GaN	**Ga**llium **N**itride
InP	**In**dium **P**hosphide
CNT	**C**arbon **N**anotube
LSTM	**L**ong **S**hort **T**erm **M**emory
ARIMA	**A**utoregressive **I**ntegrated **M**oving **A**verage
ACF	**A**utocorrelation **F**unction
PACF	**P**artial **A**utocorrelation **F**unction
RMSE	**R**oot **M**ean **S**quared **E**rror
MAPE	**M**ean **A**bsolute **P**ercentage **E**rror
R&D	**R**esearch and **D**evelopment
EDA	**E**lectronic **D**esign **A**utomation
IoT	**I**nternet of **T**hings
5G	5th **G**eneration **W**ireless

CHAPTER I

INTRODUCTION

1.1 Background

The outbreak of the COVID-19 pandemic has brought about unprecedented challenges and changes to various aspects of human life, including the economy, healthcare, and daily lifestyles. In response to the pandemic, governments around the world have implemented various measures and restrictions to limit human activities and prevent the spread of the virus. However, these measures have also resulted in significant disruptions to many industries and supply chains, including the semiconductor and automotive industries (Winterfeldt, Edwards, and Ward, 1986).

The "Chip Shortage" phenomena is one of the most pressing issues currently facing the automotive industry. With the rising demand for technological devices, the semiconductor industry has been allocating more resources towards the production of chips for electronic gadgets, resulting in a global scarcity of semiconductor chips for the automobile industry and other industries. The imbalance between silicon chip supply and demand has had a significant impact on the automotive industry's supply chains, production, and sales.

This research aims to examine the causes, consequences, and potential solutions to the current global shortage of semiconductor chips that has affected the automobile industry. It will analyze the impact of the shortage on the industry, identify the key players and stakeholders involved in the crisis, and evaluate potential solutions or strategies that could help alleviate the shortage and prevent similar crises from happening in the future. The ultimate goal of this analysis is to provide insights and recommendations to industry stakeholders, policymakers, and other interested parties on how to effectively manage and respond to the chip shortage crisis in the automobile industry.

This section will begin with an overview of the current state of the semiconductor industry, followed by a discussion of the impact of the COVID-19 pandemic on the industry and its supply chains. It will then explore the causes and consequences of the chip shortage crisis in the automotive industry, and examine potential solutions and strategies to alleviate the shortage.

1.1.1 Global Chip Production Capacity

The worldwide semiconductor industry is projected to invest more than $500 billion in 84 volume chip-making facilities starting construction from 2021 to 2023, with segments including automotive and high-performance computing fueling the spending increases, as reported by SEMI's latest quarterly World Fab Forecast report (SEMI, 2023). The report highlights the increasing strategic importance of semiconductors to countries and a wide array of industries worldwide, underscoring the significant impact of government incentives in expanding production capacity and strengthening supply chains. The report identifies China as expected to outnumber all other regions in new chip manufacturing facilities, with 20 supporting mature technologies planned. The Americas is forecast to start construction on 18 new facilities, whereas Europe/Mideast investment in new semiconductor facilities is expected to reach a historic high for the region, with 17 new fabs starting construction between 2021 and 2023. Taiwan, Japan, Southeast Asia, and Korea are also expected to contribute to the growth of the semiconductor industry by beginning to build new facilities over the forecast period. The latest update of the SEMI World Fab Forecast report lists more than 1,470 facilities and lines globally, including 162 volume facilities and lines with various probabilities that are expected to start production in 2022 or later.

In light of the ongoing semiconductor shortage, McKinsey & Company has released a report titled "Semiconductor shortage: How the automotive industry can succeed" (McKinsey and Company, 2023b) The report examines the causes of the shortage, the current state of the semiconductor market, and the implications for industries that rely on these chips, particularly the automotive industry.

The report identifies several key drivers of the shortage, including the COVID-19 pandemic, which disrupted supply chains and caused a surge in demand for consumer electronics, and geopolitical tensions, such as the trade war between the US and China. The report also notes that the complexity of the semiconductor supply chain, with its many layers of suppliers and subcontractors, has made it difficult for companies to accurately predict and manage their chip supplies (McKinsey and Company, 2023a).

The automotive industry has been hit particularly hard by the shortage, with some automakers forced to temporarily halt production and others forced to cut features from their vehicles. The report suggests that automotive companies can mitigate the impact of the shortage by developing stronger relationships with their chip suppliers, investing in alternative sourcing models, and optimizing their production processes to reduce chip usage.

The report also offers recommendations for semiconductor companies, such as increasing capacity and investing in new technologies to improve the efficiency of the chip manufacturing process. The report concludes that the semiconductor shortage is likely to persist for some time, and that companies in all industries will need to adapt their strategies to navigate this challenging environment.

1.1.2 Automotive Chip Industry

The automotive industry has been hit hard by the ongoing semiconductor chip shortage, which has caused delays in production and forced many manufacturers to halt production lines. This shortage has been exacerbated by the increasing demand for semiconductor chips in all modern products, including smartphones, PCs, and tiny IoT devices. Electric vehicles (EVs) also require a significant number of semiconductor chips to be produced.

The COVID-19 pandemic has disrupted the balance between upstream chip producers and downstream auto manufacturers, leading to a shortage of semiconductor chips. Major automobile manufacturers such as Toyota, Volkswagen, Fiat Chrysler, Nissan, and Daimler have been forced to shut down production lines at multiple plants due to serious chip supply issues. The shortage has also resulted in a sharp decrease in auto stock prices on the Chinese A-share market.

The shortage of semiconductor chips is not limited to the automotive industry but has impacted many other chip-based sectors as well. The raw materials required for semiconductor chip production are also in short supply, leading to slower production rates in many manufacturing companies.

As the semiconductor chip shortage persists, it is essential for the automotive industry to investigate and debate how automobile firms can respond to the "chip scarcity" scenario and improve their emergency readiness. The industry may benefit from new sourcing models and stronger bonds between OEMs, Tier 1 suppliers, and semiconductor suppliers. Overall, the industry needs to refine its strategy by focusing on the creation of strong technology maps, reliable short-term demand planning, and guidance for long-term demand planning to overcome the ongoing instabilities in the semiconductor supply chain.

The increasing adoption of electric and autonomous vehicles is expected to have a significant impact on the automotive semiconductor market. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) require more semiconductor components than traditional gasoline-powered vehicles due to the complex power electronics systems used in EVs, such as batteries, electric motors, and inverters. The growth of EVs and HEVs is expected to drive the demand for power electronics components, such as power modules, power transistors, and gate drivers, which are critical for controlling the flow of electricity (Intelligence, 2023).

Similarly, the growth of autonomous vehicles is also expected to drive the demand for semiconductor components. Autonomous vehicles require various sensors, such as radar, lidar, and cameras, to perceive the environment and make decisions. The data collected by these sensors need to be processed in real-time, requiring high-performance processors, memory, and communication components. As the adoption of autonomous vehicles increases, the demand for these semiconductor components is expected to rise significantly.

According to a report by Allied Market Research, the global market for semiconductors in autonomous vehicles is expected to grow at a CAGR of 47.6% from 2020 to 2027. The report also states that the market for semiconductors in EVs is expected to grow at a CAGR of 20.7% from 2020 to 2027.

The market for electric vehicles (EVs) is expanding rapidly, driven by environmental concerns, government regulations, and advances in technology. EVs require a significant amount of semiconductors to operate, including power management ICs, microcontrollers, and sensors, among others. The increased demand for EVs is therefore driving the growth of the automotive semiconductor market. As governments worldwide aim to reduce carbon emissions, they are offering incentives to promote the use of EVs. For instance, in the United States, the federal government offers a tax credit of up to $7,500 for EV buyers, while some states provide additional incentives. Similarly, European countries have established ambitious targets for electric vehicle adoption, and many offer financial incentives and tax breaks to encourage consumers to buy EVs. As a result, the demand for EVs is expected to grow significantly, driving the automotive semiconductor market.

The trend of connected cars, which refers to vehicles equipped with internet connectivity and advanced sensors, is gaining popularity in the automotive industry. Connected cars enable drivers to access real-time traffic information, entertainment, and other services, as well as enable vehicle-to-vehicle and vehicle-to-infrastructure communication. The increasing adoption of connected cars is driving the demand for automotive semiconductors, including microcontrollers, sensors, and wireless communication ICs. The integration of advanced technologies such as 5G, artificial intelligence, and machine learning is further fueling the demand for semiconductors in the automotive sector (Intelligence, 2023).

The COVID-19 pandemic had a significant impact on the automotive industry, including the semiconductor market. The pandemic disrupted the global supply chain, leading to production shutdowns, delays, and shortages of critical components such as semiconductors. The automotive semiconductor market was particularly affected, as automakers cut production due to decreased demand and supply chain disruptions. However, the market has started to recover as the automotive industry recovers from the pandemic's impact, and demand for vehicles increases.

1.1.3 Impact of COVID-19 on the Automotive Chip Industry

The global passenger car market experienced a severe downturn as a result of the far-reaching effects of the coronavirus pandemic. Sales and demand plummeted, leaving automotive manufacturers grappling with production plant closures and substantial losses. Throughout the first and second quarters of 2020, automotive production witnessed a staggering decline of approximately 9.6%, equivalent to around 7.7 million vehicles (Frieske and

Stieler, 2022). Consequently, original equipment manufacturers (OEMs) adjusted their capacity planning for supplier parts, including electronic components and semiconductors.

Remarkably, demand rebounded unexpectedly towards the end of 2020, driven primarily by the remarkable recovery of the Chinese automotive market and the increased sales of electrified vehicles due to the German innovation premium. China alone witnessed passenger car sales surpassing the figures projected in the autumn of 2020 by approximately 500,000 vehicles (Frieske and Stieler, 2022).

Concurrently, the coronavirus pandemic prompted a surge in demand for consumer electronics such as smartphones, game consoles, and TVs. This shift in prioritization compelled semiconductor manufacturers to realign their capacities towards serving the needs of the IT and consumer electronics sectors. Consequently, the production and supply of electronic components for the automotive industry experienced bottlenecks, primarily affecting suppliers in the fourth quarter of 2020. However, these challenges have persisted into 2022, impacting not only suppliers but also nearly all automotive manufacturers, who have been compelled to curtail or even halt production due to component and parts shortages.

The growing prominence of electromobility and autonomous driving ensures the continued rise in semiconductor usage within vehicles. Therefore, ensuring the stability of the supply chain has become a strategically critical objective for both the German and European automotive industries.

1.2 Research Objective

The objective of this research is to explore and analyze the impact of supply chain disruptions on operational and financial performance, with a focus on internal and external interruptions. Internal disruptions, such as factory fires, and external disruptions, including economic shocks and natural disasters, have been found to have detrimental effects if not effectively managed (Hendricks and Singhal, 2005). The COVID-19 pandemic, which can be seen as an unforeseen external disruption, shares similarities with previous disruptions caused by events like terrorist attacks, tsunamis, financial crises, and earthquakes (Wagner and Bode, 2006).

Over the past decade, disruptions in global supply chains have increased in frequency and severity due to factors such as globalization, climate change, a dynamic corporate environment, and the growing complexity of these networks (“Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation” 2015). Consequently, the capabilities of supply chains must adapt to the evolving environment, aiming not only for effectiveness but also resilience. The pandemic has exposed vulnerabilities arising from over-reliance on a single source, particularly China, underscoring the importance of supply chain resilience (SCRes). A survey conducted among supply chain executives at top global corporations revealed that 93 percent of them intend to strengthen their supply chains (Ho et al., 2015).

Previous research has focused on the integration of supply chain risk management (SCRM) and SCRes, defining SCRM as an inter-organizational collaborative effort utilizing quantitative and qualitative risk management methodologies to identify, evaluate, mitigate, and monitor unexpected events or conditions that could impact any part of a supply chain (Ho et al., 2015). Scholars have proposed resilience strategies and recovery approaches, framing the COVID-19 disruption from an SCRes perspective.

While initial studies on the effects of supply chain disruption during the early stages of the pandemic have been conducted, further research is warranted to gain a deeper understanding of the performance of supply chains in industries such as automotive and electronics applications after a year has passed since the initial disruption (Ivanov, 2020). This research aims to examine the long-term effects of supply chain disruption using the SCRes aspect.

Although the chip shortage during the COVID-19 pandemic is expected to diminish in the next 1-2 years, it is crucial to address three significant problems that require complete or partial resolution in the near future. The increasing demand for semiconductor chips, utilized in various devices such as vehicles, smart appliances, and sensing devices, poses a challenge as the supply of semiconductors is limited. To mitigate this problem, alternative raw materials that offer a large and cost-effective supply for chip development need to be identified.

Assuming an adequate supply of semiconductor raw materials, the preprocessing and chip manufacturing stages require substantial amounts of labor, water, and other resources that may be scarce in certain regions. Semiconductor industries face challenges in finding suitable geographical locations to establish their infrastructure due to these constraints. Currently, there are only a few locations, like Taiwan, where chip manufacturing is thriving. The limited chip supply and high demand create disruptions in the supply chain for various industries, not only the automotive sector.

The past few years have witnessed a global disruption of supply chains due to global lock-downs, which is now mostly resolved. However, these incidents serve as a reminder to take precautions and develop techniques to mitigate the impact of future global disasters, severe conflicts, or similar disruptions on supply chains. It is imperative to be prepared and resilient in the face of potential future challenges.

In short, the research objective is to examine the market growth and various use cases of semiconductor chips, with a focus on understanding the increasing demand and developing a model to project future demand patterns. Drawing insights from past incidents like the COVID-19 pandemic, the study aims to investigate the impact of the crisis on vehicle manufacturing and other sectors closely linked to semiconductor supply chains. The following goals will be pursued:

- Generate new insights to enhance supply chain management strategies for effectively navigating global disasters or war-like situations.
- Evaluate the modifications implemented by manufacturers in response to the pandemic outbreak.
- Explore alternative approaches to chip development or identify methods to mitigate the depletion of raw materials used in chip manufacturing across different sectors.

The study will primarily focus on the automobile sector, given its economic significance and extensive coverage in supply chain literature (Holweg, 2007; Belhadi et al., 2021). Analyzing multiple industries will allow for comparative analysis and enhance the overall validity of the research.

1.3 Research Questions

To address the research objective of understanding the market growth and impact of the semiconductor chip shortage, as well as identifying strategies to enhance supply chain resilience, the following research questions will guide this study:

1. How did the COVID-19 pandemic disrupt the supply chains in the automobile sector, and what were the specific challenges faced by manufacturers and other industries reliant on semiconductor supply?

2. What measures were taken by automobile manufacturers and other sectors to mitigate the impact of the chip shortage during the pandemic, and what lessons can be learned from their experiences?

3. What are the implications of the pandemic outbreak on supply chain management practices in the automobile industry, particularly in terms of modifications made by manufacturers?

4. How can supply chain resilience be enhanced to better navigate global disasters or war-like situations, taking into account the lessons learned from the COVID-19 crisis?

5. What alternative approaches can be explored to develop semiconductor chips or slow down the depletion of raw materials used in chip manufacturing, ensuring a sustainable supply for various sectors?

6. How can information obtained from the study be used to improve supply chain management strategies and enhance the resilience of supply chains in the face of future disruptions?

By addressing these research questions, this study aims to contribute valuable insights into the semiconductor industry, supply chain management, and the strategies needed to cope with disruptions and increase resilience.

CHAPTER II

REVIEW OF LITERATURE

2.1 Overview of the Semiconductor Industry

The COVID-19 pandemic has brought about significant challenges and restrictions, affecting various industries worldwide. Among them, the semiconductor industry and integrated circuit companies have faced the phenomenon of *Chip Shortage*. The surge in demand for electronic gadgets such as smartphones, computers, and laptops during this period has led to the utilization of available semiconductor stocks by global chip companies for developing chips for these devices. On the other hand, the automotive industry has experienced a decline in sales due to decreased demand compared to the electronics sector. The reallocation of resources from the market has disrupted the balance between supply and demand for silicon chips. This global shortage of semiconductor chips not only impacts the automotive industry but also poses a risk of disrupting the entire industrial chain.

The semiconductor industry relies heavily on efficient cross-border collaboration. However, there might be a lack of international prevention and control cooperation mechanisms. China, facing both challenges and opportunities in this situation, should take initiatives to strengthen international cooperation and enhance the core competitiveness of its chip industry. This can be achieved through top-level design, encouraging domestic enterprises to invest in research and development, and improving technical performance.

Nowadays, semiconductor chips are integral to various products, including mobile phones, computers, and smaller IoT devices. However, the ongoing trend of Chip Shortage, which emerged in late 2020, has severely impacted the automotive industry and other chip-based industries. Today, the production of a single car requires hundreds of semiconductor chips. The rise of Electric Vehicles (EVs) has further increased the demand for these chips in the automotive sector. The balance between upstream chip suppliers and downstream car manufacturers has been disrupted during the COVID-19 pandemic.

The shortage of chips has compelled several automobile manufacturers to halt their production lines. For example, Toyota and Volkswagen had to temporarily shut down production lines in Chengdu and Guangzhou, China, due to severe chip supply concerns. Fiat Chrysler, Nissan, and Daimler also faced production reductions or halts in various regions. The Chip Shortage has had a significant impact on auto stocks in China's A-share market.

Understanding the reasons behind the chip shortage in the automotive industry and finding effective solutions are of utmost importance. It is crucial to investigate how automotive companies are managing the chip scarcity situation and enhancing their emergency preparedness to address this issue. By exploring and discussing these matters, we can gain insights into the strategies employed by automotive companies to overcome the challenges posed by the Chip Shortage.

2.2 Semiconductor Demands and Price Hikes

In today's scenario, a large number of semiconductor chips are required to develop almost any device. The COVID-19 pandemic has had a significant impact on global economic growth, causing strain in the supply chain for various products, including semiconductor materials. Higher shipping costs and delays in shipping have further exacerbated the situation, leading to empty stocks for chip manufacturing companies. Well-functioning supply chains and labor market shortages can contribute to inflationary pressures, as highlighted in studies (Leibovici and Dunn, 2021; Daly, 2022). Industries that have not experienced significant changes in demand may witness price increases due to shortages of essential raw materials. Supply chain disruptions can exacerbate the shortage of certain inputs, making the situation even more challenging. Thus, investigating the role of the supply chain in inflation becomes essential, and the semiconductor industry serves as an important case study.

The significance of semiconductor chips extends to various industries, including computers, toys, IoT devices, cars, and more. According to a report, semiconductor chips are used as a direct input in nearly 25 percent of 226 industrial sectors. Despite representing a small portion of total import expenses, semiconductor shortages can slow down the production speed in many industries due to the lack of viable alternatives. Increasing production capacity is costly, leaving sectors heavily reliant on semiconductors with limited short-term options to address shortages.

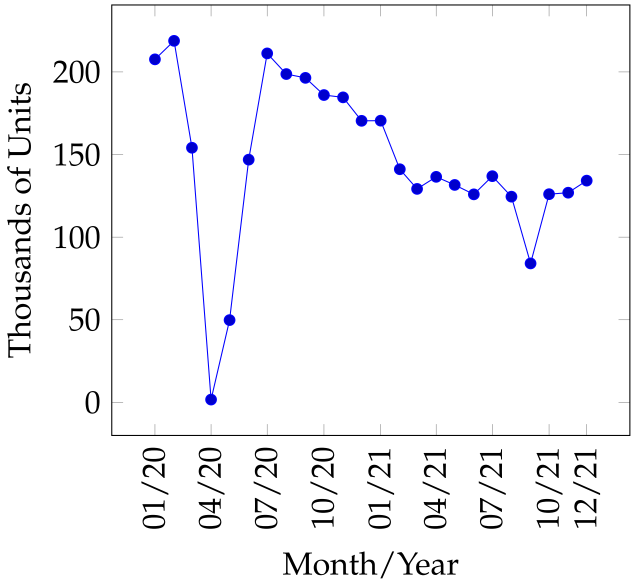
To understand the impact of the Chip Shortage on the automotive industry, it is crucial to examine the production and price trends. The production of automobiles heavily depends on semiconductor chips, with a single vehicle requiring hundreds of them for complete control. The production rate experienced a significant drop in April 2020 during the COVID-19 period, gradually recovering but still exhibiting a declining trend over time, as shown in Figure 2.1a. The statistics for US car production over a two-year period indicate the challenges faced by the industry.

Simultaneously, the price index has been affected by the shortage, as depicted in Figure 2.1b. The US Producer Price Index by Industry for New Car Dealers: Vehicle Sales shows a rising trend during 2020 and 2021. From January 2019 to January 2021, the average monthly price change for both semiconductor-dependent and non-semiconductor-dependent vehicles was relatively similar. However, in 2021, the price increase became more significant for manufacturing companies using semiconductor devices, with a 4 percent higher price change compared to non-semiconductor-dependent vehicles in September 2021.

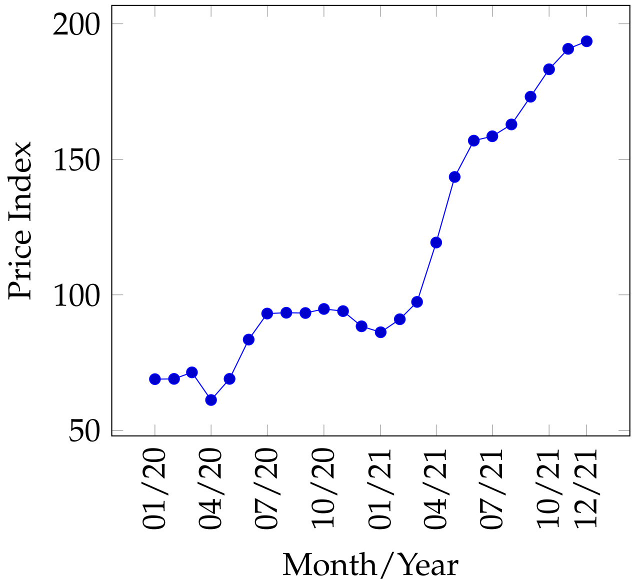
The disruption in the production of semiconductor-dependent automobiles in 2021 can be attributed to the high demand for electronic gadgets, such as phones, entertainment consoles, and TVs (Voas, Kshetri, and DeFranco, 2021). As a result, companies relying on semiconductor access have had to reduce their production capacities, leading to delays in new product launches.

Figure 2.2 illustrates the revenue generated by different companies utilizing semiconductor chips in their products. The data for the years 2019-2020 reveals an overall increase in revenue, particularly driven by electronics and computing products. However, the revenue rate has decreased in the automobile and other industrial sectors, indicating a significant decline in their profit margins.

The global chip shortage after the COVID-19 pandemic can be attributed to several key factors that have greatly impacted semiconductor scarcity.



(A) U.S. Domestic Production of Autos (*Domestic Auto Production* 2022)



(B) U.S. Producer Price Index by Industry: New Car Dealers: Vehicle Sales (*Producer Price Index by Industry: New Car Dealers: Vehicle Sales* 2022)

FIGURE 2.1: US Car Production rate and Producer Price Index in the year 2020-2021

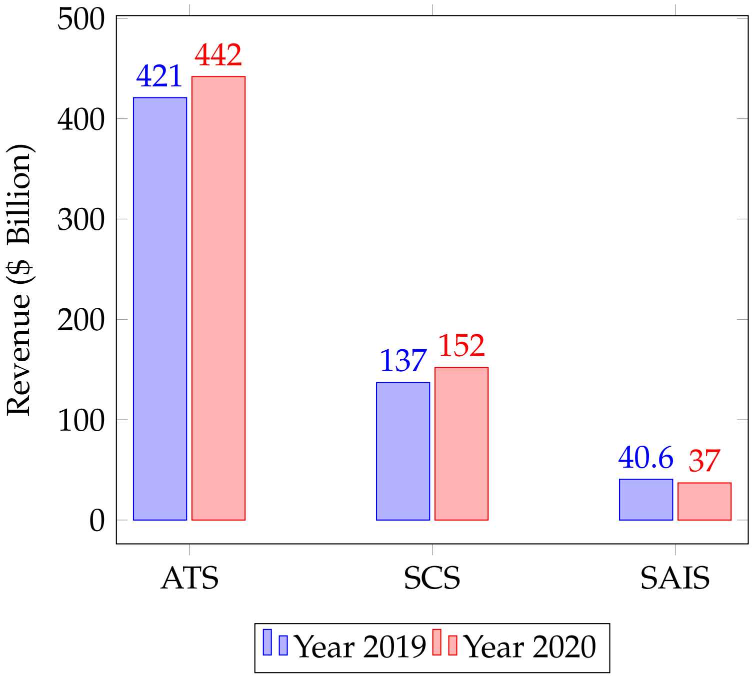


FIGURE 2.2: Worldwide semiconductor revenues in 2019 and 2020 ($ Billions). ATS: All Type Semiconductor, SCS: Semiconductors used in Computing Systems, SAIS: Semiconductors used in Automotive and Industrial Sectors (Voas, Kshetri, and DeFranco, 2021)

Even before the pandemic, the demand for semiconductor chips was on the rise due to the production of self-driving cars, the implementation of 5G communication technology, and the proliferation of Internet-of-Things devices and applications. The initial weeks of the COVID-19 lockdown resulted in widespread company shutdowns, leading to a rapid reduction in sales. Leading companies such as Apple, Samsung, and Caterpillar expressed concerns over the high demand and price hikes of microchips for their product development. Their quarterly profit reports highlighted the need to address semiconductor scarcity, as continued shortages would significantly impede manufacturing operations in the future. The report titled "Chip shortage spreads, hurting sales at Apple and Samsung" (Whalen, 2022) emphasized the challenges faced by leading car manufacturers in producing new models that rely on an adequate supply of semiconductor chips. In 2021, Ford was expected to produce 1.1 million fewer vehicles due to the chip shortage, while Volkswagen announced the suspension of several models in Mexico due to the high cost of importing microchips (Whalen, 2022).

The lockdown measures during the pandemic facilitated the growth of PC, smartphone, and other electronic gadget sales as individuals relied on these devices for education and remote work. This trend is also reflected in Figure 2.2. The demand for microprocessors experienced rapid growth, while the demand for cars showed signs of rebounding. Semiconductor manufacturers adjusted their production to fulfill orders from other industries.

Natural disasters also contributed to production delays in semiconductor chips during these years. A Japan-based semiconductor manufacturing company suffered fire damage, while a Texas-based company temporarily shut down due to a cold weather outbreak. Water scarcity is another constraint in semiconductor production. In 2021, Taichung, Taiwan, the manufacturing hub for Taiwan Semiconductor Manufacturing Company (TSMC), the world's largest semiconductor manufacturer, experienced severe drought conditions, exacerbating the scarcity. Businesses in the city were mandated to reduce their water usage by 15 percent, and TSMC resorted to transporting water via tanker trucks from other regions, with each truck carrying only 20 tonnes of water. TSMC typically consumes around 200,000 tonnes of water per day. The stockpiling of chips by Chinese companies has further exacerbated the semiconductor scarcity in the United States and other countries. In Q1 2021, China's imports of integrated circuits (IC) increased by over a third compared to Q1 2020. This growing stockpile of semiconductors by Chinese technology corporations may lead to additional sanctions against Chinese IT businesses. While China has long-term plans to develop its domestic semiconductor industry, its technology companies believe that increasing chip imports in the short term is a more viable solution (Whalen, 2022).

2.3 A Thematic Model of the System Disruption to Automobile Industry

A study has been conducted to understand the reasons for the Semiconductor shortage in the automobile industry in the post-COVID-19 era. This study (Ramani, Ghosh, and Sodhi, 2022) has shown a thematic model of systematic disruption, shown in Figure 2.3 includes various reasons causing global chip shortage.

2.3.1 Global Pandemic

COVID-19 infections were first reported in December 2019 in Wuhan China. After three to four months, it has declared a *global pandemic* in March 2020.

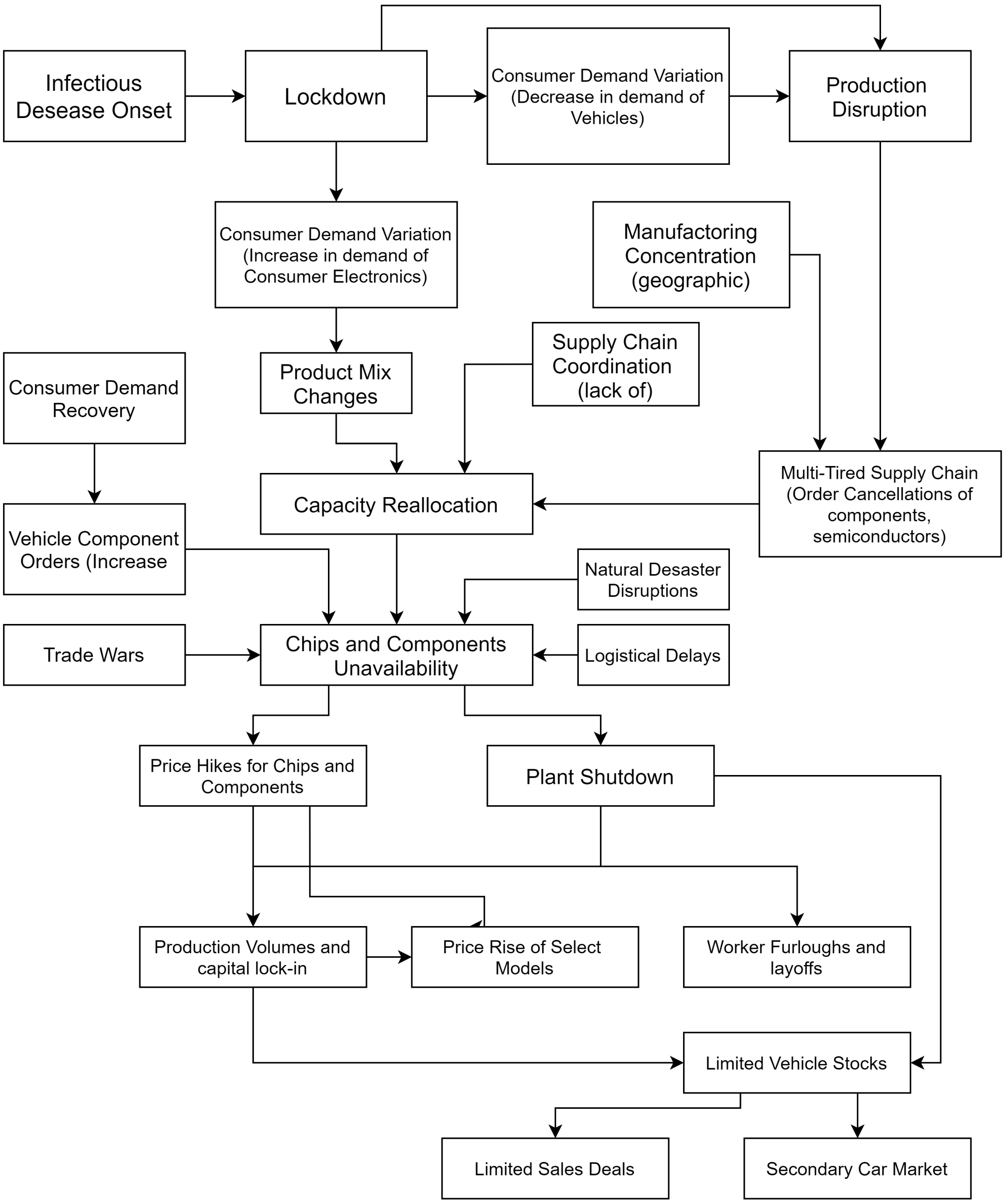


FIGURE 2.3: A thematic model of the systemic disruption to the auto industry, particularly concerning the shortage of semiconductor chips (Ramani, Ghosh, and Sodhi, 2022).

Subsequently, governments of different countries imposed lockdowns to slow down the rapid spread of infection. In almost every country, the government has completely shut down non-emergency sectors. Cross-border travel or import-export was stopped during this global lockdown. Several industries have shut down their production temporarily to prevent the spread of infection among workers. Automobile companies generally have many factories at different locations which were suspended production entirely.

2.3.2 Supply Chain Disruption

In Figure 2.3 the production plan disruption, logistical delays, other natural disaster based disruptions. Congestion at the ports and shipping delays contributed to the problem's logistical complications. The loading and unloading of cargo were delayed as a result of infections at different busy ports. Chip producers had to deal with rising shipping costs as containers became backed up at several ports, with the price of using containers virtually doubling (Ramani, Ghosh, and Sodhi, 2022).

2.3.3 Automobile Supply Chain and its Complications

In the automobile industry, the supply chain is not straightforward like other industries. There are a few phases that we should consider when we are talking about the automobile industry. (a) The automobile supply chain is multi-tiered, (b) Manufacturing Concentration and, (c) Supply chain coordination. The complexity of automotive supply chains made shortages a bigger issue. For instance, General Motors (GM) purchases its automotive components from 250 vendors, who in turn buy their chips from 11 various semiconductor chip fabrication companies. A manufacturer of automobiles places orders with Tier-1 vendors, who then place their orders with Tier-2 vendors such as any Semiconductor manufacturing firm. These Tier-2 suppliers make orders with significant semiconductor chip producers like TSMC since they are aware that they might not be able to complete all of the orders with their current capacity. With production centered in Asia and communication delays in the multi-tiered global networks, order cancellation and shortages spread throughout the supply networks. Therefore, shortages had a significant impact on suppliers' ability to buy more chips.

2.3.4 Re-Alignment of Chip Manufacturing

Instead of the poor margins on the chips created for auto manufacturers, consumer electronics makers profit more from the high technology processors. As a result, high-end chip fabrication became the focus of the semiconductor industry's production capacity reallocation. The growing demand for 5G smartphones, tablets, video game consoles, and gaming platforms made Sony and Microsoft more profitable for semiconductor producers. Only 4 percent of TSMC's revenue came from the manufacturing and selling of automotive chips in 2020, whereas approximately 50 percent came from the manufacturing of chips for smartphones. Given that they were already operating at maximum capacity, semiconductor manufacturers' better margins gave them less motivation to change the composition of their product line.

2.3.5 Post Pandemic Recovery

After completing the lockdown period, customer demand is slowly increasing and automobile companies have started ordering different components like Electric Vehicles plugs, Dashboard Displays, Stabilizers, Sensors, and other components. Demand for cars rose in the second half of 2020 as nations started to gradually phase out lockdown because people wanted to drive their vehicles. As automakers produced more vehicles, they also raised the.

2.3.6 Geopolitical Risk

A few businesses in China are no longer allowed to import machinery for manufacturing semiconductor chips, according to the US authorities. The biggest chip maker in China, Semiconductor Manufacturing International (SMIC), was harmed by this. Advanced and complicated technology is used in the manufacture of chips, and US-based businesses hold a large portion of the intellectual property for chip design. Some of SMIC's customers began hoarding chips as a result of the trade embargo. To stop the sale of semiconductor chips to Huawei and ZTE, the US government also sanctioned Huawei Technologies and worked with TSMC. The company started hoarding chips in 2019 in preparation for being included in a US trade blacklist, which resulted in a capacity crunch at TSMC, Huawei's top foundry supplier (Ramani, Ghosh, and Sodhi, 2022).

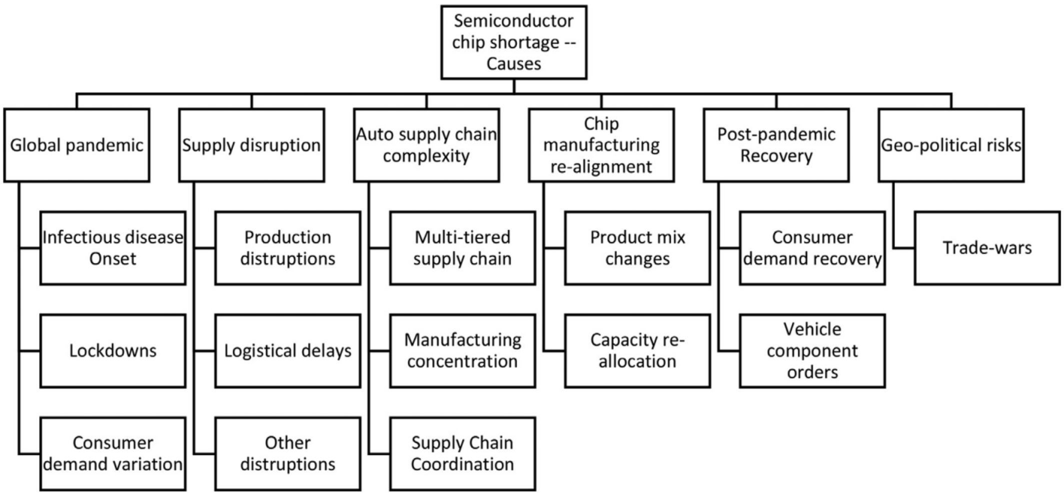


FIGURE 2.4: Causes of semiconductor chip shortage (Ramani, Ghosh, and Sodhi, 2022).

2.3.7 The Volkswagen Case

Figure 2.4 represents the causes of the global semiconductor chip shortage (Ramani, Ghosh, and Sodhi, 2022). Volkswagen, a leading car manufacturing company, faced a hard time during this period. The incident is described as "The Volkswagen Case" in the article (Ben-Meir, LeMay, and McMahon, 2022). Volkswagen uses the port of Embden to ship goods. Its ability to control its shipping schedule rather than relying on space provided by ocean carriers during the epidemic was made possible by the utilization of its charter ships, not the port. The Emden port predominantly exports commodities to the US East coast. Automobiles offloaded at the port are headed for the US market, while the remaining vehicles are sent to Mexico. Volkswagen's organizational resilience has increased as a result of this control over the ships, and this resilience extends across its supply chain. Additionally, it highlights the issues with supply chain resiliency. Volkswagen is unable to obtain microchips, not even with its ships (Ben-Meir, LeMay, and McMahon, 2022).

The ships are initially unloaded, after which the pieces are reloaded and sent back to Germany for assembly. Little's law would assess the bottlenecks related to the ports, including offloading delays, unloading times, and turnaround times. The length of the entire journey should be 45 to 50 days. Volkswagen has its charters, so the business may load the 20- and 40-foot containers to capacity, taking advantage of the available space. The corporation can reduce costs and strategically organize its moves by moving cars from the factory to the vessel and combining commodities that are offloaded in Mexico and on the East Coast.

The corporation operates several vessels, moving at least four of them to North America each month. By spreading out the ships to depart every two weeks, there will always be at least one ship sailing through the ocean and one stationed at the port for offloading and unloading. Each ship spends up to 50 days—up to one month and a half at sea—traveling between Germany, the US, Mexico, and back to Germany. In the same way that automobiles are considered inventory by Volkswagen, so are the ship and the containers. Due to delays at some ports, they become a part of work-in-process inventory (WIP), which has significant effects on carrying costs.

Due to the overflowing ports, it can take weeks to deploy and unload containers from ships. The ports have developed into significant bottlenecks, lengthening vessel transit times and delaying delivery timetables. It becomes impossible to even reroute the ships to alternate ports on the East Coast and in Mexico because these port delays are widespread around the world. Volkswagen will be able to accommodate other ports' timetables if they can use ports that are around the same distance from Embden. They might experience even greater congestion, causing inventory to remain in the port for longer and delaying the ship's departure time. Many ports lack the staff necessary to run the equipment, which limits their ability to offload and upload containers to the vessels in addition to the equipment scarcity. When it came to redirecting ships, Volkswagen demonstrated excellent flexibility and a thorough understanding of the ramifications of Little's Law. To accommodate the busy schedules, they frequently used some ports on the East Coast and in Mexico. Due to the various capacities at the ports, where one vessel can be delayed, another might travel the route more quickly.

2.3.8 Cryptocurrency Mining and Chip Demand

In the previous subsections, we have covered four major reasons behind the chip shortage, which are causing many such problems in the global economy. Another very important reason behind the chip shortage is *Cryptocurrency Mining*. The leading cryptocurrencies like Bitcoin and Ethereum use the *Proof-of-Work* mechanism to validate distributed transactions, and computers are continuously solving a complex cryptographic puzzle to successfully validate and generate a new token. This Proof-of-Work mechanism requires huge resources and power. To achieve extremely fast computation power, miners use GPUs over CPUs. However, general-purpose GPUs are not capable of executing computations as fast as needed. Miners frequently switch from graphics cards to more expensive specialized processors that are tuned for the algorithm they target, which caused a decline in demand for graphics cards. The GPU suppliers' sales would decline as a result of falling demand for chips as coin prices fell. When cryptocurrency prices collapsed in October 2018 in response to increased scrutiny from international regulators, AMD's stock fell 20% in a single trading day after the company disclosed its lower-than-expected sales and explained that it was due to a decline in demand for its graphics processors from the blockchain industry. Nvidia also suffered. Nvidia had to lower its yearly sales prediction in November 2018 to $2.7 billion since it fell $700 million short of experts' projections. The company decided to introduce the crypto-mining processors (CMP) solely for miners in order to protect itself from the crypto hangover and stop them from grabbing up traditional graphic chips (Li, 2022).

The report also states that some cryptocurrency proponents contend that it is worthwhile to invest in such a deflationary asset that is not controlled by any person or government, despite the energy consumption and chip waste, particularly at a time when global inflationary pressure brought on by COVID-related supply chain disruptions is ruining businesses and households. Because there is a finite total supply of bitcoin tokens in circulation, unlike other currencies issued by the central bank, they cannot be discounted by a government. However, cryptocurrency's potential as an inflation hedge may be harmed by the fact that its values have been extremely volatile recently (Li, 2022).

Every country will need its national security strategy for ensuring the reliability of the semiconductor supply, just as they do for ensuring the stability of its energy supply. It is a fact that we can no longer avoid acknowledging. ASICs. Mining equipment is useless if you don't have the electricity to run it, yet running miners requires energy, which is useless if you don't have miners. The only players in town with 7-nm-or-less fabrication capacity (the cutting edge) are Intel, Samsung, and TSMC. This gives these businesses a lot of political clouts when it comes to producing cutting-edge ASICs. As states recognize the value of reducing reliance on foreign actors to maintain such capability, the dynamics of who can and cannot make semiconductors, in general, are already rising to the fore of politics. It won't be long before they start to see how these problems connect to Bitcoin mining as well. It serves as another stimulus for larger countries to increase their local manufacturing capability. Perhaps countries with the ability forbid the export of miners to rival countries. Countries may engage in espionage to obtain the intellectual property for cutting-edge fabrication methods (*Bitcoin Mining And The Global Semiconductor Shortage Are On A Collision Course* 2022).

2.4 Semiconductor Shortage and its Effects

In the last section, we have discussed the price hikes and supply chain status after the COVID-19 pandemic. India and other countries are planning to develop their semiconductor manufacturing infrastructure to reduce dependence on other suppliers and also reduce the cost including import charges. There is a lot of work are being done in the field of R&D in India, but it has lack strong fabrication infrastructures. These infrastructures need an uninterrupted power supply, a sufficient amount of water, and key resources. The government is continuously trying to invest in semiconductor production in India. However, the Global semiconductor shortage creates a great delay to develop fabricating infrastructure in developing countries like India (Casper et al., 2021a). This study focuses on three major impacts of semiconductor shortage. One of the major and obvious reasons is that the semiconductor key materials Silicon is a natural element with a finite amount of sources. Day by day semiconductor demands is growing so fast. A smart vehicle needs almost 3500 semiconductor chips to effectively design different features including cruise control, parallel parking, self-driving features, and many others. The global lockdown after the COVID-19 pandemic shutdowns production and supply and cannot keep up with demands. Economic experts predicted that consumer spending would decline as people lost jobs and bought fewer non-essential goods after COVID-19 finally hit US soil and triggered a national lockdown in mid-March 2020; as a result, automotive companies stopped buying new semiconductors and shut down their production lines. Due to the recent orders for stay-at-home orders, semiconductor makers have switched their supply from the declining automobile market to the increasing demand for other electronic devices like TVs, video games, and PCs.

After a few months, the demand for automotive semiconductors increased more quickly than anyone had anticipated. Numerous automobiles are now in urgent need of semiconductors because it is nearly impossible to instantly bring supply back up to levels where it was before. The lack of semiconductors is a worry for the US government. They asked the president to reallocate a small amount of their existing output to the fabrication of auto-grade wafers, much as other foreign nations. These automakers and suppliers support hundreds of jobs and are crucial to the post-COVID-19 economic rebound. The president was compelled by this to assess the supply chain's weaknesses right now. The next section describes how advancements have been made in other areas because there are still some that need to be made (Casper et al., 2021a).

Besides the harmful impacts of *Chip Shortage* phenomenon, few companies are looking for their profit and increased revenue in this crucial time. Electronic Design Automation (EDA) has followed a strategy to increase its revenue and profitability. Overall, the software development sector was able to increase its profit throughout this challenging time. According to the CEO of EDA, sustained and long-term expenditures in research throughout the years were one of the factors that contributed to the industry's rising revenues. The surge in cloud EDA at the same time as the growing demand for EDA tools during extended shutdowns is an intriguing trend. During this period, it is anticipated that the EDA cloud market would expand and draw special attention. Utilizing the cloud can assist businesses in providing designers with the resources they need around the clock and for less money. Because of the trade conflict between the USA and China, the US government is investing in a system-level design that will aid in the production of sophisticated and high-level security chips. This is another factor contributing to the stable and sustainable growth of US EDA companies (G. Marinova and Bitri, 2021).

According to the study, (G. Marinova and Bitri, 2021), the governments of the two nations have created strategies to strengthen their presence and create cutting-edge instruments to help their country become independent and secure as a result of this technological conflict. One of the reasons why this is being discussed in U.S. precedent is the security issues that come with cutting-edge technology. The European Union is the third to join this battle over the chips. A European industry estimates that 22 European nations have banded together to collaborate on creating a regional semiconductor ecosystem. The EU is emphasizing domestic chip manufacturing to distance itself from the US, Taiwan, and other east Asian nations. The future is still unclear, but there are several possible outcomes, one of which is China becoming the dominant nation in the sector. The investment and development plans for semiconductors in China are described in general in the parts that follow. As a result of this technical conflict, the governments of the two countries have developed policies to increase their presence and produce cutting-edge tools to help their country become independent and secure. Security concerns associated with cutting-edge technologies are one of the reasons U.S. precedent is taking this move. The third participant in this war is the European Union. Almost 22 countries in Europe are working together to develop a regional semiconductor ecosystem. To set itself apart from the US, Taiwan, and other east Asian countries, the EU is emphasising domestic chip production. Although the future is still uncertain, there are several potential outcomes, one of which is China overtaking other countries in the industry. The parts that follow provide an overview of China's investment and development ambitions for semiconductors.

2.4.1 Impact of Semiconductor Shortage

The semiconductor shortage has had several significant effects on various aspects of the industry. We will explore four major effects in this section: Production Disruptions, Inflationary Pressures, Labor Issues, and End Consumer and Dealer Issues. The visualization of these effects is shown in Figure 2.5 (Ramani, Ghosh, and Sodhi, 2022).

2.4.2 Production Disruptions

The shortage of semiconductor chips has caused disruptions in manufacturing. Chip manufacturers, already operating at maximum capacity, struggled to meet the increased demand from vehicle manufacturers and their suppliers. This led to factory closures and production line modifications. General Motors (GM), Ford, Volkswagen, Honda, Nissan, Tesla, and Chinese electric car start-ups all experienced production delays or adjustments due to the scarcity of semiconductor chips. Automakers had to make changes to their production plans, pause production, or build vehicles without specific components, causing significant disruptions in the production process. Additionally, some automakers resorted to making full payments in advance to secure chip supply, resulting in capital lock-in (Casper et al., 2021a).

2.4.3 Inflationary Pressures

The shortage of semiconductor chips has contributed to inflationary pressures in the auto industry. The increased demand and higher delivery charges for chips led to price hikes. Vehicle prices in the US increased, with customers having to pay extra for specific models. Dealers also reduced discounts and offers due to the limited availability of models. The shortage of newer models shifted consumer demand to the used car market, leading to an increase in used car prices by approximately 10 percent. The rising costs of other consumer goods, such as refrigerators and washing machines, can also be attributed to the global chip shortage, demonstrating the cross-sector inflationary pressures caused by the chip scarcity (Casper et al., 2021a).

2.4.4 Labor Issues

The semiconductor shortage has also created labor-related challenges. Both the semiconductor and auto industries faced manpower shortages at various levels. Highly skilled workers are required in the chip manufacturing process, and the pandemic affected the availability of personnel. Automakers had to reduce shift lengths, lay off workers, or place them on furlough. Daimler, Ford, and Jaguar Land Rover were among the companies that had to make such workforce adjustments. The labor issues further exacerbated the challenges faced by the industries during the shortage (Casper et al., 2021a).

2.4.5 End Consumer and Dealer Issues

The shortage of semiconductor chips has had implications for end consumers and dealers. The limited availability of vehicles due to the chip shortage has restricted options for buyers, leading to a reduced number of vehicles and promotional offers at auto dealerships. The scarcity of new cars also impacted the secondary market for used and rental cars, driving up prices as demand increased. Furthermore, the pandemic-related travel restrictions reduced the need for rental cars, leading rental car companies to auction off their inventory to generate revenue. These factors have created challenges for end consumers and dealers in the automotive industry (Casper et al., 2021a).

2.5 Addressing the Chip Shortage: Possible Solutions

In the preceding sections, we extensively examined the semiconductor chip shortage that emerged during the COVID-19 pandemic and its severe impact on the automotive industry. As this remains an ongoing challenge, researchers and automobile companies are actively seeking ways to mitigate

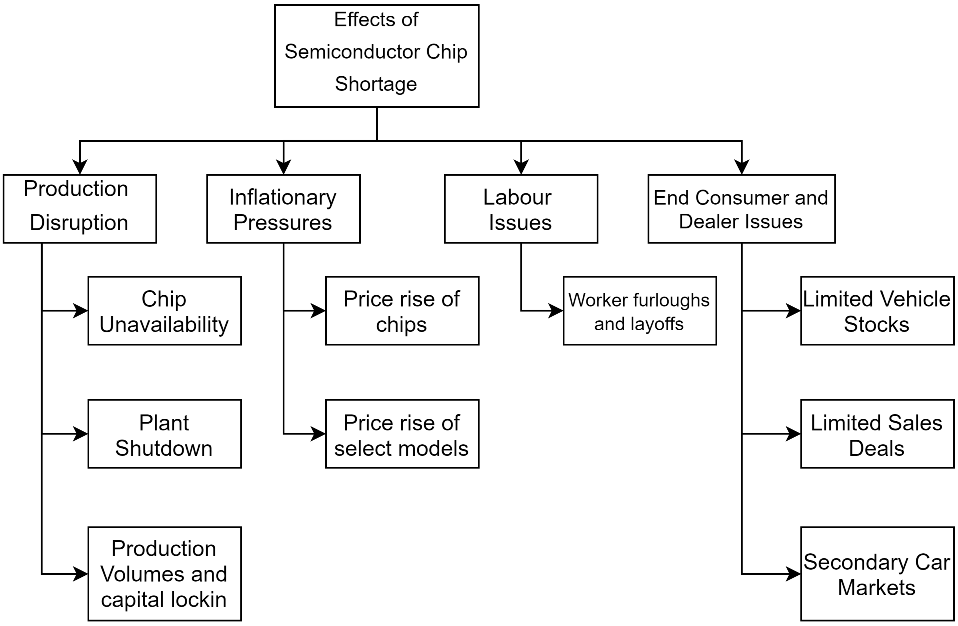


FIGURE 2.5: Effects of Semiconductor Chip Shortage (Ramani, Ghosh, and Sodhi, 2022).

the global disruption. Several studies and reports have been reviewed to explore potential short-term and long-term solutions on a global scale.

Finding immediate solutions to the automotive semiconductor dilemma, as highlighted in earlier sections, proves to be a challenging task. If there is available capacity without the need for growth, chip manufacturers typically require a minimum of four months. However, if growth is necessary, the timeline extends to a minimum of 18 months. Although increasing output may seem like an apparent solution, constructing a new fabrication facility and ramping up wafer production requires more than three years. The COVID-19 pandemic, intricate supply chains, and extended lead times for manufacturing equipment have further complicated expansion efforts over the past two years, making the situation even more challenging (Ondrej Burkacky and Werra, 2022).

Companies are now focusing on both short- and medium-term needs, as well as long-term resilience and survival strategies, in response to the semiconductor scarcity. To ensure an adequate supply of semiconductors, many original equipment manufacturers (OEMs) and automotive Tier 1 suppliers are contemplating the establishment of control rooms that bring together personnel from procurement, supply chain management, and sales. Although these teams have devised some effective ways to address the current supply-demand imbalance, they often lack the necessary resources, expertise, or capacity to handle the issue in the medium to long term and develop strategic solutions. Companies can adopt various measures to tackle the most frequent challenges, as discussed in this report (Ondrej Burkacky and Werra, 2022), which outlines three levels of solutions to alleviate the problem.

- **Strengthening technology roadmaps:** In many cases, companies themselves struggle to define their actual semiconductor dependency and lack clear visibility into their technology roadmaps. As a result, these roadmaps may offer insufficient information about the semiconductor content of future products or fail to consider all the variables that influence semiconductor supply and demand, such as the impact of orders for customized cars.

- **Improving short-term demand planning:** Addressing the problem requires better short-term demand planning from OEM providers in multiple aspects. By strategically designing products, OEMs can enhance transparency regarding short-term automotive chip demand and share this information with semiconductor vendors. In other industries, suppliers and manufacturers maintain effective communication about demand and supply throughout the entire supply chain, facilitating the identification of potential issues before they escalate. The automotive sector, due to its market dominance and stable expansion, has not traditionally required this level of end-to-end transparency, and OEM suppliers have yet to achieve it. To achieve the necessary level of knowledge, OEMs and suppliers can adopt a universally accepted nomenclature, such as a common definition of chip families and technology nodes, and utilize demand predictions. Investing in data-driven processes and automated solutions can further improve the quality of end-to-end planning, enabling OEMs and Tier 1 suppliers to enhance their planning process and build strategic alliances. Moreover, digital technologies can assist in making informed decisions and allocating chips efficiently, while risk cockpits can help reduce the possibility of unexpected semiconductor shortages. By leveraging improved end-to-end planning and data-driven procedures, OEMs and Tier 1 suppliers in the automotive sector can become more reliable and desirable partners.

- **Facilitating long-term demand planning:** To address long-term demand, collaboration on mature node project investments becomes crucial. OEMs and semiconductor manufacturers can work together to develop semiconductors for cutting-edge or advanced nodes, thereby sharing costs while increasing the availability of low-margin or highly innovative technology. As control rooms may continue to be semi-permanent aspects of the automobile industry, even after strategy improvements by OEMs and Tier 1 suppliers, companies should establish long-term talent strategies to ensure adequate staffing. Given the current challenges faced by employees during the pandemic, automotive businesses can reduce the workload by streamlining control room procedures and tools. They can also maintain a steady influx of talent by inviting various individuals, whether existing employees or new hires, to join the control room team while allowing others to rotate out (Ondrej Burkacky and Werra, 2022).

To address their business and production needs, several auto manufacturing companies in India have resorted to producing vehicles with reduced chip usage. With no permanent solution to the chip shortage expected in the coming years, these companies are finding alternatives to mitigate the impact. For instance, Tata Motors, Mahindra and Mahindra, and Hyundai Motor India are offering models without entertainment systems or with less complex systems, reducing the demand for microchips. Tata Motors now provides only one remote key at the time of purchase and delivers the second one later. Additionally, automakers have decreased the production of diesel vehicles, which require a higher number of chips, and increased the production of petrol variations. The market share of higher-end variations of different models is also declining (Chaliawala and Thakkar, 2022).

Some car manufacturers are resorting to ordering chips from the open market. For example, Hyundai has introduced updated versions of its popular Creta and Venue SUVs, replacing the infotainment systems with touchscreens equipped with basic audio players instead of more advanced systems (Chaliawala and Thakkar, 2022).

In preparation for the forthcoming festive season, when sales in India typically increase, the auto sector is ramping up efforts to ensure adequate manufacturing. However, popular automobile models now have waiting times of up to eight months, which may further increase due to factory shutdowns and chip scarcity. Some companies are even purchasing chips from the open market at higher costs. In some cases, automakers continue manufacturing vehicles despite part shortages and fit the missing components later in the stockyard or showrooms (Chaliawala and Thakkar, 2022).

The report (Schröders, 2022) discusses a similar long-term strategy. It highlights the potential conflict between supply chain security and environmental sustainability. Rising demand and supply deficits may lead to production with lower environmental requirements due to producer pressure to meet demand. Semiconductor manufacturing has been associated with negative environmental and health effects, including the use of toxic metals and chemicals linked to employee health issues. The sector also contributes to pollution and the production of toxic waste. To mitigate these issues, adopting cleaner production techniques and establishing zero-waste manufacturing processes are crucial. A circular economy for semiconductors can address shortages and environmental compliance. Transatlantic cooperation between the US and Europe can also facilitate the circularity of semiconductor supply chains (Schröders, 2022).

The report (Schröders, 2022) also emphasizes the need for circular approaches to microchips. While recycling compound semiconductor materials is technically feasible, recycling smaller semiconductor materials remains challenging. Novel design-for-disassembly techniques are required to enable high-volume and low-cost disassembly for microchips. Leading microchip design and production companies, such as Intel and Nikon, are exploring refurbished products and improvements to outdated lithography equipment systems as part of embracing circular economy concepts. However, circular strategies are still in their early stages and require adoption by the entire sector. Addressing the growing amount of technological waste and justice issues related to e-waste recycling are essential components of the solution. Extending the lifespan of tools and semiconductors through repair and salvaging chips from electronic waste can contribute to sustainability. However, existing electronics design standards pose a barrier to these efforts (Schröders, 2022).

While the semiconductor chip shortage has significantly impacted most automobile manufacturers worldwide, Tesla has implemented a successful strategy to navigate this challenging period. According to the report (Gopani, 2022), Tesla managed to deliver approximately one million cars in 2021, doubling its deliveries from the previous year. Unlike other companies, Tesla anticipated strong demand during the pandemic and ensured a consistent chip supply by internally generating chips and forging close relationships with suppliers. Tesla's software was also rewritten to integrate seamlessly with alternative manufacturers, enabling the company to modify firmware and software instead of simply replacing chips. This approach has made Tesla a case study for effective chip management and production (Gopani, 2022).

Furthermore, the development of semiconductor chips is a complex process that typically takes 6-8 months. However, AI-powered techniques can significantly reduce the design time, leading to more efficient chip production. Companies like Samsung, Google, IBM, and NVIDIA are exploring AI-designed chips, which could potentially revolutionize the semiconductor industry and alleviate supply chain issues. By implementing continuous defect scanning and real-time monitoring, AI-designed chips can enhance overall efficiency. Although the semiconductor supply chain problem has negatively impacted various sectors, efforts are being made to find alternative solutions (Gopani, 2022).

Various businesses heavily reliant on semiconductor chips are continuously seeking better solutions to address this widespread issue. Proactive and disciplined supply chain and inventory management strategies are being adopted, utilizing data analytics to comprehend and mitigate risks. Micron, a well-known corporation, actively anticipates shortages to ensure the availability of raw materials and integrated circuits necessary for their products. The company's diverse manufacturing facilities help distribute risk and serve consumers globally. Collaborations with clients in end markets experiencing non-memory component shortages enable a better understanding of demand patterns (Shein, 2022).

Another IoT hardware manufacturer, RAKwireless, has implemented a three-pronged strategy to boost sales and address supply chain challenges. They engage in long-term planning, maintain significant buffers, and secure crucial components through regional marketplaces and collaborations with partners worldwide. By conducting extensive investigations into the supply chain, they gather essential information beyond what online portals provide. Maintaining continuous communication with partners is also crucial for effective management, not just during emergencies (Shein, 2022).

2.6 Modeling Stylized Planning To Maximize Profit

An optimization problem has been framed in this study (Ramani, Ghosh, and Sodhi, 2022) to maximize the profit for the entire supply chain. The given parameters are described here. For a corresponding plaint i, it receives $X_{i,t}$ chips from chip manufacturing company, and produces a quantity of $Y_{i,t}$. Additionally, the plant can hold an inventory at time t which is represented as $I_{i,t}$. The sales quantity size is represented as $Z_{i,t}$ to meet the demand $D_{i,t}$. Sometimes, it may have backlog $B_{i,t}$. While the sales decision can either fulfill customer demand or result in a backlog, the production decision can either meet sales demand or produce stockpiles. We assume that each plant's backlog at I will decrease over time with a factor λ that must be less than or equal to 1 ($\lambda \leq 1$). So only $\lambda B_{i,t-1}$ are carried over from the prior period. In every industry, one chip is needed to produce a single product. At the time t each plant, which is manufacturing product i has the capacity of $C_{i,t}$, and the chip-making company capacity is C. The R_i is the marginal revenue for any product i, and P_i is the penalty per period for the backlog. In their assumption, H_i is the holding expense for each unit of the i-th product during a given period. Here c_i' represents the cost of production of the i-th product. Table 2.1 has shown these parameters in a better way.

TABLE 2.1: Model Notations for Optimization Function

Notation	Description
R_i	Marginal revenue for product i
P_i	Penalty per period for backlog of product i
H_i	Unit Holding cost per period for each unit of product i
c_i'	Unit cost of product i
$D_{i,t}$	Demand of product i at time t
$X_{i,t}$	Chips production quantity for product i at time t
$Y_{i,t}$	Finished good production quantity of product i at time t
$Z_{i,t}$	Sales quantity of product i at time t
$I_{i,t}$	Inventory of product i at time t
$B_{i,t}$	Backorder product i at time t
$C_{i,t}$	Capacity of plant i at time t
λ	Decay Factor for backlog
C'	Capacity for Semiconductor Manufacturer

$$\text{minimize} \sum_t \sum_i \left[\left\{ R_i Z_{i,t} - P_i B_{i,t} - H_i I_{i,t} - c_i' X_{i,t} \right\} \right], \tag{CHAPTER II:.1a}$$

$$\text{subject to: } \textstyle\sum_i X_{i,t} \leq C' \; \forall i, t, \tag{CHAPTER II:.1b}$$

$$Y_{i,t} \leq \min\left(C_{i,t}, X_{i,t}\right) \; \forall i, t, \tag{CHAPTER II:.1c}$$

$$Z_{i,t} + I_{i,t} = Y_{i,t} + I_{i,t-1}, \tag{CHAPTER II:.1d}$$

$$D_{i,t} + \lambda B_{i,t-1} = Z_{i,t} + B_{i,t}, \tag{CHAPTER II:.1e}$$

$$X_{i,t}, Y_{i,t}, Z_{i,t}, B_{i,t} I_{i,t} \geq 0 \; \forall i, t, \tag{CHAPTER II:.1f}$$

The optimization function is given in the Equation CHAPTER II:.1a where the chip manufacturer company has limited capacity shown in Equation CHAPTER II:.1b. The production quantity is controlled by the flow of resources and the capacity of the chips at each facility during each period for the car maker. Equation CHAPTER II:.1c. It must be ensured that each plant's flow constraint can be satisfied by the amount of output in the current period and inventory from the prior period, which could lead to the creation of new inventory, to satisfy sales in the current period Equation CHAPTER II:.1d. Sales must also balance consumer demand in the current period with the backlog from the previous period in order to avoid a current period backlog Equation CHAPTER II:.1e. And all are non-negative Equation CHAPTER II:.1f.

The model described in the research (Ramani, Ghosh, and Sodhi, 2022) has been tested for different scenarios across four years. In the very first case there is no backlog, indicating that even when the central planner perceives demand to be flat or increasing, systemic disruptions can result in ongoing, severe shortages that may influence other sectors. Plant shutdowns cause the automotive plant's backlog to grow quickly. Chip allocation has increased and manufacturing has risen to match demand as a result of the consumer electronics industry's expanding need for chips. In case 2, once auto production is resumed, the backlog is decreased. A capacity crunch at the chip manufacturer is caused by the increased demand for electronics chips and the allotment of chip capacity for the electronics industry, which lowers the number of chips allocated to the automotive sector. As a result of the chip shortage, the backlog is once again increasing in the automotive industry. In the third case, shifting toward high-end cars with larger margins is viewed as a mitigation approach that automotive manufacturers have taken. The car industry has a smaller backlog since demand is weaker and more chips are devoted to the creation of luxury vehicles. However, another sector has a growing backlog. And at the end in case 4, the backlog of the other fields is reduced, and chip allocation and production of finished goods for all three sectors are restored with a hefty infusion of additional chip capacity in place. The Figure 2.6 depicts the supply demand in these four scenarios and accordingly Figure 2.7 shows the backlog and manufacturing levels for each scenario stitched together over time.

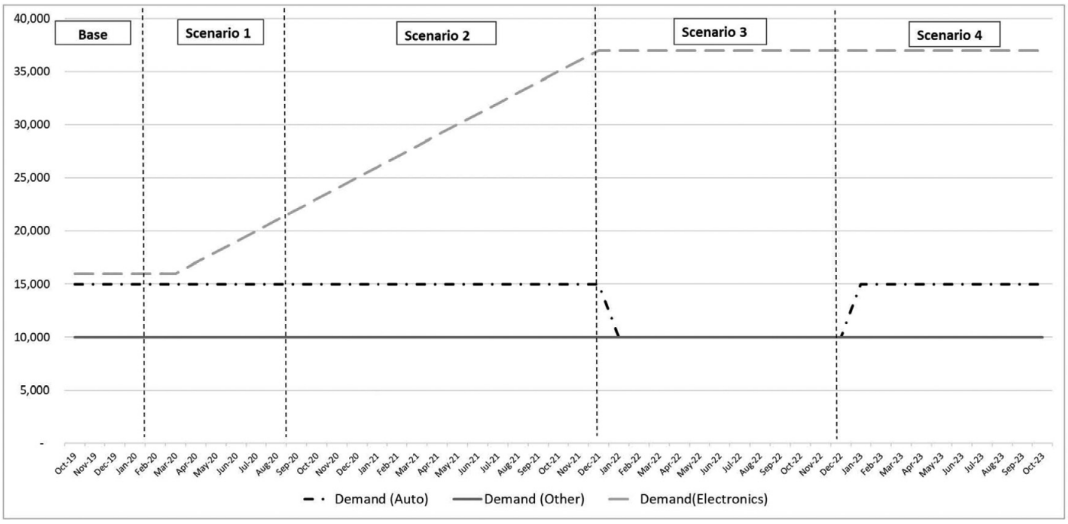


FIGURE 2.6: Demand Data (Ramani, Ghosh, and Sodhi, 2022).

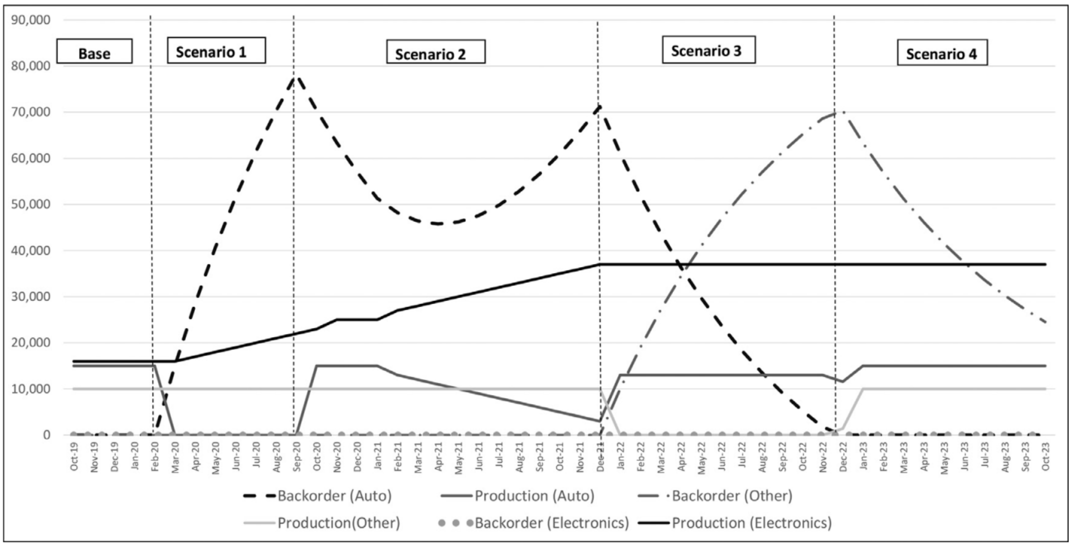


FIGURE 2.7: Backlog and production quantities for all scenarios (Ramani, Ghosh, and Sodhi, 2022).

2.7 A deeper understanding the Problem on chip shortage

So far we have talked about the problems of global chip shortage in many aspects and also in the field of automobile industries. Here in this section we will study the existing literatures which are mostly focusing on chip shortage analysis and a few techniques that can save us in the near future.

2.7.1 The Semiconductor Shortage: an Analysis of Potential and Ongoing Remediation Efforts and their Implications on the Industry & Macroeconomy

This research paper provides an in-depth examination of the recent global semiconductor shortage, analyzing the potential and ongoing remediation efforts and their complex implications on the industry and macroeconomy. The paper outlines how the COVID-19 pandemic led to severely fluctuating demand and supply imbalances in the semiconductor industry, causing acute chip shortages as economies reopened and manufacturing demand spiked. With automakers, appliance makers, and many other manufacturers demanding more semiconductors but semiconductor firms having cut production during pandemic slowdowns, substantial supply-demand mismatches arose. A key finding is that the cyclical business cycles and shocks experienced in the semiconductor industry are largely determined by production capacity and inventory management. The high fixed costs of semiconductor foundries and fabrication facilities incentivize manufacturers to maximize production output in order to lower per-unit costs. However, oversupply and demand mismatches can crash the industry. Careful inventory management and forecasting to align supply and demand is crucial yet exceedingly challenging. The paper utilizes empirical analysis and industry data to demonstrate how global semiconductor revenue variation over time is significantly explained by inventory management practices and total units produced by firms. To address the current shortages, semiconductor firms are substantially increasing capital expenditures to construct new fabrication facilities and expand production capacity. However, the simultaneous ramping up of construction strains supplies of resources and compounds shortages of engineering talent. Fabless semiconductor design firms must also strategically invest in efficient capital equipment and product development platforms that enable continual innovation. Analytical frameworks help these firms optimize their innovation inputs, like research and development spending, to maximize outputs such as sales revenue and new patents. Firms use discretionary R&D budgets and capital expenditures very strategically to balance iterative technological development with financial viability. The paper also examines the complex, vertically integrated supply chain logistics unique to the semiconductor industry due to its segmentation and specialization. Manufacturers tend to focus on high-volume commodity chip production while design firms pursue more specialized and customized products. Coordinating demand forecasts and production schedules across this landscape is enormously complex yet critical. Discrete event simulation is one analytical tool to help model uncertainties like production cycle times and chip fabrication yields. Greening the energy-intensive semiconductor supply chain is another important consideration needing more attention. Government subsidies and oversight are analyzed as potential shortage remedies. Subsidies can assist domestic manufacturers in acquiring capital to expand production capacity, while research funds help progress innovation. However, excessive subsidies risk firm dependence on government support. Chinese semiconductor firms already have a multi-year head start in receiving subsidies. Firms must also better support suppliers to improve supply chain stability. While capacity increases will help meet demand in the near-term, overinvestment risks future gluts when markets inevitably shift. No single approach can fully resolve the fundamental fragility and fluctuations of the industry. Ultimately, the analysis emphasizes semiconductors' broad macroeconomic importance. Firms must continually balance financial, innovation, and supply chain coordination to remain viable. But the endless arms race of iterative technological development per Moore's Law is crucial for competitive advantage within the industry. Current shortages spotlight the need for proactive supply chain changes, but some degree of fluctuations will persist. Sustaining semiconductor advancement and production growth remains contingent on this delicate equilibrium, as does broader economic growth that depends on a stable semiconductor supply (Young, 2021).

2.7.2 An Analysis on the Crisis of chips shortage in Automobile Industry - Based on the Double Influence of COVID-19 and Trade Friction

This paper provides an in-depth analysis of the recent crisis in the automotive industry stemming from a severe shortage of semiconductor chips. It examines the complex factors that disrupted the delicate supply-demand balance between chip manufacturers and automakers. The analysis identifies several key reasons the auto industry was hit hard by chip shortages. Aggressive pandemic control measures like lockdowns and travel restrictions directly suspended production at chip fabrication facilities, sharply reducing capacity. As auto production declined, chipmakers opportunistically reallocated capacity to serve spiking demand in consumer electronics like mobile phones and laptops. This mismatch in supply versus demand continued even as auto demand rebounded faster than anticipated, since chipmakers remained maxed out serving other booming sectors. The paper argues the automotive chip shortage may persist indefinitely due to the auto industry's highly interconnected, globalized supply chain and associated geopolitical sensitivities. The long and intricate process of producing automotive-grade chips involves multiple companies across different factories worldwide over a timeline of several months from design to delivery. This complex, lengthy sequence with many vulnerabilities makes the auto chip supply ecosystem prone to disruptions that cannot quickly self-correct. Ongoing pandemic impacts and rising trade tensions further cloud uncertainties. Several strategies to proactively address the shortage are examined. Governments are issuing policies insisting firms urgently resolve supply issues while also investing in domestic semiconductor research and production capacity. Companies are being compelled to strengthen communication and coordination all along the supply chain, from materials to finished chips. For the long term, coordinated top-level strategic planning is required to substantially increase domestic chip production and reduce dependence on imports. Firms must also diversify their supplier relationships and component sources to mitigate future shortage risks. The paper concludes the pandemic and rapid reallocation of chip supply to electronics were short-term shocks that disrupted the auto industry's precarious chip supply balance. However, the semiconductor supply chain's inherent fragility from its globalized, lengthy structure and geopolitical issues may perpetuate such shortages indefinitely absent major structural changes to the ecosystem. Recommended solutions include increased international cooperation on production and distribution, proactive government industrial policies supporting domestic chip industry growth, and supply chain diversification efforts by firms. While presenting challenges, the crisis also offers opportunities for Chinese firms to substantially advance innovation and self-sufficiency. In summary, the paper provides an incisive analysis

of how the pandemic exposed and exacerbated existing structural vulnerabilities in automotive chip supply chains. It advocates collaborative policy and business strategies to strengthen resilience against future disruptions. The ongoing semiconductor shortage illustrates the serious macroeconomic risks posed by highly concentrated, globally dispersed supply sources, especially for critical industries like automotive manufacturing.

2.7.3 Coronavirus, chip boom, and supply shortage: The new normal for global semiconductor manufacturing

This article undertakes a comprehensive examination of the global semiconductor manufacturing industry. It analyzes recent exponential market growth and acquisition trends while arguing the COVID-19 pandemic has laid bare the risks of excessive manufacturing concentration and outsourcing. In light of severe supply-demand imbalances, the article advocates for proactive government incentives and agile supply chain management to strengthen domestic production and prevent future shortages ("Coronavirus, chip boom, and supply shortage: The new normal for global semiconductor manufacturing" 2021). The author highlights how the semiconductor industry has

demonstrated resilience during the pandemic, with sales increasing over 20% year-over-year across most regions in early 2021. Several metrics point to significant growth, including record monthly semiconductor unit shipments and rising R&D spending. However, supply shortages persist, especially for 200mm fabs, driving demand in the U.S. and Europe as manufacturers seek to reshore production. The article delves into how governments worldwide

are offering generous incentives, such as tax breaks, grants, loans, and infrastructure upgrades to attract semiconductor manufacturers. It provides a detailed comparison of incentive programs in the U.S., E.U., China, South Korea, and Japan. For example, the U.S. CHIPS Act would allocate $52 billion to expand domestic manufacturing and R&D. The author argues such incentives could strongly influence future fab location decisions over the next few years as companies weigh economic factors. In response to shortages, new

manufacturing collaboration models are emerging, including fab refurbishment deals and joint fab sharing arrangements between firms. With limited brownfield fabs available, more companies are opting to build new megafabs from scratch leveraging government support. The article provides recent examples of these trends globally. In conclusion, the pandemic has laid

bare the risks of excessive concentration of manufacturing capacity along with over-reliance on outsourced production. The author argues temporary trade wars are not the solution. Instead, proactive government incentives and policies combined with agile supply chain management are essential to strengthen domestic semiconductor production and prevent future shortages. With the world heavily dependent on Taiwan for chips, increased dialog between global partners is also critical to address supply chain vulnerabilities. In summary, the article provides crucial context on the semiconduc-

tor industry's explosive growth, how government incentives are reshaping manufacturing location decisions, and the supply chain risks demanding innovative public-private solutions. It makes a cogent case for collaborative policies and business strategies to ensure resilient domestic production and a balanced global supply chain ("Coronavirus, chip boom, and supply shortage: The new normal for global semiconductor manufacturing" 2021).

2.7.4 Confronting Technology's Greatest Crisis: Global Chip Shortage

This thesis comprehensively analyzes the global microchip shortage crisis and proposes an innovative solution to design a new European supply chain with regional chip foundries. It first provides crucial historical context on the semiconductor industry's exponential growth into an extraordinarily complex and technologically advanced sector. With demand continuously rising across virtually all industries and products, shortages inevitably emerged, especially after COVID-19 severely disrupted production. The analysis thor-

oughly identifies several key interrelated factors constraining the industry's ability to expand supply, including the sheer technical complexity of fabricating advanced chips limiting new market entrants, the high geographic concentration of production capacity in Asia, and the major shocks from the COVID-19 pandemic's impacts on manufacturing. With global demand projected to further increase in the long term, traditional supply-side solutions of attracting new competitors or expanding capacity at existing firms are rendered largely infeasible. Therefore, the thesis proposes a comprehensive plan for multinational semiconductor firms Intel and GlobalFoundries to collaboratively establish an innovative network of new chip foundries across multiple strategic locations in Europe. This sweeping strategic initiative would substantially reduce the industry's overreliance on Asia-based manufacturing, directly increase overall production capacity at a regional level, and dramatically minimize transportation delays and distribution risks. The thesis carefully examines several key strategic decisions integral to successfully locating these foundries in Europe, including proximity to critical upstream suppliers, proximity to downstream buyer demand in the auto and electronics sectors, in-depth cost and profitability analyses, and assessment of political and cultural risks. After thorough comparison, Germany and Italy are selected as ideal locations for Intel's new foundries, while Spain and Italy are chosen for GlobalFoundries' facilities. Precise production levels are estimated to meet approximately 10% of European chip demand. Detailed construction timelines and schedules are provided, stretching over four years until full production is achieved. Comprehensive supplier selection protocols and foundry distribution roles are also defined. Overall, the ambitious plan requires an estimated $19 billion in upfront investment, with a payback period of around 20 years. In conclusion, the establishment of four strategically placed new large chip foundries in Europe by Intel and GlobalFoundries would effectively alleviate shortages within a four-year timeline. Europe's relatively central geographic position would significantly cut distribution distances and delays compared to the current reliance on Asia and the United States. Building in redundant capacity further enhances supply chain resilience to disruptions. While requiring substantial capital investment, the long-term profit outlook remains favorable. With appropriately coordinated policies and business strategies, the plan would considerably strengthen the semiconductor supply chain, enabling it to dramatically boost production capacity, consistently meet accelerating demand, and prevent future crises. Overall, the thesis provides an extremely insightful and detailed solution framework to rectify the acute global microchip shortage predicament based on redesigning industry supply chains for sustainability. The regional expansion establishes a stable middle ground between fully localized and extended globalized networks. The comprehensive plan clearly demonstrates the crucial systems perspective urgently required to proactively ensure adequate supply in the face of daunting industry growth limitations and vulnerabilities(Prieto, n.d.).

2.7.5 Challenges and opportunities for semiconductor and electronic design automation industry in post-Covid-19 years

This paper analyzes the challenges and opportunities for the semiconductor and electronic design automation (EDA) industry presented by the COVID-19 pandemic. It focuses on how the pandemic exacerbated existing weaknesses in the semiconductor supply chain, causing chip shortages that severely impacted industries like automotive. The analysis identifies several factors that contributed to the shortage. Global shutdowns and restrictions closed manufacturing facilities, reducing production capacity. Work-from-home arrangements increased consumer demand for electronics like laptops, phones, and gaming systems, boosting orders for chips. Automakers had cut chip orders early in the pandemic, assuming car sales would plunge, but demand rebounded faster than expected. However, foundries had already reallocated capacity to serve spiking electronics orders. The paper notes this mismatch revealed automakers' lower priority versus consumer electronics firms in getting chip orders filled. The paper examines industry reactions to the crisis. Some chipmakers are expanding capacity by building new fabrication plants, but this will take years. Firms aim to better match production to actual demand through enhanced coordination. Governments are also responding, with the U.S., E.U., and China all enacting policies and incentives to strengthen domestic semiconductor research and manufacturing. A key focus is the growth of China's semiconductor industry influence. Through subsidies and incentives, China seeks to reduce reliance on foreign firms like Taiwan's TSMC and build up its domestic chip production capacity and supply chain. However, China still lags in key areas like electronic design automation software. The paper concludes the shortage exposed vulnerabilities in the semiconductor ecosystem's coordination and responsiveness. It argues the crisis may catalyze lasting changes as governments boost local manufacturing and new players emerge. The analysis suggests firms should focus on building resilient supplier relationships and demand forecasting. It also advocates strengthening semiconductor-related education. In summary, this paper provides useful insights into how the pandemic impacted the semiconductor industry, revealing supply chain fragility. It highlights the policy reactions underway to improve domestic self-sufficiency and capacity. The analysis of China's ascent also underscores risks from geopolitical tensions. The paper emphasizes the need for agile, collaborative strategies between firms to manage future crises (G. I. Marinova and Bitri, 2021).

2.7.6 Taiwan's Economy and the Big Chip on its Shoulder

This in-depth article provides an incisive economic analysis of Taiwan, with a particular focus on exploring the outsized and multifaceted role of semiconductor manufacturer TSMC in driving the country's growth story over the past decades. It critically examines TSMC's global leadership position in advanced chip fabrication and the intensifying geopolitical implications of this technology dominance amid escalating US-China strategic rivalry tensions. The article comprehensively outlines Taiwan's remarkably successful economic development trajectory, enabled by a pragmatic mix of political leadership evolution along with sound industrial policies and an export-oriented economic model. Electronics comprise over 60% of total exports, with TSMC representing the single most important pillar of this manufacturing prowess. The company saw 25% revenue growth in 2020, now capturing over half of total global chip sales based on its cutting-edge fabrication technology and production capacity. TSMC's market capitalization nears a staggering 50% of Taiwan's overall GDP, quantitatively highlighting the company's monumental significance both economically and strategically. However, the analysis highlights Taiwan faces innate economic challenges of an aging population and limited domestic consumer market. Far more critically from a geopolitical perspective, Taiwan remains at the very epicenter of intensifying US-China strategic rivalry, with the specter of potential coercive reunification by China posing an existential threat to Taiwan's democracy and autonomy. The acute global semiconductor shortage coupled with TSMC's virtually irreplaceable dominance in advanced chip fabrication have dramatically amplified these geostrategic pressures. With integrated chips representing the technological backbone for vital economic and national security applications, TSMC's capabilities confer the country unmatched leverage as well as vulnerability. The article strongly argues China avidly seeks to massively boost

its own domestic chip industry capabilities in order to reduce strategic dependence and catch up to Taiwan's lead, aided by substantial government subsidies and incentives. However, the extraordinary technical complexity inherent in replicating TSMC's generational manufacturing edge poses monumental challenges. Acquiring or otherwise controlling TSMC could provide China enormous strategic advantage, but also carries major risks, such as loss of vital American customers. In conclusion, the article provides illu-

minating and nuanced economic context regarding TSMC's profoundly outsized significance for Taiwan, both in terms of economic prosperity as well as geostrategic gravitas in the context of regional power dynamics. It underscores how the global chip shortage coupled with intensifying rivalry with China further amplify these multifaceted pressures on Taiwan and TSMC. While aggressively boosting domestic semiconductor capacity may help reduce China's technological reliance on Taiwan over the long term, TSMC's persistent fabrication capabilities edge greatly benefits Taiwan for now, but also leaves it deeply vulnerable to geopolitical forces beyond its control. In

summary, the analysis offers crucial insights into TSMC's uniquely central role, both as the anchor of Taiwan's export-led economic miracle as well as a pivotal factor in the country's complex technology, security, and foreign policy interests. It highlights the rising stakes and tensions at the intersection between commercial technology leadership and national security priorities (Long, n.d.).

2.7.7 Semiconductor Shortages and Vehicle Production and Prices

The research article titled "Semiconductor Shortages and Their Impact on Vehicle Production and New Car Prices: A Detailed Analysis" delves into the significant role of semiconductor shortages on vehicle production and new car prices, aiming to provide a comprehensive assessment of the transitory effects of these shortages. The study is of utmost relevance, considering the recent high inflation readings in the United States, particularly within components facing supply issues and those linked to the economic reopening. The key hypothesis of the analysis revolves around the impact of semiconductor shortages on the automobile industry, specifically focusing on the constraints faced in vehicle production and the subsequent rise in new car prices. The authors undertake a meticulous examination of capacity utilization in both the US semiconductor industry and transportation equipment manufacturing, utilizing various data sources to construct a coherent narrative. Methodologically, the study employs data from the US Census Bureau's Quarterly Survey of Plant Capacity Utilization (QPC) and the Federal Reserve Board's (FRB) estimates of capacity utilization. These sources allow the researchers to gauge the extent of semiconductor shortages and their effects on different sectors of manufacturing. The authors substantiate their findings through a thorough analysis of capacity utilization rates, examining changes over time and comparing them to historical averages. This approach not only adds credibility to their conclusions but also establishes a strong foundation for their subsequent arguments. The outcomes of the research are multifaceted. The study reveals that capacity utilization in the US semiconductor industry has surged to exceptionally high levels, signifying a global shortage of semiconductors. This shortage is found to be a significant driver of reduced vehicle production in the transportation equipment manufacturing industry, particularly among automobile manufacturers. Notably, the analysis identifies that insufficient supply of materials, including semiconductors, has become a primary reason for reduced production, overshadowing issues related to demand. Furthermore, the research delves into the impact of semiconductor shortages on new car prices and vehicle inventories. The acceleration of new car prices, demonstrated through changes in the personal consumption expenditure (PCE) price index, highlights the scarcity-driven upward pressure on prices due to inadequate supply. Simultaneously, the decline in vehicle inventories, coupled with robust sales, underscores the insufficiency of supply relative to demand. These findings collectively provide a comprehensive picture of the semiconductor-induced challenges faced by the automobile industry, substantiating concerns over inflationary pressures. The study's most notable contribution lies in its prediction that these semiconductor shortages and their attendant effects on new car prices and vehicle production are likely to subside within the next six to nine months. This forecast is based on assessments from key industry leaders and analytical reports, which project a gradual improvement in supply constraints. In conclusion, the research paper meticulously analyzes the impact of semiconductor shortages on vehicle production and new car prices, employing a rigorous methodology to support its key insights. The study underscores the significance of semiconductor shortages in shaping the dynamics of the automobile industry and the broader economy. By delving into capacity utilization rates, examining changes over time, and providing empirical evidence of the effects, the analysis contributes to a deeper understanding of the current economic landscape. As semiconductor supply chains evolve and bottlenecks are resolved, the study's projections offer valuable insights into the potential trajectories of vehicle production and pricing in the coming months(Krolikowski and Naggert, 2021).

2.7.8 Processor Problems : An Economic Analysis of the Ongoing Chip Shortage and International Policy Response

The research paper under consideration provides a comprehensive analysis of the semiconductor industry's market structure, its implications for the global economy, and its influence on key macroeconomic variables. The study, authored by an adept researcher, navigates through intricate economic nuances to illuminate the intricate interplay between the semiconductor industry and broader economic dynamics. The central theme of the paper

revolves around the pivotal role of microchips, also known as integrated circuits or semiconductors, in contemporary society. The opening remarks underscore the industry's significance, citing a finance scholar's assertion that microchips represent a pinnacle achievement in human engineering. This introduction effectively sets the tone for the subsequent exploration of the industry's intricate intricacies. The study delves into the complex

market structure of the semiconductor industry, adeptly contextualizing it within the framework of classical economic market typologies. With erudition, the author elucidates how the industry aligns with the characteristics of an oligopoly, wherein a limited number of firms wield significant market influence. This perspective is complemented by a meticulous comparison of the semiconductor industry with other market structures, revealing the industry's unique traits such as rapid product cycles, high capital investment, and formidable barriers to entry. Two predominant models of semiconductor

production are scrutinized with precision: the foundry-fabless model and the integrated device manufacturer (IDM) model. The author expounds upon the intricacies of each model, aptly highlighting their differential capital requirements, vertical integration strategies, and geographic distributions. Notably, the study cogently discusses the pandemic's influence on these models, offering astute observations about how IDMs' vertical integration positioned them advantageously in the wake of supply chain disruptions. A key insight emerges in the exploration of the semiconductor industry's role as an upstream supplier, with downstream sectors dependent on microchips for their operations. This crucial link prompts a judicious examination of how disruptions within the semiconductor industry cascade through the broader economy, exemplified by automotive manufacturers' production line closures due to chip shortages. The interconnectedness of various sectors underscores the nuanced interdependencies that pervade modern economies. Methodologically, the paper adeptly employs economic models to unravel the complex interplay between semiconductor prices, inflation, and real GDP. Rigorous analysis of data, specifically the Consumer Price Index (CPI) and Producer Price Index (PPI) for semiconductors, is employed to elucidate correlations and temporal lags between price fluctuations. The incisive approach adopted highlights the pandemic-induced demand and supply shocks, shedding light on their contribution to contemporary macroeconomic challenges. A notable finding of the research pertains to counter-inflationary measures, with emphasis on the Federal Reserve's policies. The nuanced argument posits that while the Fed's interest rate adjustments can influence short-term inflation trends, their impact on supply-driven inflation is less pronounced. This key insight underscores the complex interplay between monetary policy and macroeconomic dynamics, adding depth to the paper's contributions. In sum, the research paper provides a scholarly and intricate analysis of the semiconductor industry's market structure, its implications for the global economy, and its multifaceted influence on macroeconomic variables. The author's adept navigation through theoretical frameworks, methodological rigor, and incisive insights collectively contribute to a nuanced understanding of the interrelationships within the semiconductor ecosystem. The paper's academic rigor and insightful findings position it as a valuable resource for policymakers, economists, and researchers seeking to unravel the complexities of contemporary economic landscapes impacted by the semiconductor industry(Jensen, 2022).

2.7.9 Effect of Rising Cost and Worker Shortage on Industry

The article titled "Effect of Rising Cost and Worker Shortage on Industry" by Sheikh F. Ferdous and M. Affan Badar presents a comprehensive analysis of the multifaceted impacts of the COVID-19 pandemic on various industries, particularly focusing on technology, manufacturing, healthcare, education, and service sectors. The authors delve into critical aspects such as supply chain disruption, worker shortage, chip shortage, rising costs, and the response of governments and industries to mitigate these challenges. The research highlights the far-reaching consequences of the pandemic on global industries. The authors emphasize the disruption caused by the shortage of skilled workers, particularly those possessing tribal knowledge, which is critical for maintaining operational efficiency. This issue is magnified by the simultaneous phenomenon of higher worker turnover driven by factors such as workers seeking higher wages and better work environments, as well as the lingering effects of COVID-19. These dynamics have created a vacuum of expertise, necessitating the retraining and recruitment of new employees, which in turn disrupts supply chains and exacerbates the problem. A significant concern addressed in the paper is the shortage of semiconductor chips, affecting various sectors including automotive manufacturing. The demand for chips has surged due to remote work and online activities during the pandemic, leading to supply chain bottlenecks. The article underscores the intricate link between chip shortages, supply chain disruptions, and rising consumer prices. This issue is compounded by the globalization of chip manufacturing, which concentrates a significant portion of production in East Asia. The authors propose that the US government's investment in domestic chip manufacturing aligns with efforts to bolster local production and mitigate supply chain vulnerabilities. Another noteworthy aspect discussed is the rising inflation and costs attributed to multiple factors, including stimulus packages, reduced workforce, and disrupted supply chains. The authors draw attention to the challenge faced by workers in sectors with lower demand, where increasing prices create additional hardships. The Federal Reserve's consideration of interest rate hikes and other measures to curb inflation is explored as a potential solution. The paper concludes by highlighting the need for a comprehensive approach to address the complex challenges posed by the pandemic. The authors stress the importance of preserving tribal knowledge, reevaluating long-standing operational practices, and investing in better employee training to enhance productivity and mitigate the impacts of labor force fluctuations. Furthermore, the authors underscore the role of vaccines and vaccine mandates in managing the pandemic and facilitating economic recovery. In summary, Ferdous and Badar's research provides an insightful exploration of the intricate interplay between the COVID-19 pandemic and its multifaceted impacts on industries, ranging from worker shortages and supply chain disruptions to rising costs and chip shortages. The article underscores the interconnectedness of these challenges and the necessity of strategic responses to ensure resilience and recovery. The authors' analysis offers valuable insights for policymakers, industry leaders, and researchers navigating the evolving landscape of global economies in the wake of the pandemic (Ferdous, Badar, and Lin, 2023).

2.7.10 The Impact of the Computer Chip Supply Shortage

The article titled "The Impact of the Computer Chip Supply Shortage" authored by Hannah Casper, Autumn Rexford, David Riegel, Amanda Robinson, Emily Martin, and Mohamed Awwad focuses on the recent shortage of computer chips and its implications for various industries, particularly the automotive sector. The research delves into the technicalities of the computer chip supply chain, the causes of the shortage, and potential solutions to prevent and manage such shortages in the future. The authors begin by highlighting the global shortage of computer chips and its impact on product costs and production in industries such as automotive. The widespread use of computer chips in various applications, from smartphones to cars, has created a high demand for these components. However, disruptions caused by the COVID-19 pandemic, particularly in China, have led to a rise in prices and limited supply. The research objectives include exploring methods to ensure the availability of computer chips in non-vertical supply chains, preventing waste due to outdated microchips, and analyzing the impacts of the shortage on various countries' supply chains. The article provides an overview of computer chip technology, emphasizing their integral role in modern technology. Computer chips, which consist of integrated circuits or wafers, serve as memory units and processors for various devices. The processing power of devices is determined by the number of microchips within them. The authors also mention Moore's Law, which predicts that the size of microchips will continue to decrease, allowing for more chips to be placed in the same space. The manufacturing and supply chain aspects of semiconductors are discussed in detail. The production of semiconductors involves three major steps: design, fabrication, and assembly, testing, and packaging (ATP). The authors explain various components required for semiconductor fabrication, including materials like silicon, semiconductor manufacturing equipment (SME), core intellectual property (IP), and electronic design automation (EDA). The article also discusses different semiconductor manufacturing methods, such as integrated device manufacturers (IDMs) and fabless foundries, which play a crucial role in the semiconductor supply chain. The authors highlight the global distribution of semiconductor supply chain segments across countries, with the United States leading in research and development (R&D) and various other countries specializing in different production steps. Notably, the article focuses on India's efforts to strengthen its semiconductor industry through government incentives and policies aimed at encouraging semiconductor manufacturing. The causes and impact of the shortage are addressed, with increased demand for semiconductors due to trends in automotive safety and connectivity being a significant factor. The authors discuss how the COVID-19 pandemic and subsequent shutdowns affected chip production and demand, leading to shortages in various industries. The impact on the automotive industry is emphasized, with automakers struggling to secure chip supplies, resulting in production halts and factory closures. The article concludes by suggesting potential solutions and improvements to the semiconductor supply chain. Reshoring production, mathematical modeling to optimize supply chains, and government policies to encourage investment and technological development are identified as strategies to mitigate shortages and improve supply chain resilience. Overall, the research provides a comprehensive overview of the computer chip supply chain, its challenges, and potential solutions to address shortages and enhance the stability of supply chains across industries. The authors emphasize the importance of proactive measures to prevent future shortages and maintain the availability of computer chips for various applications(Casper et al., 2021b).

2.7.11 Overcoming Chip Shortages: Low-Cost Open-Source Parametric 3-D Printable Solderless SOIC to DIP Breakout Adapters

The global economy's intricate supply chain structures have long been pivotal for attaining competitive advantages among corporations. However, the onset of the COVID-19 pandemic posed unprecedented challenges, disrupting supply chains worldwide and casting a spotlight on the need for supply chain resilience. While the initial disruptions were prominent in the medical sector, subsequent waves of supply chain interruptions extended to the electronics and semiconductor industries, leading to an acute chip shortage with far-reaching consequences. This article presents a novel solution to this predicament through the conception of an open-source 3-D printable device, known as the Additive Manufacture Breakout Board (AMBB), designed to facilitate the use of surface-mount components in conventional through-hole prototyping setups.

The study leverages a data-driven approach to unveil the disparity between the availability of through-hole and surface-mount components in the electronics market. The authors sourced data from the Digi-Key Electronics website, extracting information on stock quantity and product offerings for various component categories. This comprehensive dataset was subjected to meticulous analysis, allowing the authors to gauge the extent of supply chain disruptions. Building on this foundational analysis, the authors embarked on the design and manufacturing of the AMBB, a device that bridges the gap between through-hole and surface-mount components, affording designers the flexibility to utilize the latter in prototyping scenarios. The analysis of the Digi-Key Electronics dataset yielded revealing insights into the supply chain dynamics of electronic components. The scarcity of through-hole components was starkly evident, with only a mere 12% of available electronics stock categorized as through-hole. This scarcity was particularly pronounced in the context of the COVID-19 pandemic, underscoring the need for innovative solutions to facilitate electronic prototyping. The authors' pioneering concept, the AMBB, offers a versatile means of prototyping with surface-mount components, effectively mitigating the challenges posed by the dearth of through-hole options. Through the use of 3-D printing technology, the AMBB enables the integration of surface-mount components into breadboard or protoboard setups, obviating the need for soldering or specialized breakout boards. The core principle of the AMBB lies in its ability to establish secure electrical contacts and precise alignment between the surface-mount components and the prototyping medium. Furthermore, the authors emphasize the reusability of the AMBB, promoting a sustainable and cost-effective approach to electronic prototyping. The results

of this study highlight a paradigm shift in electronic prototyping, signifying a departure from conventional through-hole components to the integration of surface-mount alternatives. The AMBB's success in enabling efficient prototyping with surface-mount components underscores its potential to streamline the design and development process, saving both time and costs. By providing a bridge between surface-mount and through-hole technologies, the AMBB holds promise for expanding the design options available to electronics engineers and designers. The device's accessibility, simplicity, and cost-effectiveness render it a viable tool for distributed manufacturing initiatives, empowering a wider range of users to contribute to electronics innovation. The study's holistic approach, encompassing data analysis, innovative

design, and practical implementation, underscores the viability of the AMBB as a transformative solution in the face of chip shortages and supply chain disruptions. The broader implications of this research extend beyond addressing immediate challenges to shaping the future landscape of electronics prototyping, with potential applications in open scientific hardware, low-resource settings, and sustainable additive manufacturing endeavors. As the electronic industry continues to evolve, the AMBB stands as a testament to the power of innovative thinking and collaborative solutions in overcoming complex supply chain issues and fostering resilience in the face of adversity(Brooks, Peplinski, and Pearce, 2023).

2.7.12 Summary and Other Related Factors:

These papers collectively highlight the significant impact of the semiconductor shortage, particularly as exacerbated by the COVID-19 pandemic. They analyze the causes, consequences, and potential solutions from various angles, such as supply chain disruptions, worker shortages, rising costs, and implications for industries like automotive and technology. Several key themes emerge from the comparison:

1. **Cause of Shortage:** The shortage is attributed to a combination of factors, including pandemic-induced disruptions, increased demand for electronics, supply chain complexities, and geopolitical tensions.
2. **Impact on Industries:** Various industries, such as automotive, technology, and manufacturing, are adversely affected by the shortage, leading to production halts, price hikes, and supply chain challenges.
3. **Policy Responses:** Governments and industries are responding with policies to strengthen domestic production, invest in research, incentivize manufacturing, and promote collaboration.
4. **Supply Chain Vulnerabilities:** The interconnectedness of global supply chains is a common theme, emphasizing the need for diversification, resilient supplier relationships, and proactive measures to prevent future disruptions.
5. **Innovative Solutions:** Explore innovative solutions like new chip foundries, 3-D printable adapters, and strategies to bridge the gap between through-hole and surface-mount components.
6. **Global Implications:** The shortage has geopolitical and macroeconomic implications, highlighting the importance of balancing economic growth and national security.
7. **Long-Term Resilience:** The need for long-term planning, workforce retention, retraining, and capacity expansion is emphasized to build resilience against future disruptions.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Research Design

In this research, our primary objective is to thoroughly investigate the critical issue of the semiconductor chip shortage, which has had a profound impact on the automotive industry. The shortage, further exacerbated by the COVID-19 pandemic, has created disruptions in vehicle production and supply chains, presenting significant challenges for automakers and suppliers worldwide. Our study aims to delve into various facets of this problem and explore potential strategies to effectively mitigate its adverse effects.

This chapter comprises several sections that outline our research approach, including the formulation and expression of research questions, the identification and acquisition of suitable data sources, and the parameters related to data granularity, volume, and other essential factors. Furthermore, we will discuss the initial analysis performed on automotive data as a foundational step. Emphasizing the importance of analysis, we will explore how it aligns with our research goals and helps address the research questions.

3.1.1 Research Questions

To guide our investigation, we have formulated specific research questions that provide a clear focus for our study. These research questions serve as the basis for our exploration and analysis. By addressing these questions, we aim to gain a comprehensive understanding of the semiconductor chip shortage and develop meaningful solutions.

Research Question 1: *How did the COVID-19 pandemic disrupt the supply chains in the automobile sector, and what were the specific challenges faced by manufacturers and other industries reliant on semiconductor supply?*

This research question aims to investigate the impact of the COVID-19 pandemic on the supply chains in the automobile sector and the specific challenges encountered by manufacturers and other industries that heavily rely on semiconductor supply. The disruption caused by the pandemic has been widely acknowledged and has led to significant difficulties in maintaining a steady flow of semiconductors, essential components for various automotive applications. Understanding the nature and extent of the disruptions in the supply chains is crucial for comprehending the overall impact on the automotive industry. By examining the effects of the pandemic on the supply chains, we can gain insights into the specific challenges faced by manufacturers and other industries that rely on semiconductor supply, such as consumer electronics and telecommunications.

The significance of investigating this research question lies in its potential to uncover the root causes of the disruptions and challenges. By identifying these causes, we can develop effective strategies and solutions to mitigate the impact of future disruptions on the supply chains. Furthermore, the findings can assist policymakers, industry stakeholders, and decision-makers in formulating contingency plans and improving resilience in the face of similar crises.

Research Question 2: *What measures were taken by automobile manufacturers and other sectors to mitigate the impact of the chip shortage during the pandemic, and what lessons can be learned from their experiences?*

This research question focuses on examining the measures implemented by automobile manufacturers and other sectors to alleviate the impact of the semiconductor chip shortage during the COVID-19 pandemic. The chip shortage has had severe repercussions on the automotive industry, leading to production delays, supply chain disruptions, and financial losses. It is essential to explore the actions taken by manufacturers and other sectors to address this issue and extract valuable lessons from their experiences. By investigating the measures adopted by automobile manufacturers, we can identify the strategies and tactics employed to mitigate the impact of the chip shortage. These measures may include diversifying suppliers, prioritizing production of high-demand vehicles, reallocating available chips to critical systems, or collaborating with semiconductor companies to secure the necessary supply. Similarly, exploring the actions taken by other sectors, such as consumer electronics or telecommunications, can provide insights into alternative approaches and potential cross-industry learning's.

Understanding the effectiveness of these measures and the challenges encountered in their implementation can contribute to the development of best practices and recommendations. By analyzing the experiences of automobile manufacturers and other sectors, we can identify successful strategies as well as potential pitfalls to avoid. This knowledge can be invaluable for future situations where supply chain disruptions occur, enabling proactive decision-making and reducing the impact on the automotive industry and other sectors reliant on semiconductors.

Research Question 3: *What are the implications of the pandemic outbreak on supply chain management practices in the automobile industry, particularly in terms of modifications made by manufacturers?*

This research question delves into the implications of the COVID-19 pandemic outbreak on supply chain management practices in the automobile industry, with a specific focus on the modifications made by manufacturers. The pandemic has had a profound impact on global supply chains, forcing industries to reevaluate and adapt their existing practices to navigate the unprecedented challenges. The automobile industry heavily relies on complex and interconnected supply chains, involving numerous suppliers, components, and logistics networks. The pandemic disrupted these supply chains in multiple ways, including factory shutdowns, travel restrictions, labor shortages, and fluctuations in demand. As a result, automobile manufacturers had to make significant modifications to their supply chain management practices to ensure business continuity and minimize disruptions.

By investigating the implications of the pandemic outbreak, we can gain insights into the specific changes implemented by automobile manufacturers in their supply chain management strategies. These modifications may include diversifying supplier networks to mitigate risks, enhancing visibility and transparency in the supply chain, adopting advanced technologies for demand forecasting and inventory management, or redesigning production processes to accommodate new safety protocols. Understanding the implications and modifications in supply chain management practices is crucial for several reasons. Firstly, it allows us to assess the resilience and adaptability of the automobile industry in response to the pandemic. By studying the modifications made by manufacturers, we can identify innovative solutions and strategies that have emerged as a result of the crisis. Secondly, it provides a basis for evaluating the effectiveness of these modifications in mitigating the impact of future disruptions and improving supply chain performance in the long term.

Research Question 4: *How can supply chain resilience be enhanced to better navigate global disasters or war-like situations, taking into account the lessons learned from the COVID-19 crisis?*

This research question focuses on the enhancement of supply chain resilience in the face of global disasters or war-like situations, with a specific emphasis on the lessons learned from the COVID-19 crisis. The COVID-19 pandemic has served as a significant global disruption, highlighting vulnerabilities and weaknesses in supply chains across various industries, including the automobile sector. Therefore, understanding how to bolster supply chain resilience is crucial to ensure business continuity and mitigate the impact of future crises. The COVID-19 crisis has provided valuable insights into the challenges faced by supply chains during a global disaster. It has exposed the risks associated with over-reliance on single-source suppliers, lack of visibility and transparency, and limited flexibility in adapting to sudden changes in demand and supply dynamics. Therefore, leveraging the lessons learned from this crisis is essential to identify strategies that can enhance supply chain resilience.

To address this research question, it is important to examine the measures taken by organizations during the COVID-19 crisis to build resilient supply chains. These measures may include diversifying supplier networks to reduce dependency on specific regions or countries, implementing advanced technologies for real-time tracking and monitoring of inventory and shipments, establishing collaborative relationships with key suppliers and partners, and adopting agile and flexible production and distribution models. Additionally, this research question also entails an exploration of existing frameworks and best practices for supply chain resilience in the context of global disasters or war-like situations. By studying literature and case studies, we can identify successful strategies implemented by organizations that have effectively navigated such crises. These strategies may involve the development of contingency plans, risk assessment and mitigation strategies, scenario planning, and investment in robust infrastructure and logistics capabilities.

Research Question 5: *What alternative approaches can be explored to develop semiconductor chips or slow down the depletion of raw materials used in chip manufacturing, ensuring a sustainable supply for various sectors?*

This research question focuses on identifying alternative approaches to develop semiconductor chips or mitigate the depletion of raw materials used in chip manufacturing. The semiconductor chip shortage has revealed the vulnerability of the automobile industry and other sectors heavily reliant on chips, highlighting the need to explore sustainable solutions for chip production and raw material management. To address this research question, it is important to consider various avenues for semiconductor chip development. This may involve investigating alternative materials or manufacturing processes that can reduce the reliance on scarce or depleting resources. For example, exploring the use of novel materials, such as graphene or organic compounds, as potential alternatives to traditional semiconductor materials like silicon, can offer new opportunities for chip development. Additionally, researching innovative manufacturing techniques, such as additive manufacturing or 3D printing, may enable more efficient and sustainable chip production.

Furthermore, this research question also emphasizes the importance of slowing down the depletion of raw materials used in chip manufacturing. This can be achieved through several strategies. Firstly, exploring recycling and recovery technologies to extract and reuse valuable materials from end-of-life or obsolete chips can help reduce the demand for new raw materials. Additionally, promoting circular economy principles, such as designing chips for longevity and reparability, can extend the lifespan of chips and reduce the need for frequent replacements. Moreover, studying material substitution possibilities and developing supply chain strategies that prioritize sustainable sourcing and responsible mining practices can contribute to a more sustainable supply of raw materials for chip manufacturing.

The findings from this research question will have implications not only for the automobile industry but also for various other sectors reliant on semiconductor chips, such as electronics, telecommunications, and healthcare. By exploring alternative approaches for chip development and raw material management, organizations can work towards building a more sustainable and resilient supply chain.

Research Question 6: *How can information obtained from the study be used to improve supply chain management strategies and enhance the resilience of supply chains in the face of future disruptions?*

This research question focuses on utilizing the information gathered from the study to improve supply chain management strategies and enhance the resilience of supply chains in the face of future disruptions, not limited to the semiconductor chip shortage. By analyzing the findings and insights obtained throughout the research process, organizations can identify key areas for improvement and develop strategies to mitigate the impact of future disruptions. The study's findings can be used to inform supply chain management strategies in several ways. Firstly, the research can shed light on the specific challenges faced by the automobile industry and other sectors during the semiconductor chip shortage. By understanding the root causes and consequences of the disruption, organizations can develop proactive measures to address similar challenges in the future. This may involve reassessing inventory management practices, diversifying suppliers, or establishing contingency plans to ensure a more robust and resilient supply chain.

Additionally, the study can provide valuable insights into the measures taken by automobile manufacturers and other sectors to mitigate the impact of the chip shortage during the pandemic. Examining these measures and their effectiveness can guide organizations in developing best practices and lessons learned for future disruptions. For instance, the study may reveal successful strategies such as fostering closer collaboration between manufacturers and suppliers, implementing real-time monitoring systems, or adopting agile production processes. By adopting these strategies, organizations can enhance their ability to respond and adapt quickly to unforeseen disruptions.

Furthermore, the research can contribute to the development of frameworks or decision-making models that support supply chain resilience. By analyzing the factors that contributed to the resilience or vulnerability of supply chains during the pandemic, organizations can identify critical success factors and design strategies to enhance resilience. This may involve assessing the role of digitization, the importance of risk assessment and mitigation, or the significance of building strong relationships with suppliers and partners. Integrating these findings into supply chain management strategies can help organizations proactively identify and address potential vulnerabilities, making the supply chain more resilient to future disruptions.

The ultimate goal of using the information obtained from the study is to create a knowledge base that supports evidence-based decision-making in supply chain management. By disseminating the research findings to industry practitioners, policymakers, and researchers, organizations can foster a collaborative environment where best practices are shared and implemented. This can lead to the development of industry-wide standards, guidelines, or initiatives that enhance supply chain resilience and mitigate the impact of future disruptions.

3.1.2 Data Collection

In this subsection, we will discuss the various types of data that will be collected for our research and their relevance to our study. The data collection process is a crucial step in obtaining relevant and reliable information to address our research questions and achieve the research goals.

To gain insights into the semiconductor chip shortage and its impact on the automobile industry, we will collect a diverse range of data from multiple sources. Firstly, we will gather car manufacturing data, including production figures, manufacturing capacity, and assembly line data. This data will provide us with a comprehensive understanding of the scale of the chip shortage and its effect on car production. By analyzing these manufacturing data, we can identify the specific disruptions caused by the shortage and their implications for the industry.

In addition to car manufacturing data, we will collect sales data to evaluate the impact of the chip shortage on car sales. This data will include sales volumes, revenue figures, and market share data from various automobile manufacturers. By examining the sales trends and patterns, we can assess the direct impact of the shortage on consumer demand and identify any shifts in market dynamics. This information will be crucial in understanding the challenges faced by manufacturers and other industries reliant on semiconductor supply.

To gain a broader perspective on the impact of the chip shortage, we will also collect relevant economic data. This will include data related to stock prices of automobile manufacturers and semiconductor companies, commodity prices (specifically those related to raw materials used in chip manufacturing), inflation rates, and unemployment figures. By analyzing these economic indicators, we can assess the macroeconomic implications of the shortage and understand its ripple effects on the broader economy. This data will help us examine the interplay between the chip shortage, economic factors, and the automotive industry.

The collected data will be relevant to our research in several ways. Firstly, it will enable us to analyze the magnitude and severity of the chip shortage and its impact on car manufacturing and sales. By examining the data, we can identify the specific challenges faced by manufacturers and other industries reliant on semiconductor supply. This understanding will help us propose suitable solutions and strategies to mitigate the impact of similar disruptions in the future.

Moreover, the economic data will provide us with insights into the broader implications of the shortage. By examining the relationship between economic factors and car sales, we can identify the key drivers and dynamics that influence consumer demand and market behavior during a supply chain disruption. This knowledge will be valuable in developing effective supply chain management strategies and enhancing the resilience of supply chains in the face of future disruptions.

3.1.3 Data Pre-processing and Analysis

In this subsection, we will discuss the importance of data pre-processing and analysis in our research. Once we have collected the raw data, it is essential to clean and pre-process it to ensure its quality and usability. Subsequently, we will explore various visualization techniques and statistical plots to gain a better understanding of the data. By doing so, we can identify patterns, trends, and relationships that will help us achieve our research objectives.

Data pre-processing plays a crucial role in ensuring the quality and reliability of the data. It involves several steps such as data cleaning, handling missing values, removing outliers, and standardizing variables. By cleaning the data, we eliminate any errors, inconsistencies, or inaccuracies that may affect the analysis. Handling missing values ensures that we have a complete dataset to work with, while removing outliers helps to address any extreme values that may skew the analysis. Standardizing variables brings uniformity to the data, allowing for meaningful comparisons and interpretations.

Once the data has been pre-processed, we can move on to data analysis. Visualizing the data through statistical plots is an effective way to explore the characteristics and patterns within the dataset. We can employ various types of plots such as histograms, scatter plots, line graphs, and box plots to visualize different aspects of the data. These visual representations provide us with a visual summary of the data distribution, central tendencies, and relationships between variables.

By examining the visualized data, we can start to derive meaning and insights. The data may reveal trends in car manufacturing and sales, fluctuations in stock prices, inflation rates, and unemployment figures. We can analyze the relationships between these variables to understand their impact on the semiconductor chip shortage and the automobile industry as a whole. The visual exploration of the data helps us identify potential research objectives and questions that can be further investigated.

For instance, by analyzing the car manufacturing data, we may observe a decline in production during the peak of the chip shortage. This could lead us to explore the specific challenges faced by manufacturers and their strategies to mitigate the impact. Similarly, by examining the sales data, we may identify changes in consumer behavior and market dynamics in response to the shortage. This could prompt us to investigate the factors influencing car sales during a supply chain disruption.

The statistical plots and visualizations also assist us in identifying correlations and dependencies between variables. We can uncover relationships between car sales and economic indicators such as commodity prices, inflation rates, and stock prices. This enables us to assess the broader implications of the chip shortage on the economy and explore strategies to enhance supply chain resilience.

In the next section, we will discuss on a case study for data collection, data pre-processing, visualization and insights of the collected data.

3.2 Case Study: Analysis of the Impact of the Chip Shortage on the Automotive Industry

In this section, we present a case study focusing on the analysis of the impact of the semiconductor chip shortage on the automotive industry. To conduct this analysis, we collected data from reliable sources such as Yahoo Finance and the International Organization of Motor Vehicle Manufacturers (OICA). The data-set spans from the year 2000 to 2022, providing us with a comprehensive time frame to assess the effects of the chip shortage.

The data collected from Yahoo Finance includes stock prices of major automotive companies, commodity prices, and other relevant economic indicators. These data points offer insights into the financial performance and market dynamics of the automotive industry, allowing us to understand the effects of the chip shortage on company valuations and investor sentiment. Additionally, the dataset from OICA provides information on global car production and sales, enabling us to analyze the impact of the chip shortage on manufacturing and market demand.

Before conducting the analysis, it is essential to describe the data and the pre-processing techniques employed. The dataset consists of multiple variables, including car production and sales figures, stock prices, commodity prices, and economic indicators such as inflation rates and unemployment rates. Each variable offers a unique perspective on the chip shortage's impact and its implications for the automotive industry.

To ensure the quality and reliability of the data, we applied various preprocessing techniques. Firstly, we performed data cleaning, which involved removing any inconsistencies, errors, or missing values in the data set. This step ensures that the subsequent analysis is based on accurate and complete information. Next, we conducted data normalization and standardization to bring the variables to a common scale and enable meaningful comparisons. By standardizing the data, we can identify relative changes and trends across different variables.

3.2.1 Data Collection APIs and Sources

For this analysis, we collected data from two primary sources: Yahoo Finance and the International Organization of Motor Vehicle Manufacturers (OICA).

The data spans from the year 2000 to 2022 and provides valuable insights into the impact of the chip shortage on the automotive industry.

Yahoo Finance Data: To obtain the "Chip Stock Price" data, we utilized the yfinance API [1] from Yahoo Finance. This API allows access to historical stock price data of various semiconductor companies. We fetched data for several tickers, including "TSM," "NVDA," "ASML," "AVGO," "AMD," and "QCOM." The dataset contains the following attributes:

- *Date*: The date of the stock price.
- *Ticker*: Ticker symbols representing publicly traded semiconductor companies.
- *Price*: The stock price of the respective ticker.

Yahoo Finance is renowned for offering a wide range of market data on stocks, bonds, currencies, and crypto-currencies. It also provides market news, reports, analysis, and additional options and fundamentals data, distinguishing it from other platforms. Although Yahoo Finance had its official API, it was decommissioned in May 2017 due to data misuse. However, the yfinance library, developed by Ran Aroussi, enables access to the same data. Ran Aroussi recommends using yfinance directly for accessing financial data.

OICA Data: To gather car production data, we scraped the information from the website of the International Organization of Motor Vehicle Manufacturers (OICA) [2]. The dataset includes data from the year 2000 to 2022. The attributes in the dataset are as follows:

- *Year*: The year of car production.
- *Country/Region*: The name of the country where the cars were produced.
- *Cars*: The count of cars manufactured.
- *Commercial vehicles*: The count of commercial vehicles manufactured.
- *Total*: The total count of cars manufactured (cars + commercial vehicles).

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[1] https://finance.yahoo.com

[2] https://www.oica.net/

- *% Change*: The percentage change in total car production.

OICA is an international organization that provides comprehensive data on motor vehicle production and statistics. By scraping the data from their website, we obtain valuable insights into the global car production trends and the impact of the chip shortage on the industry.

3.2.2 Data-set Information & Data Description

The dataset includes the stock prices of semiconductor companies and car production figures. It enables us to analyze the relationship between the chip shortage and the automotive industry. The dataset spans over two decades, offering a long-term perspective on the impact of the shortage.

Before conducting the analysis, we pre-processed the data by cleaning, normalizing, and standardizing it. This ensures that the dataset is accurate, consistent, and suitable for analysis. Data cleaning involved removing any inconsistencies, errors, or missing values. Normalization and standardization techniques were applied to bring the variables to a common scale and facilitate meaningful comparisons.

By utilizing these datasets and conducting thorough data pre-processing, we aim to uncover insights and trends related to the impact of the chip shortage on stock prices and car production. This analysis will provide valuable information for understanding the repercussions of the shortage on the automotive industry and inform potential strategies to mitigate its effects.

TABLE 3.1: Chip Stock Price Data Description

Name	**Date**	**Ticker**	**Price**
Type	DateTime	Categorical	Numeric
Null Values (%)	0%	0%	0%
Outliers	-	-	60
Minimum	-	-	0.65455186
Maximum	-	-	782.28088
Q1	-	-	6.453459
Q2	-	-	22.931038
Q3	-	-	57.459951

Table 3.1 summarizes the data description for the "Chip Stock Price" dataset. It includes the column names (Name, Date, Ticker, Price) and their respective types (DateTime, Categorical, Numeric). The table also provides information

on the presence of null values (0% for all columns) and the number of outliers (60). Additionally, it presents statistical measures such as the minimum value (0.65455186), maximum value (782.28088), and quartiles (Q1, Q2, Q3) for the Price column.

TABLE 3.2: Car Production Data Description

Name	**Year**	**Region**	**Cars**	**Commercial Vehicles**	**Total**	**Change %**
Type	DateTime	Categorical	Numeric	Numeric	Numeric	Numeric
Null Values (%)	0%	0%	0%	2.2%	0%	0.5%
Outliers	-	-	100	111	87	61
Minimum	-	-	0	0	1490	0
Maximum	-	-	24806687	8518734	29015434	9323
Q1	-	-	189776.25	19458.5	230484.75	25
Q2	-	-	487023.5	120062.5	624656	82
Q3	-	-	1431193.5	423729.5	2015493.2	209.5

Table 3.2 provides a data description for the "Car Production" dataset. It includes the column names (Name, Year, Region, Cars, Commercial Vehicles, Total, Change %) and their respective types (DateTime, Categorical, Numeric, Numeric, Numeric, Numeric). The table also presents information on the presence of null values (in percentage), the number of outliers for each column, as well as statistical measures such as the minimum and maximum values, and quartiles (Q1, Q2, Q3).

The concept of a ticker symbol in the stock market is a unique combination of letters assigned to a publicly traded company. It serves as an identifier for a company's stock and allows for quick access to financial information about the company's performance. Ticker symbols typically consist of a few letters and are listed on stock exchanges such as the NYSE and NASDAQ. Here in Table 3.4 showcasing the ticker symbols and their corresponding company names used in our research:

The Figures 3.1 and 3.2 presented in this section showcase the count distribution of six different tickers using bar chart and pie chart. These visualizations provide valuable insights into the distribution of the tickers in the dataset. The bar chart (Figure 3.1) illustrates the count of each ticker. The x-axis represents the tickers, while the y-axis represents the count. Each ticker is represented by a bar whose height corresponds to its count value. This

TABLE 3.4: Ticker Symbols and Company Names

Ticker Symbol	Company Name
ASML	ASML Holding N.V.
AVGO	Broadcom Inc.
DODGX	Dodge & Cox Stock Fund
F	Ford Motor Company
FUJHY	Fujitsu Limited
GM	General Motors Company
GOLD	Barrick Gold Corporation
HMC	Honda Motor Co., Ltd.
MZDAY	Mazda Motor Corporation
NVDA	NVIDIA Corporation
QCOM	Qualcomm Incorporated
TM	Toyota Motor Corporation
TSLA	Tesla, Inc.
TSM	Taiwan Semiconductor Manufacturing Company Limited
VWAGY	Volkswagen AG
X	United States Steel Corporation

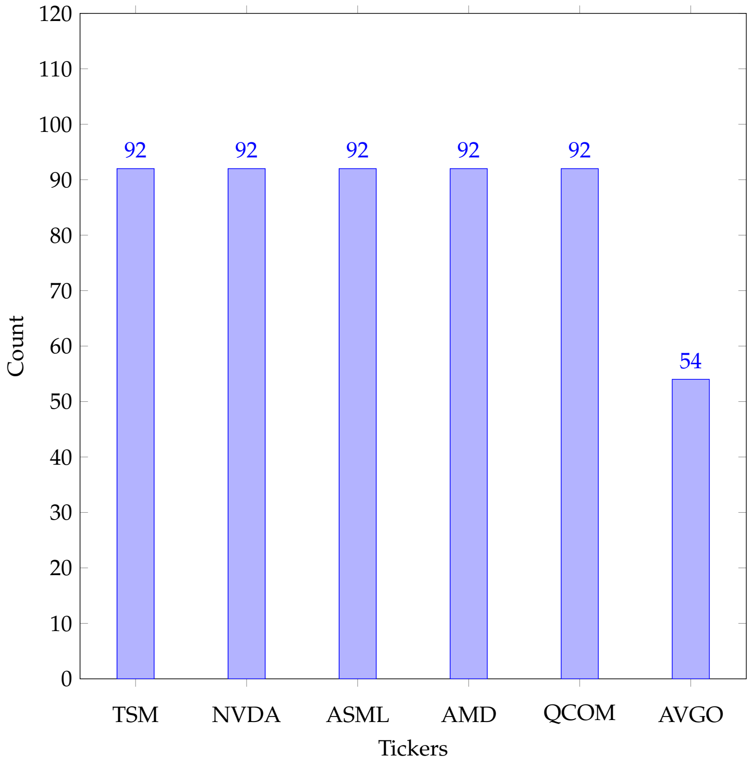

FIGURE 3.1: Count Plot of Tickers

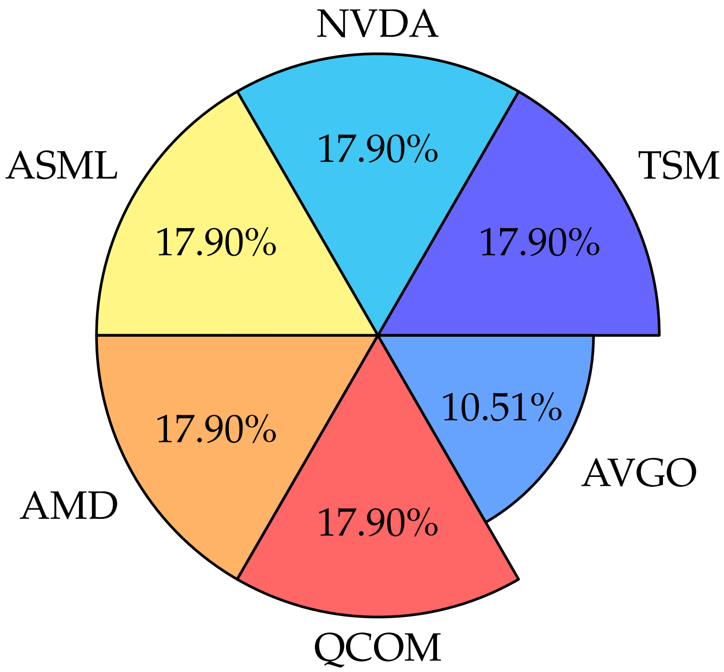

FIGURE 3.2: Distribution of tickers data volume

chart allows for easy comparison of the ticker counts, highlighting any variations or discrepancies among them. In our dataset, the tickers TSM, NVDA, ASML, AMD, and QCOM have a count of 92, while AVGO has a count of 54.

The pie chart (Figure 3.2) provides a different perspective on the data distribution. Each ticker is represented by a slice of the pie, with the size of the slice proportional to its count value. This chart allows for a quick understanding of the relative distribution of tickers. In our dataset, TSM, NVDA, ASML, AMD, and QCOM each occupy an equal 17.9% of the pie, while AVGO occupies a smaller slice representing 10.51% of the total.

Both charts provide complementary information about the data distribution. The bar chart emphasizes the absolute count of each ticker, enabling a more precise analysis of the variations among them. On the other hand, the pie chart provides a visual representation of the relative proportions of each ticker, allowing for a quick understanding of the overall distribution.

In the next a few subsections, we will see different data items those are collected as chip price over the last 22 years, the commodity, inflation and other parameters. We will discuss about the data with suitable plots to understand the insights of these data samples.

3.2.3 Chip Price Data

The chip price data collected from the year 2000 to 2022 reveals interesting trends and patterns in the semiconductor market. A detailed analysis of the data highlights significant changes in chip prices, particularly after the year 2015. In Figure 3.3 clearly shows the chip prices across different tickers showed a relatively stable or gradually increasing trend. However, starting from 2015, a noticeable increase in chip prices can be observed for almost all tickers. This period marked a significant shift in the semiconductor market, with prices experiencing a substantial upward trajectory.

Moreover, the years 2020 to 2022 witnessed a particularly remarkable surge in chip prices across all tickers. This period was characterized by a massive increase in prices, suggesting unprecedented market dynamics and potentially reflecting the impact of various factors such as supply chain disruptions, global demand, and technological advancements. The observed trend of increasing chip prices after 2015 and the substantial surge from 2020 to 2022 highlight the volatile nature of the semiconductor market. Such fluctuations can significantly impact various industries relying on semiconductors, such as the automotive sector, which has faced challenges due to the chip shortage.

Understanding the historical price patterns and trends in the chip market is crucial for manufacturers, investors, and policymakers. It provides insights into market dynamics, helps anticipate future price movements, and enables strategic decision-making. The identified trends can inform pricing strategies, inventory management, and supply chain planning to mitigate the impact of price fluctuations and optimize business operations.

3.2.4 Data Volume per Country/Region

The bar plot in Figure 3.4 represents the country-wise car production data volume, indicating the number of cars produced in each country (in thousands). The data is well sampled, with each country having a count of 23,000, except for a few countries with slightly lower counts. The bar plot provides a visual representation of the distribution of car production across different countries. It reveals that several countries have an equal volume of car production, with each country contributing cars to the dataset. This indicates a well-balanced sampling approach, ensuring that the data adequately represents each country's car production.

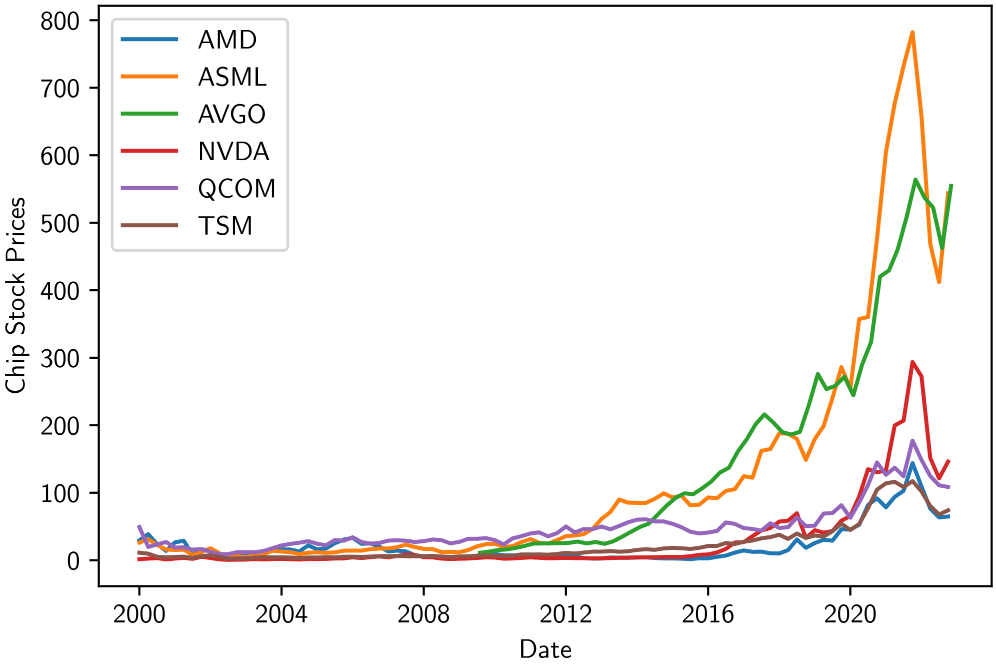

FIGURE 3.3: Semiconductor chip price over last 22 years

Among the countries with a count of 23,000, we can observe a diverse range of regions represented in the dataset. Countries from various continents, including Argentina, Malaysia, Poland, Portugal, Russia, Serbia, Slovakia, Slovenia, South Africa, South Korea, Spain, Taiwan, Thailand, Turkey, Ukraine, USA, Uzbekistan, Mexico, Romania, Japan, France, Canada, China, Belgium, Austria, Finland, Germany, Hungary, India, and Indonesia, all have an equal number of cars produced. Additionally, there are a few countries with slightly lower counts, such as Egypt with 22,000 cars, Others with 22,000 cars, Iran with 21,000 cars, the UK with 20,000 cars and so on.

Furthermore, there are a few countries with even lower counts, including Netherlands with 18,000 cars, similarly for Sweden and, Australia, Morocco with 6000 cars, Czech Republic, Kazakhstan, and United Kingdom with 3000 cars. These countries have a comparatively lower representation in terms of car production volume in the dataset.

3.2.5 Yearly Total Car Production Data

The yearly total car production data shown in Figure 3.5 a general increasing trend over time, indicating a growth in the automotive industry. However, there is a noticeable sudden decrease in car production in the years 2020 and

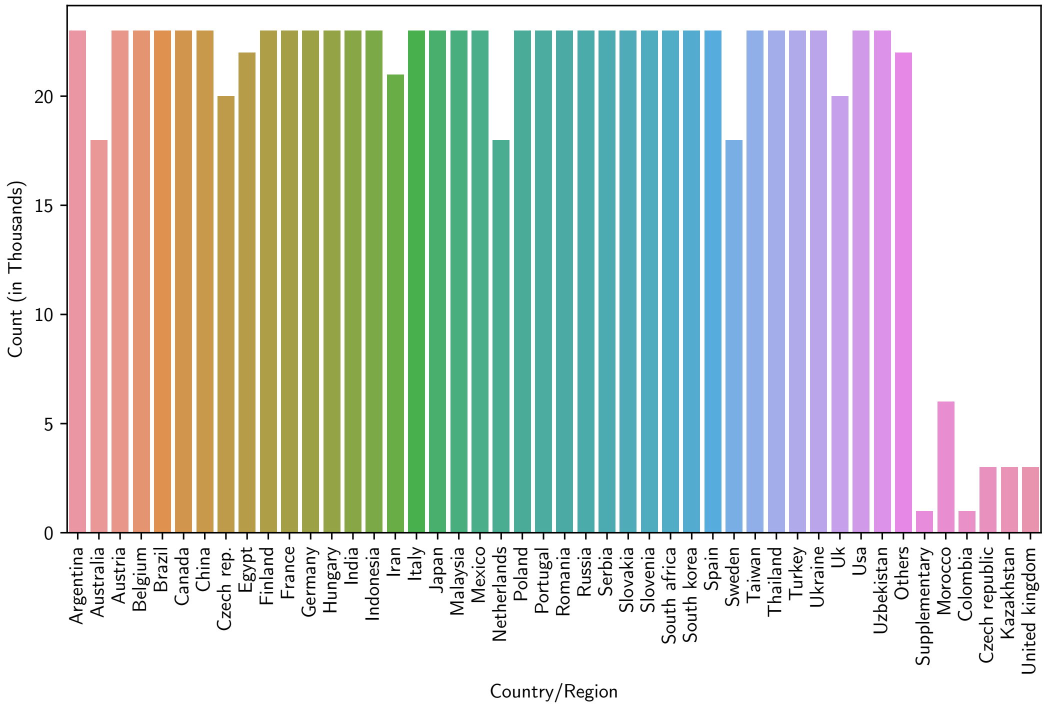

FIGURE 3.4: The Country wise Car Production Data Volume

2021, which can be attributed to the impact of the COVID-19 pandemic on the global economy and supply chains. Before the pandemic, the car production data consistently exhibited a rising pattern, reflecting the industry's expansion and increased demand for vehicles. The growth in car production signifies the continuous development and advancement of the automotive sector, driven by factors such as technological innovations, changing consumer preferences, and economic growth.

However, in 2020, the COVID-19 pandemic emerged as a global health crisis, leading to widespread disruptions in various industries, including automotive manufacturing. The pandemic-induced lockdowns, supply chain disruptions, and reduced consumer demand significantly affected car production worldwide. As a result, there was a significant decrease in the total car production compared to previous years. The impact of the pandemic continued to be felt in 2021, with car production remaining below the pre-pandemic levels. This decline in production reflects the challenges faced by the automotive industry in adapting to the new operating conditions and mitigating the effects of the ongoing crisis.

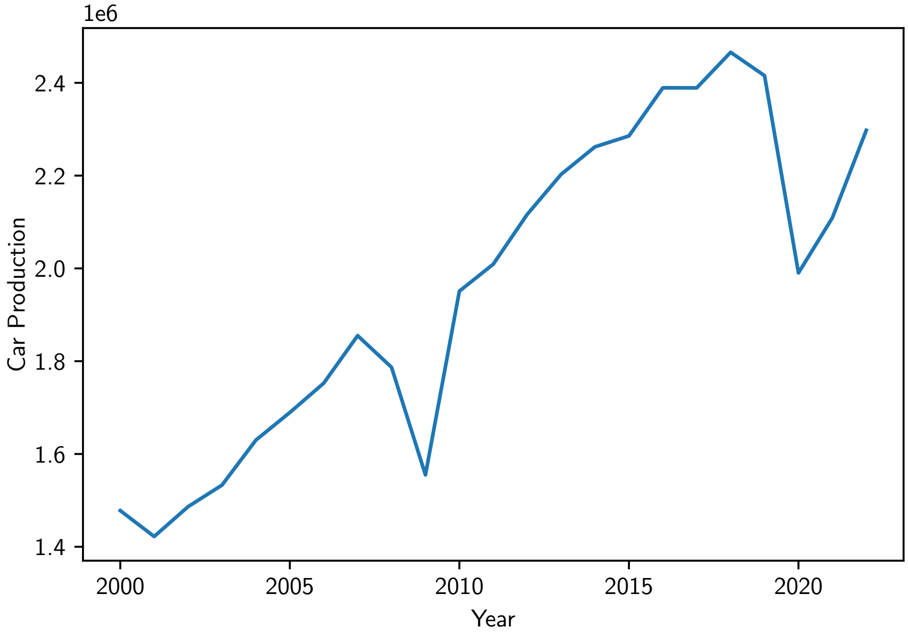

FIGURE 3.5: Total Yearly Car Production Data

CHAPTER IV

SILICON ALTERNATIVES, FUTURE OF CHIP MAKING

4.1 Introduction

For over half a century, silicon has been the foundational material underpinning the exponential advancement of semiconductor technology and computing power. First leveraged in transistors and integrated circuits in the 1950s, silicon offered an optimal combination of abundance, manufacturability, and electronic properties that facilitated its dominance across the semiconductor industry. Through continuous refinement, silicon has enabled the realization of successive generations of microprocessors and silicon wafers with ever-increasing performance and complexity. However, silicon is approaching both practical and economic limitations that motivate the exploration of complementary or even alternative materials that can propel the industry into the future.

While still poised to remain integral for years to come, silicon is reaching theoretical performance ceilings in critical parameters including switching speeds, power efficiency, and miniaturization potential. Simultaneously, the costs and complexity required for cutting-edge silicon fabrication facilities continue to skyrocket, posing challenges for ongoing innovation momentum and access. These weaknesses have catalyzed research into promising alternatives, ranging from elemental semiconductors like germanium to compound semiconductors such as gallium arsenide to novel two-dimensional materials including molybdenum disulfide. On the substrate side, materials like sapphire, glass, and various polymers have demonstrated potential manufacturing, cost, or flexibility advantages relative to traditional silicon wafers.

As silicon bumps against physical limits, the opportunity emerges to elevate successor materials that can unfetter the industry's trajectory. By assessing the contemporary research landscape regarding silicon alternatives, semiconductor manufacturers and technology leaders can make informed strategic pivots. The computing demands of emerging high-performance, mobile, and ultra-low power applications are unlikely to be fully addressed through silicon alone. The time has come to seek fresh semiconductor materials that can reignite the pace of innovation and usher the electronics industry into an upgraded era. This review aims to provide perspective on candidate materials and synthesize insights into manufacturing, integration, adoption timelines, and the overall importance of looking beyond silicon for future computing advances.

4.1.1 Background and Motivation

For decades, silicon has been the preeminent material underpinning the modern computing era. Starting in the 1950s, silicon technology enabled the development of the first transistors, integrated circuits, microprocessors, and silicon wafers. Silicon offered an optimal mix of abundance, manufacturability, and semiconducting properties that catapulted it to dominance in the semiconductor industry. Generations of steady refinement have led to today's highly advanced silicon-based microchips.

However, as Moore's Law approaches practical limits, the constraints of silicon technology have motivated research into complementary or even replacement materials. Even with incredible nano-scale engineering feats, silicon is nearing its theoretical performance limits in key aspects like switching speed and energy efficiency. Additionally, the skyrocketing costs and complexity required for next-generation silicon fabrication facilities have spurred interest in alternative materials and substrates. After decades of unquestioned dominance, silicon's future prospects face rising uncertainty (*Beyond Silicon - What will Replace the Wonder Material?* 2023).

Several promising semiconductor candidates have emerged to address the growing limitations of silicon technology. Elemental semiconductors like germanium and graphene offer enhanced transport properties compared to silicon. III-V compound semiconductors such as gallium arsenide and indium phosphide boast higher electron mobility and device switching speeds. And novel two-dimensional materials like molybdenum disulfide display intriguing possibilities for low-power electronics. On the substrate side, alternative materials like sapphire, glass and plastics are being investigated for potential advantages in manufacturability, cost, and flexibility compared to traditional silicon wafers. An enormous amount of research has coalesced around identifying and developing materials that can complement, or perhaps someday replace, silicon in next-generation semiconductor manufacturing. While silicon will certainly dominate the electronics landscape for years to come, its weaknesses have been clearly exposed. By thoughtfully assessing the current research landscape for materials poised to augment or succeed silicon, industry leaders can make informed strategic decisions and investments. The computing needs of the future, encompassing high-performance computing, ubiquitous smart devices, and ultra-low-power applications, are unlikely to be met solely by pushing silicon to its limits. The dawn of a new era of semiconductor materials has arrived.

The motivation behind newer research into alternatives to silicon is clear and compelling. Silicon's strengths are no longer unassailable in the face of shifting economic and technological realities. Vast opportunities await in identifying and elevating the next generation of semiconductor materials that will define the electronics, computing, and technological landscape for decades to come. With so much at stake, the semiconductor industry must proactively seek out promising successors to silicon's computing throne. The exalted but fading monarch awaits relief from promising princes like germanium, gallium arsenide, graphene, and beyond (Guisinger and Arnold, 2010).

4.1.2 Research Objectives and Scope

This research aims to thoroughly assess the current state of knowledge regarding emerging alternatives and complements to silicon for semiconductor applications. The exponential growth of computing power and ubiquity of microchips has been fueled by continuous advances in silicon technology. However, as the limitations of silicon become increasingly apparent, the industry is actively exploring new materials and manufacturing techniques that may eventually augment or supplant silicon. This research endeavor seeks to clearly map the silicon alternative landscape so that researchers, companies, and policymakers can chart informed strategies (Guisinger and Arnold, 2010).

The sheer breadth of active research into post-silicon materials necessitates careful delineation of scope. This review will focus primarily on assessing the most promising elemental, compound, and 2D semiconductors that have shown potential to match or exceed silicon's capabilities. For context, the properties and historical role of silicon will be briefly summarized, but silicon itself is not the central subject. Among the myriad semiconductor candidates, priority will be given to materials which have demonstrated viable transistor, logic gate, or integrated circuit operation. Additionally, the most common alternative substrate materials which could offer advantages over silicon wafers will be surveyed, including glass, sapphire, and various polymers.

Advanced manufacturing techniques that aim to extend silicon's capabilities, such as spintronics and gate-all-around FETs, fall outside the scope of this survey. The focus is restricted to materials that could plausibly serve as direct replacements, not stopgap enhancements. However, novel processing methods will be discussed in the context of improving the manufacturability of the materials under examination. The timeframe of interest spans from approximately the year 2000 onward, as contemporary research offers the most relevant insights into future trends. However, historical context will be provided where beneficial. The geographic scope encompasses worldwide research, although trends within specific regions will also be highlighted.

In terms of specific objectives, this review ultimately aims to synthesize perspectives on:

- The limitations of silicon that justify seeking alternative materials
- Criteria by which to evaluate viability and potential of alternatives
- The most promising elemental, compound, and 2D semiconductors based on recent research
- The relative merits and challenges of leading substrate options
- Manufacturing and integration issues influencing adoption prospects
- Likely future timescales for adoption within the semiconductor industry

- The importance of expanding beyond silicon for future computing advances

To accomplish these objectives, findings will be synthesized from a wide array of sources, including journal publications, conference proceedings, technology roadmaps, and market reports. Particular attention will be paid to the most recent results within the past 5 years. By integrating insights and perspectives from the full spectrum of contemporary research, this review will produce a comprehensive landscape analysis of silicon successor candidates.

4.2 Semiconductor Materials

In the chip making industry, silicon is one of the well suited material and being used for years. In this section we will analyze why silicon became so much useful and appropriate in this field of chip making and also analyze why we are facing issues in future chip making industry due to the silicon shortage.

4.2.1 Silicon, the most suited material in chip making

Silicon has been the foundational material enabling the exponential advancement of semiconductor technology over the past several decades. First leveraged in transistors and integrated circuits back in the 1950s, silicon offered an optimal combo of abundance, manufacturability, and electronic properties that facilitated its rise to dominance across the industry. Through ongoing refinement, silicon has permitted the realization of successive generations of microprocessors and silicon wafers with ever-increasing performance and complexity.

However, silicon is starting to bump up against both practical and economic limitations that are motivating the exploration of complementary or even alternative materials to propel the industry going forward. While poised to stay integral for years to come, silicon is aproaching theoretical ceilings in critical areas like switching speeds, power efficiency, and miniaturization potential. At the same time, the costs and complexity needed for cutting-edge silicon fabrication facilities continue to skyrocket, introducing challenges for ongoing innovation momentum and access.

These weaknesses have catalyzed research into promising alternatives, from elemental semiconductors like germanium to compound semiconductors such as gallium arsenide to novel two-dimensional materials including molybdenum disulfide. On the substrate side, materials like sapphire, glass, and various polymers have shown potential manufacturing, cost, or flexibility advantages compared to traditional silicon wafers.

As silicon starts bumping into physical limits, the opportunity opens up to elevate successor materials that can unfetter the industry's trajectory. By surveying the contemporary research landscape on silicon alternatives, semiconductor manufacturers and technology leaders can make informed strategic pivots. The computing demands of emerging high-performance, mobile, and ultra-low power apps are unlikely to be fully addressed through silicon alone. The time has come to seek out fresh semiconductor materials that can reignite the pace of innovation.

In this section, we will provide an overview of the properties and applications that have made silicon the dominant material in semiconductors. We will also discuss the limitations it is increasingly facing and how that is driving interest into alternatives. The potential and challenges of various alternatives will be introduced.

4.2.1.1 Use of Silicon in Chip Manufacturing

As discussed in the introduction, silicon has been the dominant material used in semiconductor chip manufacturing for over half a century. This is due to its unique properties that make it exceptionally well-suited for use in integrated circuits and transistors. Silicon is a semiconductor, meaning it conducts electricity under certain conditions but acts as an insulator under others. This enables it to readily switch between on and off states, which is essential for digital logic operations. Now let us explore how silicon is practically leveraged across the chip fabrication process.

The manufacturing of silicon chips begins with the purification of raw silicon in the form of sand. The sand is first melted, then refined through multiple steps to remove impurities. Trace amounts of elements like iron, aluminum, and calcium must be reduced to parts per billion levels to achieve the purity required. The refined molten silicon is then cast into cylindrical ingots, which are sliced into thin circular wafers about 300mm in diameter forming the foundation for chips (Zortman, Trotter, and Watts, 2010).

A critical next step is growing a thin silicon dioxide layer on the wafer surface. Silicon dioxide, commonly known as silica, acts as an electrically insulating material separating the future transistor components from the base silicon. This is accomplished by exposing the wafers to oxygen at high temperature in a process called thermal oxidation. The resulting silicon dioxide layer protects the wafer from contamination during subsequent processing.

Photolithography is next used to transfer the intricate circuit patterns onto the silicon wafer. This optical lithography process projects light through a mask containing the required chip layouts onto a light-sensitive material coating the wafer. The exposed photoresist material is either hardened or softened, allowing precise regions to be selectively etched away, leaving only the desired circuit paths (Zortman, Trotter, and Watts, 2010; Lim et al., 2014).

Dopant atoms like phosphorus or boron are then implanted into the exposed silicon features to alter the semiconductor's electrical properties in precise areas, forming the source, drain and gate regions of transistors. Ion implantation accelerates dopant ions into the wafer surface, allowing precise control of their distribution. The dopants change silicon from an insulator to a conductor in defined locations based on the etched pattern.

The final front-end step is transistor fabrication. Alternating layers of conductive and insulating materials are deposited and etched to create the transistors' physical structures. The wafer backplane is also metalized to facilitate electrical contact. The individual transistors are then interconnected by thin metal wires through back-end metallization processes. The completed chips are tested, cut from the wafer, and packaged onto protective frames (Moguilnaia et al., 2005).

In short, silicon provides the ideal blank canvas for chip manufacturing thanks to its elemental semiconductor properties. With robust purification, thermal oxidation, photolithography, ion implantation, and precision materials processing, silicon wafers can be transformed into the complex integrated circuitry powering the digital age. The scale and sophistication of silicon chip fabrication represents one of humanity's greatest manufacturing achievements

4.2.1.2 Advantages of Using Silicon

As explored in the prior sections, silicon possesses a number of properties that have made it the material of choice for semiconductor fabrication over the past several decades. Let us examine these advantages in more detail to understand why silicon has dominated integrated circuit manufacturing. Let us talk about a few key factors which makes silicon a truely advantegeous material in chip making.

Abundance, The relatively high natural abundance of silicon is a major factor in its long-standing suitability for mass chip production. Silicon is the second most abundant element in the Earth's crust, making up over 25% of the crust by mass. It does not need to be mined but is readily extracted from common sand or quartz. This widespread availability of raw silicon contributes to lower materials costs compared to rare semiconductors. Higher purity silicon for electronics can be economically produced in large volumes without supply concerns.

Semiconducting Properties, The intrinsic semiconducting properties of silicon enable its transformation into the variety of active and passive circuit components needed to realize integrated functions. Silicon's four outer shell valence electrons bond covalently with neighboring atoms, yet can still move somewhat freely as charge carriers. By adjusting silicon's purity and introducing tiny quantities of doping atoms, its conductivity can be finely tuned between insulating and metallic states. This control of conductivity lends itself ideally to fabricating the kinds of diodes, transistors, capacitors, resistors and inductors found in chips (Maning, 2023; *Semiconductors | University Wafer*$_2$018 2023).

Processability, In addition to its fundamental semiconductor properties, silicon also benefits from decades of process refinement in device fabrication. The ability to obtain large high-purity single silicon crystal ingots makes it possible to slice many wafers with consistent properties. Established processes like thermal oxidation, photolithography, etching, doping, and thin film deposition can be repeatedly performed on silicon wafers to obtain desired results. This process engineering mastery enables the mass production of silicon integrated circuits.

Robustness, Silicon also possesses favorable mechanical and chemical robustness properties relevant for chip manufacturing and operation. It has a high melting point of 1414°C enabling processing steps like diffusion and oxidation at elevated temperatures. Silicon's strong atomic bonds also make it highly resistant to corrosion and reactions with water or air. This helps maximize chip yield during fabrication and reliability once packaged. Compared to other semiconductors, silicon's superior durability is better suited for real-world introduction (Maning, 2023).

Cost Effectiveness, The combination of abundant raw supply, high manufacturability, and process maturity makes silicon very cost-effective for large-scale chip production. The capability to fabricate complex integrated circuits containing millions of transistors on silicon has far outpaced any other semiconductor material. As a result of economy of scale, the cost per functioning silicon transistor today can be less than a hundredth of a cent. This low cost enables the integration of sophisticated silicon chip circuitry into consumer devices of all types.

Silicon provides the right mix of fundamental properties, real-world practicality, manufacturability at scale, and cost-effectiveness that has solidified its role as the workhorse material of semiconductor technology. The electronics industry has been precisely engineered around exponentially advancing silicon's capabilities to create today's ubiquitous computing landscape.

4.2.1.3 Challenges in using Silicon

While silicon possesses clear advantages that have made it the dominant material in semiconductors, it is increasingly facing fundamental limitations. As discussed earlier, silicon is approaching theoretical performance ceilings in key aspects like switching speed, power efficiency, and miniaturization. Let us explore these challenges confronting the continued reliance on silicon into the future.

Difficulty Miniaturizing Transistors: For decades, the semiconductor industry has upheld Moore's Law, with the number of transistors packed onto integrated circuits doubling about every two years. This exponential growth has been sustained through relentless miniaturization of silicon transistors to smaller nanometer scales. However, silicon is nearing the physical limits of how tiny transistor components can get before collisions with electrons and quantum effects disrupt reliability. At the leading edge, transistor features today measure just several nanometers wide. Achieving this has required complex multi-patterning of silicon wafers during photolithography to circumvent diffraction limitations. But transistor leakage current rises dramatically with each new node, eroding energy efficiency gains. Further incremental miniaturization of silicon devices to maintain historical scaling is proving increasingly difficult.

Limitations for High Speed/Low Power Chips, The inherent material properties of silicon also impose performance restrictions as transistors shrink to microscopic scales. Silicon has a relatively poor electron and hole mobility compared to other compound semiconductors. This limits the speed at which charge carriers can move through transistors and interconnects. Additionally, silicon has a moderate bandgap wavelength that leads to substantial thermally generated leakage current at small scales. These combined factors make it challenging for silicon chips to deliver both the high speeds and low power consumption demanded by leading-edge applications. The interconnects between the billions of transistors dissipate significant dynamic power from charge and discharge. While new architectures help, power density remains a limiting factor going forward for silicon microprocessors and memory chips.

Economics of Scaled Fabrication, As silicon transistors approach atomic dimensions, the foundry costs associated with their fabrication have skyrocketed. Cutting-edge lithography, deposition, etch, implantation and metrology tools needed to pattern nanometer features require substantial upfront capital investments. The complexity of defect-free high-volume silicon nanofabrication together with low yield requirements has rapidly raised the bar for building new facilities. The costs associated with pushing silicon fabrication to the next node could become prohibitive for sustaining the historical pace of Moore's Law. The technical challenges may require complex patterning and vertical stacking techniques that could neutralize silicon's cost advantage. Maintaining historical scaling trajectories with silicon is looking increasingly economically impractical.

Interrelated technical hurdles, power and performance limitations, and fabrication economics pose threats to the continuation of Moore's Law using conventional bulk silicon transistors alone. While silicon will retain dominance for complex chips in the near future, these challenges necessitate consideration of supplementing or eventually supplanting silicon with superior semiconductor options.

4.2.1.4 Alternatives to Silicon

Given the challenges confronting further scaling of silicon described earlier, research has intensified into exploring semiconductor alternatives. These materials offer potential advantages over silicon that may enable the continuation of Moore's Law-level advances in integrated circuit capabilities. Let us survey some of the promising options being investigated as complements or successors to silicon.

Gallium Nitride, Gallium nitride (GaN) has emerged as a leading candidate thanks to its superior electron mobility and higher critical electric field strength compared to silicon. This makes GaN suitable for high-frequency, high-power transistor applications where silicon faces limitations. GaN has over double the electron mobility enabling faster switching speeds. The wider bandgap of GaN also means lower leakage current for given device dimensions. While most GaN research has focused on discrete power transistors, progress is being made on integrating more complex GaN circuitry monolithically. Approaches for building GaN transistors on silicon wafers have also been demonstrated, offering a pathway for hybrid integration. However, defect reduction remains a key hurdle for GaN nanoelectronics. The associated costs for epitaxial growth on silicon also need to decrease for broader adoption. But GaN's properties show encouraging potential for next-generation microwave components and power electronics (Manocha, Kandpal, and Goswami, 2020).

Carbon Nanotubes, Carbon nanotubes (CNTs) are another emerging candidate thanks to their nanoscale structure and superior electrostatic control. Metallic and semiconducting CNTs can be synthesized using chemical vapor deposition. Aligning and precisely placing individual CNTs on substrates still remains a challenge. But progress has been made in constructing basic CNT field-effect transistors with excellent switching behavior and current density exceeding silicon and GaN. CNTs have the potential for ballistic transport of electrons thanks to the strength of their sp2 carbon bonds. This could enable new paradigms in low-voltage nanoelectronics. Their nanometer diameter also means outstanding electrostatic control for reduced short-channel effects as transistors shrink. However, manufacturability and integration of CNT components into viable large-scale circuits still remains far from commercial viability currently (Kalkandjiev et al., 2011).

2D Materials, Transition metal dichalcogenides (TMDCs) like molybdenum disulfide have also arisen as intriguing 2D semiconductor options. TMDCs can be either metallic or semiconducting depending on their structure. They offer thickness-dependent bandgaps enabling tunable optoelectronic properties. While TMDCs face similar manufacturability challenges as CNTs, their strong in-plane bonds and electronic flexibility make them promising candidates for future high-performance devices (Manocha, Kandpal, and Goswami, 2020; Saraswat, 2020).

These represent just a sample of the emerging alternatives under investigation to address the limitations of silicon computing. Each material exhibits advantageous electronic properties but also has associated process integration and manufacturability challenges yet to be overcome. Further research and development is still required to assess their ultimate viability as successors to silicon for next-generation electronics.

4.2.1.5 Reducing Silicon Use

The prior sections examined the challenges confronting the continued scaling of silicon integrated circuits along with some of the alternative materials being researched. But there are also avenues for reducing silicon's usage within certain components or developing hybrid approaches to sustain the industry's rapid advancement. Let us explore some ways silicon consumption may be minimized moving forward.

Alternative Materials in Select Components, Rather than wholly replacing silicon transistor technology, emerging materials can be strategically integrated just for specific circuit components requiring their advantages. For example, a chip may use silicon CMOS logic but employ GaN or CNT elements for particular high-frequency functions where higher speed is needed. Or sensitive analog amplifiers on a silicon chip could leverage graphene components to lower noise. By judiciously substituting alternative materials only where their strengths are required, overall silicon usage can be optimized on a single chip. This fabless approach leverages new materials but avoids the daunting task of fully reengineering billion-transistor designs. It also reduces the manufacturability burdens for new materials down to just specialized components (Keyes, 2001).

Thinner Silicon Structures, Another concept for reducing silicon usage is pushing its physical dimensions down through thinner substrate wafers and multi-gate transistor structures. Manufacturing methods for reliably producing silicon-on-insulator (SOI) wafers with just 10-25 nm thick silicon layers have been developed. Using SOI as a base substrate reduces silicon volume by over 50% compared to conventional wafers. SOI also helps cut substrate leakage allowing lower-voltage operation. In transistors, new gate-all-around architectures utilize nanosheet or nanowire channels with silicon thicknesses below 10 nm. By moving from planar to 3D structures, the volume of silicon required per transistor is significantly decreased. Combined with SOI substrates, these advanced transistor architectures could achieve dramatic silicon reduction. However, their manufacturability at scale still presents cost and production challenges currently (Saxenian, 1991).

Chip Design Optimization, In addition to materials and structures, the architectural design of chips can also be optimized to curtail unnecessary silicon usage. Techniques like near-threshold voltage computing minimize power density, enabling scaled-back silicon geometries. Simplifying interconnect fabrics reduces routing demands that necessitate silicon area. Reconfigurable logic units can also maximize hardware reuse compared to fixed-function silicon logic blocks. Design strategies focusing on energy efficiency and functional optimization allow the same computing output to be achieved with less silicon. For example, neuromorphic architectures built around spiking neurons mimic brain information processing far more efficiently than silicon neural networks using multiply-accumulate operations. Rethinking chip design itself is key for reducing silicon needs (Hahn, 2001).

Leveraging alternative materials in targeted components, pioneering advanced thin-body structures, and optimizing chip architectural design offer paths to maintaining the performance trajectory with less silicon. These approaches build on silicon's established role while incrementally decreasing its usage where possible. They can balance cost-effectiveness with diminishing fabrication challenges going forward. The longevity of silicon technology will likely be extended through these hybrid heterogeneous integration techniques.

4.2.1.6 Coping with Chip Shortage

The ongoing global chip shortage has severely disrupted many industries that rely on access to semiconductors. With demand far outstripping supply, strategies are needed to help mitigate the shortage. Let's explore approaches both semiconductor manufacturers and consumer product companies are adopting to cope with constrained chip inventories.

Renegotiating Contracts

A starting point is for chip buyers to renegotiate existing supply contracts with manufacturers to secure more capacity. Making advanced volume commitments helps justify manufacturers allocating more production lines. Willingness to accept partial shipments or delayed delivery also provides flexibility. Guaranteeing higher per-unit pricing can incentivize suppliers to prioritize certain customers. These contractual changes help firms get the best possible chip allotments within tight supply scenarios (Mouré, 2022).

Redesigning Products, On the consumer side, companies are redesigning products to reduce or eliminate dependence on scarce components. This involves hardware and software reconfiguration to find workaround approaches using available chips. While redesign comes at a high engineering cost, it allows production to continue despite specific shortages. The goal is to flexibly adapt designs within the constraints of currently accessible semiconductors.

Component Substitution, Where outright redesign is infeasible, substituting alternative interchangeable components for those facing shortages can help. Quality and performance may be impacted, but some degree of modification is possible through extensive compatibility testing. This does however require broad pre-validation of potential backup components, adding cost even during periods of normal supply. The feasibility also depends on programmability of the end products (Heinrich, 2002).

Production Optimization, Manufacturers are also optimizing production operations for maximum output under limited chip inventories. This entails prioritizing high-demand, high-margin models and pausing low-volume products. Conserving chip usage in storage, logistics and distribution helps preserve supply. Joint ventures between companies allow combining orders to suppliers for added leverage. Allocating scarce chips to customers likely to wait for reorders also helps sustain business.

Inventory Buffering, Building inventory buffers and improving visibility into the supply chain is crucial for weathering shortages. Maintaining safety stocks of critical components mitigates disruption from supply instability. Where possible, purchasing and stocking excess chips while available helps ride out demand spikes. Securing supply commitments well beyond normal horizons provides insulation even at increased costs. The agility and resilience of procurement teams is vital for succeeding in the current climate (Heinrich, 2002).

With the combination of contractual flexibility, product redesign, component substitution, production optimization, and inventory buffering represents crucial coping techniques. A mindset of agility and adaptation is required to balance meeting customer needs with supply realities. While shortages may persist, these approaches help reduce business disruption. And they can be deployed temporarily as needed during periods of severe supply-demand imbalance to enable continuity.

4.2.2 Elemental Semiconductors

Among the alternatives to silicon being explored, elemental semiconductors like germanium and carbon offer prospects for enhanced performance. As foundational materials, refining and capitalizing on their innate electronic properties through elemental modification represents a promising research direction.

4.2.2.1 Germanium

Germanium has long been studied as a semiconductor material, with roots as an early transistor material in the 1940s before silicon rose to dominance in subsequent decades. However, germanium possesses innate properties that continue to warrant revisiting for specialized applications.

As a metalloid with four valence electrons, germanium exhibits semiconducting behavior amenable to transistor and circuit fabrication. Key advantages of germanium include high carrier mobility and a relatively narrow bandgap. The high mobility enables faster switching speeds, while the smaller bandgap allows for lower voltage operation. These attributes motivated the early adoption of germanium in transistors.

Nonetheless, silicon proved superior for broader adoption, offering greater abundance, lower cost, and easier manufacturability. Silicon also benefited from continuous enhancement and refinement of fabrication techniques designed specifically for its properties. This allowed silicon performance and scale to eventually surpass germanium capabilities (Benedikovic et al., 2021).

However, as silicon approaches scaling limits, germanium merits re-examination given fabrication advances and demonstrations of microscale devices with promising switching speeds. Research has shown top-gated germanium nanowire transistors with cutoff frequencies over 135 GHz. Furthermore, germanium integration directly on silicon substrates has been demonstrated, presenting a pathway for augmenting silicon ICs.

While unlikely to wholesale replace silicon, the integration of germanium devices for specialized performance-critical on-chip components remains a realistic prospect. Key challenges that persist include lower thermal stability and poorer interface quality relative to advanced silicon dioxide dielectrics. Nonetheless, ongoing efforts to grow or deposit high-quality germanium films with controlled doping represent encouraging progress (Curtolo, S. Friedrich, and B. Friedrich, 2017).

In optical communication applications, germanium also offers transparency in infrared wavelengths combined with potential for integration with silicon photonic devices. This further expands the range of prospective applications where germanium's properties can complement silicon (Curtolo, S. Friedrich, and B. Friedrich, 2017).

In summary, germanium's fundamental advantages for mobility, bandgap, and optics continue to merit attention as limitations of scaled silicon come into view. While commercial adoption remains limited, steady materials and fabrication improvements on multiple fronts suggest germanium will find increasing specialized niches, particularly in heterogeneous integration with silicon substrates. Ongoing germanium research promises to further unlock its performance potential.

4.2.2.2 Carbon

Carbon is an abundantly available elemental material that manifests a range of allotropes exhibiting diverse electronic properties. Selectively utilizing specific forms of carbon enables researchers to surpass limitations of silicon for next-generation semiconductor applications. The most promising carbon allotropes explored for electronics include graphene, carbon nanotubes, and diamond (Wei et al., 2013).

Graphene, a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice, has attracted enormous interest for nanoelectronic applications. Graphene possesses extremely high carrier mobilities exceeding 15,000 cm2/Vs even at room temperature along with thermal conductivity surpassing that of diamond. Additionally, graphene remains stable and conductive down to the nanometer scale (Close et al., 2008).

These exceptional traits make graphene a promising candidate material for ultra-fast transistors and circuits. However, pristine graphene lacks an intrinsic bandgap, posing challenges for achieving complete transistor switching. Ongoing research has focused on opening tunable bandgaps in graphene through techniques like nanostructuring, functionalization, and bilayer twisting. For instance, graphene nanoribbon transistors with engineered bandgaps have shown current modulation greater than 100x, indicating potential for switching behavior (Close et al., 2008).

Graphene's remarkable mechanical strength also lends itself to flexible electronics applications. Graphene films deposited on flexible plastic substrates have supported repeated bending cycles without losing conductivity. Combined with graphene's optical transparency, this opens possibilities for technologies like wearable displays and sensors. However, issues with manufacturing scale-up have thus far impeded commercial adoption. Progress is being made on large-area graphene growth using chemical vapor deposition, with continuous films up to 30 inches demonstrated.

Carbon nanotubes, comprised of concentric rolled up graphene sheets in single-walled or multi-walled configurations, offer similar advantages to graphene along with tunable geometry. Varying the diameter and chiral angles of carbon nanotubes produces electronic behavior spanning metallic to semiconducting. Researchers have fabricated carbon nanotube field-effect transistors with cut-off frequencies exceeding 450 GHz, showing potential for ultra-high frequency operation (Sharma and Ahuja, 2008).

A persistent challenge lies in large-scale sorting and assembly of purely semiconducting carbon nanotubes. Current synthesis techniques produce a mixture of metallic and semiconducting nanotubes. However, progress in density gradient ultracentrifugation has enabled sorting by electronic type. Aligned arrays of solely semiconducting nanotubes have permitted fabrication of wafer-scale integrated circuits and flexible nanotube electronics.

Finally, diamond as an ultrawide bandgap semiconductor has potential for electronics operating at high power, frequency, and temperature exceeding silicon limits. Diamond transistors leveraging selective doping have shown output powers above 100W. However, reproducible doping and junction formation in diamond remain ongoing challenges. Further research into controlled in-situ doping and surface passivation could enable unlocking the full potential of diamond (Sharma and Ahuja, 2008).

4.2.3 Compound Semiconductors

Compound semiconductors are formed through combining two or more elemental semiconductors together. The resultant materials often demonstrate enhanced properties compared to their constituent elements alone. This has driven extensive research into utilizing compound semiconductors for specialized applications where silicon limits performance (Alamo, 2011).

One extensively studied binary compound is gallium arsenide (GaAs), formed by gallium and arsenic. GaAs offers higher electron mobility compared to silicon, enabling transistors to switch faster. Its wider bandgap also allows lower voltage operation. GaAs emits light efficiently when electrons transition its direct bandgap, making it useful in LEDs and lasers. These properties have enabled adoption of GaAs in high-speed electronics and optoelectronics. However, drawbacks like higher cost and fragility have limited its mainstream penetration (Alamo, 2011).

Another promising III-V compound semiconductor is gallium nitride (GaN). GaN has an even wider bandgap than GaAs, providing advantages for high power, high frequency applications. The chemical inertness of GaN also makes it suitable for harsh environments. While GaN devices are still maturing, early adoption in areas like radio frequency amplifiers illustrates its potential. Reducing defects and wafer costs remain challenges for broader GaN adoption.

Indium phosphide (InP) is a binary III-V compound formed from indium and phosphorus. InP offers high electron velocities and a direct bandgap making it well-suited for high-speed electronics and photonic devices. InP lasers, detectors and transistors enable fiber optic telecommunication networks to transmit terabits of data daily. However, limited raw material availability and fragility impede wider InP utilization. But for niche applications benefiting from its superior transport properties, InP will continue flourishing. Here in this subsection we will see the usage, benefits, limitations and other properties of these compound semiconductors deeply (Vurgaftman, Meyer, and Ram-Mohan, 2001).

4.2.3.1 Gallium Arsenide

As discussed in the prior section, compound semiconductors offer promising performance improvements over silicon. One of the most widely researched binary III-V compounds is gallium arsenide. Formed by combining gallium and arsenic, GaAs possesses a number of attractive properties that have enabled adoption in specialized applications.

GaAs is a direct bandgap semiconductor with a bandgap of 1.42 eV. This enables efficient emission of light as electrons directly transition the conduction band minimum to valence band maximum. This makes GaAs well-suited for optoelectronic devices like light emitting diodes and laser diodes. The emitted infrared photons also match the low-loss telecommunications wavelength of 1.5 microns, facilitating use of GaAs lasers in fiber optic networks. In addition to its direct bandgap, GaAs also exhibits an electron mobility over five times higher than silicon. This higher mobility allows GaAs transistors to operate at much higher frequencies compared to silicon devices. GaAs transistors can switch on and off over 250 billion times per second, enabling microwave operation. This combination of bandstructure and transport makes GaAs ideal for RF electronics (Murakami, 2002).

Furthermore, the strong atomic bonds of GaAs impart robustness and chemical stability. The high melting point of 1238°C facilitates processing steps like ion implantation. Resistance to erosion makes GaAs suitable for deployment in harsh environments like space and military applications. These merits supplement the performance advantages of GaAs for electronics. However, GaAs does suffer disadvantages that have constrained its mainstream adoption. The limited abundance of gallium restricts supply, keeping costs higher than silicon. Additionally, the brittle mechanical properties of GaAs makes wafer handling more difficult. Nonetheless, for applications benefiting from its advantages, GaAs delivers performance justifying its niche usage (Murakami, 2002; Schoenberg et al., 1997).

Some of the key application areas where GaAs shines include:

- High-frequency transistors for telecom/radar

- Low-noise microwave amplifiers
- Laser diodes for optical data transmission
- LEDs for efficient solid-state lighting
- Multi junction solar cells with high efficiencies Power electronics and RF switching devices

While silicon remains the workhorse semiconductor for mass-produced microelectronics, GaAs offers differentiated capabilities that silicon cannot match. As GaAs material quality and manufacturing methods continue advancing, adoption will keep increasing in areas like wireless communications, LIDAR systems, and renewable energy. The future appears bright for this versatile III-V compound.

There are many different reasons for which GaAs are being used in semiconductor technology. Let us explore why we need such alternative in a better way. The compound semiconductor gallium arsenide (GaAs) possesses certain advantageous properties that have enabled its adoption in specialized chip manufacturing applications. Let us explore in more detail the specific benefits of GaAs that make it well-suited for a variety of cutting-edge devices and circuits. It has some great features, which we are covering here in detail.

High Electron Mobility, The electron mobility of GaAs is over five times higher than that of silicon, reaching up to 8500 cm2/Vs. This enables GaAs transistors to switch on and off at exceptionally fast speeds exceeding 250 billion transitions per second. The higher carrier velocity allows GaAs integrated circuits to operate at microwave frequencies unattainable by silicon. These high-frequency capabilities make GaAs ideal for RF electronics needed in radar systems, satellite communications, and more (Sturgill, Swartzbaugh, and Randall, 2000).

Wide Bandgap, GaAs has a bandgap of 1.42 eV, nearly 50% wider than silicon's 1.1 eV bandgap. This wider gap means lower likelihood of thermally excited carriers generating leakage currents that waste power. The reduced leakage results in lower noise and higher output resistance for GaAs devices. A wider bandgap also enables higher breakdown voltages important for power electronics. These attributes facilitate adoption of GaAs in low-noise amplifiers and power management applications.

Direct Bandgap, The direct bandgap of GaAs makes transitions between the conduction and valence bands more probable, enabling efficient light emission desired in LEDs and lasers. This allows GaAs optoelectronic devices to operate at lower thresholds and convert electrical signals to optical signals with minimal loss. GaAs' direct bandgap underpins its ubiquity in telecommunication laser diodes and other photonic applications, (Robinson, 1986).

Radiation Hardness, The crystalline structure of GaAs makes it resistant to radiation damage. High-energy protons, neutrons and ions in space that readily damage silicon have much reduced impact on GaAs. This radiation hardness allows GaAs devices to operate in harsh space environments unachievable by conventional silicon electronics. Satellite systems and space exploration missions leverage this resilience.

Thermal Conductivity, GaAs exhibits a thermal conductivity of 55 W/mK, nearly four times higher than silicon's. This enables more effective heat dissipation in GaAs devices, reducing thermal hotspots. Maintaining lower junction temperatures improves reliability and lifetime for chips and circuits. This thermal management capability facilitates adoption in systems requiring high device densities and output powers (Robinson, 1986).

Gallium arsenide's excellent transport properties, efficient light emission, radiation hardness, and thermal conductivity make it advantageous for specialized applications from fiber optic networks to satellite payloads. As GaAs technology continues maturing, its unique benefits will enable ever broader utilization. Let us see some of the great advantages along with limitations of GaAs in semiconductor technology.

Gallium arsenide (GaAs) possesses several key properties that give it advantages over silicon as a semiconductor material for specialized applications. Firstly, GaAs has an electron mobility exceeding 8,500 cm2/Vs, which is more than five times higher than silicon's mobility. This enables GaAs transistors and integrated circuits to operate at extremely high frequencies over 250 GHz, facilitating their use in microwave radar and communications electronics where silicon is too slow. The higher electron velocity in GaAs translates to quicker switching speeds in transistors and circuits. Secondly, GaAs has a wider bandgap of 1.42 eV compared to silicon's 1.1 eV bandgap. The wider bandgap reduces leakage currents and noise in GaAs devices, while also allowing higher voltage operation. Lower leakage results in higher output resistance and less wasted power dissipation due to stray currents. Higher breakdown voltages also enable GaAs to be utilized in power electronics and devices. Thirdly, the direct bandgap of GaAs allows efficient emission of light as electrons directly transition between the minimum conduction band and maximum valence band energy levels. This makes GaAs well-suited for optical devices like LEDs and laser diodes that require light emission from electrical injection. GaAs optics form the backbone of fiber optic telecommunication networks and CD/DVD players. Finally, the crystalline structure of GaAs imparts resistance to radiation damage, allowing it to function in harsh environments with high energy protons, ions, and electrons that would rapidly degrade silicon electronics. This radiation hardness permits utilization of GaAs for satellite, spacecraft, and military systems where resilience is critical (Cowley and Jones, 1989).

Besides these advantages, there are some great limitations of Gallium Arsenide. While gallium arsenide provides significant performance improvements beyond silicon in certain areas, it also possesses some disadvantages that have constrained its mainstream adoption. One major disadvantage is the high cost of GaAs wafers and epitaxial growth, which remains substantially higher than silicon wafer costs. This stems from the rarity of gallium, which must be separated from bauxite ore. Arsenic used in GaAs fabrication is also hazardous and toxic, necessitating costly handling procedures. Together these factors keep GaAs pricing elevated, restricting widespread use. Secondly, the mechanical fragility and brittleness of GaAs makes device fabrication more challenging. GaAs wafers are more prone to fracture during processing steps like ion implantation. This lowers yields compared to hardy silicon wafers. Extra precautions are needed during GaAs device handling and assembly. Additionally, GaAs readily oxidizes when exposed to air, unlike the native passivation of silicon in SiO2. This requires additional surface passivation steps like sulfidization during GaAs device fabrication to control oxidation. Unwanted oxidation can degrade performance in GaAs electronics. Finally, integration of GaAs devices directly with silicon is constrained due to the thermal expansion coefficient mismatch between the two materials. This restricts monolithic integration of GaAs components onto silicon integrated circuits. Adoption requires packaging of GaAs devices separately from silicon ICs (Khan et al., 2005).

While these disadvantages preclude the widespread adoption of GaAs for everyday mass-produced electronics, its unique performance benefits for RF, optoelectronic, and radiation-hard applications justify its targeted usage in specialized devices.

4.2.3.2 Indium Phosphide (InP)

Indium phosphide (InP) is a III-V compound semiconductor formed by combining indium and phosphorus that demonstrates properties making it well-suited for specialized high-speed electronic and optoelectronic devices. Like gallium arsenide, InP possesses a direct bandgap that enables efficient conversion between electrical and optical signals. But with a smaller bandgap of 1.34 eV compared to GaAs' 1.42 eV, its infrared emission wavelength of 920 nm is useful for long-haul fiber optic telecommunications as this region suffers lower optical fiber transmission losses. The direct bandgap facilitates development of InP lasers and LEDs that serve as light sources for optical communication networks.

In addition to its direct bandgap optics, InP also exhibits extremely high electron mobilities exceeding 5000 cm^2 Vs, surpassing even GaAs. This enables InP transistors and integrated circuits to reach operational frequencies exceeding 500 GHz, beyond the capabilities of silicon or GaAs devices. The fast transport properties arise from the high saturation velocity and high peak velocity of electrons in InP. Combined with high breakdown voltages, these electrical characteristics make InP an ideal material for ultrafast electronic devices pushing beyond silicon's speed limits (Klamkin et al., 2018).

Furthermore, InP demonstrates good thermal conductivity comparable to GaAs at around 70 W/mK. This thermal transport proficiency allows effective heat dissipation from high power and high device density InP circuits. Maintaining lower chip temperatures improves long-term reliability. This ability to manage heat generation supplements InP's credentials for microwave and millimeter-wave electronics where amplifier linearity must be preserved at high output powers.

Additionally, the bandstructure of InP is amenable to achieving both n-type and p-type doping at high concentrations exceeding 10^{19} cm^{-3}. This facilitates creation of low-resistance ohmic contacts that minimize voltage drops into and out of devices. Combined with advanced crystal growth techniques like molecular beam epitaxy, abrupt, highly doped InP layers can be synthesized. These doping and contact benefits further aid adoption of InP for high-frequency electronics (Raghavan, Sokolich, and Stanchina, 2000; Tol et al., 2014).

Some of the key application areas where InP is being deployed include fiber optic laser diodes for long-haul telecommunication networks, high-speed photodetectors, heterojunction bipolar transistors for RF amplification, high electron mobility transistors for low-noise microwave amplifiers, monolithic microwave integrated circuits, and thermo-photovoltaic energy conversion.

However, some challenges exist with InP adoption. As a relatively scarce element, indium costs are substantial, constraining more widespread usage. Furthermore, the brittle and soft crystalline structure of InP makes wafer handling very difficult, necessitating extra care during device processing. Nonetheless, for applications where ultrafast operation, direct bandgap optics, and high breakdown voltages are critical performance parameters, InP provides differentiated capabilities beyond conventional semiconductors like silicon and GaAs. Continued improvements in material quality and device fabrication techniques will enable fully harnessing its potential (Raghavan, Sokolich, and Stanchina, 2000).

Now the question comes, why Indium Phosphide could be an interesting material in Chip Manufacturing? As discussed in the prior section, the compound semiconductor indium phosphide demonstrates some compelling properties that make it advantageous for certain specialized chip manufacturing applications. Let us delve deeper into the specific benefits of InP that enable cutting-edge optoelectronic and electronic devices.

High Electron Mobility, The electron mobility of InP exceeds 5000 cm2/Vs, surpassing gallium arsenide and more than ten times higher than silicon. This extreme electron velocity allows InP transistors and circuits to operate at very high frequencies exceeding 500 GHz, enabling terahertz-scale speeds unattainable by conventional semiconductors. The swift transport arises from intrinsic material properties like high electron saturation velocity. For applications pushing the boundaries of microelectronic speed, InP shines (Klamkin et al., 2018).

Direct Bandgap Emission, The 1.34 eV direct bandgap of InP enables efficient conversion of electricity into infrared light at 920 nm, perfectly matched to minimum loss windows in silica optical fibers. This allows InP lasers and LEDs to serve as compact, efficient light sources for fiber optic telecommunication networks. InP's direct gap optics provides higher radiative efficiency for light emission compared to indirect gap materials like silicon or germanium.

High Breakdown Voltage, InP exhibits electric field breakdown voltages over three times higher than GaAs. This permits InP devices to operate at higher voltages without undergoing electrical breakdown. Combined with high mobility, this quality suits InP for high-power microwave electronics. The high breakdown strength also facilitates wide depletion width diodes for low-capacitance applications.

Thermal Conductivity, The thermal conductivity of InP approaches 70 W/mK, comparable to GaAs. This proficiency in heat dissipation allows high power densities to be achieved in InP circuits without overheating. Maintaining lower device temperatures improves long-term reliability. This thermal transport capacity complements InP's high speed advantages.

Doping and Contacts, Both n-type and p-type doping above 10^{19} cm^{-3} can be readily achieved in InP using silicon and zinc respectively. This high free carrier concentration facilitates low resistance electrical contacts essential for high-frequency devices. Ohmic contact resistance is minimized (Tol et al., 2014).

The remarkable electron mobility, direct bandgap emission, high breakdown strength, good thermal conductivity, and versatile doping of InP make it advantageous for specialized high-speed electronics and optoelectronics pushing performance barriers. As material and fabrication techniques advance, InP will find expanding niches exploiting its impressive capabilities.

If we talk about the advantages and limitations of InP, we can get a few different points. Indium phosphide (InP) possesses several crucial properties that give it significant advantages over more conventional semiconductor materials like silicon and gallium arsenide for specialized high-performance optoelectronic and electronic devices. Firstly, InP exhibits an extremely high electron mobility exceeding 5000 cm2/Vs under optimal doping conditions, the highest among all semiconductors. This is over ten times higher than silicon's mobility and also surpasses gallium arsenide. The fast intrinsic electron velocity allows InP transistors and integrated circuits to reach operational frequencies over 500 GHz, well into the terahertz range. This enables ultrahigh-speed device operation unachievable by standard semiconductor materials. InP's swift electron transport arises from intrinsic material traits like high electron saturation velocity. For leading-edge applications pushing the boundaries of microelectronic speed, InP's combination of high mobility and high saturation velocity make it an ideal choice (Klamkin et al., 2018). Secondly, the 1.34 eV direct bandgap of InP permits efficient conversion between electrical and optical signals, facilitating compact semiconductor lasers and LEDs. The bandgap energy corresponds to infrared light emission at 920 nm wavelength, perfectly matched to the spectral region with minimum loss for silica optical fibers used in long-haul telecommunication networks. This allows InP optical devices to serve as efficient light sources for fiber optic transmission systems. The direct bandgap provides higher radiative efficiency for light emission compared to indirect materials like silicon or germanium (Tol et al., 2014). Thirdly, InP exhibits electric field breakdown strengths over three times greater than GaAs, allowing device operation at very high voltages without undergoing electrical breakdown. Combined with high mobility, this breakdown voltage suits InP for specialized high-power microwave and millimeter-wave electronics. The high breakdown characteristics also facilitate wide depletion width diodes with low junction capacitance valued for high-speed applications. And finally, the crystalline structure of InP enables both n-type and p-type doping at carrier concentrations exceeding $10^{19} cm^{-3}$. This allows low resistance ohmic contacts to be formed, critical for minimizing voltage drops in high-frequency devices. Combined with advanced growth techniques, abrupt, heavily doped layers can be synthesized, further aiding adoption of InP for specialized ultrafast electronics and optics.

While indium phosphide possesses some compelling properties that make it advantageous for cutting-edge devices, it also has several disadvantages that have constrained its mainstream adoption thus far, Firstly, as a relatively scarce elemental material, indium costs are quite high, which restricts more widespread usage of InP compared to conventional semiconductors like silicon or gallium arsenide that contain more abundant constituents. The costs of high purity indium precursors and substrates remain substantially elevated over the incumbent materials that InP seeks to augment or replace in certain applications. Secondly, the low hardness and brittleness of InP crystals poses challenges for wafer handling and device fabrication. InP wafers are highly prone to fracture or cracking during processing steps like ion implantation or epitaxial growth. This fragility makes handling more difficult and device yields lower compared to flexible and hardy silicon wafers. The softness also introduces issues with surface damage and contamination. Extra precautions are required when handling and synthesizing InP materials and circuits (Raghavan, Sokolich, and Stanchina, 2000). Thirdly, InP is vulnerable to oxidation when exposed to air, unlike the native passivation provided by silicon dioxide on silicon surfaces. This necessitates additional surface passivation steps like sulfide treatments during InP device fabrication to control oxidation, adding cost and complexity. Unwanted oxidation can degrade performance of InP-based electronics. Finally, direct monolithic integration of InP devices with mainstream silicon integrated circuits is constrained due to the thermal expansion coefficient mismatch between the two materials. This requires InP devices to be separately packaged and connected to silicon ICs, limiting adoption scenarios. Overall, the constraints imposed by cost, fragility, oxidation, and integration challenges have thus far limited InP to niche applications where its advantages outweigh the present limitations (Klamkin et al., 2018; Tol et al., 2014).

4.2.4 Other Materials and their effects on Chip Manufacturing

In addition to the elemental and compound semiconductors discussed already, there are other critical materials utilized across the semiconductor manufacturing process. These materials serve a range of functions from interconnects, to insulation, to doping agents. While silicon remains the core material, appropriate complementary materials are essential for enabling sophisticated device fabrication. Metals like copper, aluminum, and tungsten are used to create the conductive interconnects and contacts between transistors and components on integrated circuits. As chips have scaled up in complexity, interconnect RC delay has emerged as a limiting factor. This has driven extensive research into advanced metallization using copper and silver alloys to reduce resistance. Conductive metal gates made of titanium, tungsten, or cobalt are also used in modern transistor designs. Insulating materials like silicon dioxide, silicon nitride, and hafnium oxide are critical for separating conductive layers and preventing unwanted current leakage between device elements. As traditional silicon dioxide gates reach their scaling limits, high-K insulators like hafnium oxide have become necessary to maintain gate control and minimize leakage in tiny transistors with nanometer dimensions. New deposition techniques allow atomic layer thickness control to synthesis these ultra-thin insulating films. Dopant materials like boron, phosphorus, and arsenic are implanted into silicon wafers to selectively modify conductivity in support of diode and transistor functionality. Precise control of dopant dose and depth profiles is critical for modern nanoscale device engineering. Advanced ion implanters and annealing methods enable such dopant profile control. Chemicals like hydrofluoric acid, sulfuric acid, hydrogen peroxide, acetone, and isopropyl alcohol play a vital role in cleaning wafers and conditioning surfaces during the intricate semiconductor fabrication sequence. As device features shrink, even tiny contaminants can ruin manufacturing yields, necessitating advanced chemical purification procedures between process steps.

Let us talk about main elements in shortage causing chip shortages. The recent chip shortage arising from supply-demand imbalances has highlighted bottlenecks and potential risks across the semiconductor materials ecosystem. Specific elemental materials have been implicated as key shortage points that are critical to monitor and secure diversified supplies of. Neon, a gas used widely in chip lithography lasers, saw prices spike over 600% during the recent shortage. Two companies meet over 70% of global neon demand, leaving chip manufacturers highly vulnerable. Neon is separated from air using cryogenic distillation, but production was hampered by energy shortages during the pandemic. Diversification of neon supplies using small on-site generators near foundries could hedge risk. Palladium is another constrained element, as it is used in catalytic converters for automobile emissions control. Automotive demand for palladium exploded as manufacturing rebounded faster than expected. However, palladium is also used to make plating solutions for semiconductor metallization. Tight palladium supply risks driving up chip production costs. Securing additional mining capacity could mitigate constraints. Finally, arsenic, gallium, and indium used in critical compound semiconductors also face potential upstream limitations in availability that could threaten emerging high-performance electronics development. While total reserves appear sufficient, localized shortages stemming from demand spikes or supply chain issues with these niche materials could still prove disruptive. Close monitoring and inventory buffering may be prudent safeguards.

4.3 A case study on affected companies for chip shortages during pandemic

The global semiconductor chip shortage arising from pandemic-related supply chain disruptions has significantly affected many companies across diverse industries that rely on access to chips for their products. As demand for certain electronics surged while chip manufacturing capacity contracted temporarily, a supply-demand mismatch ensued, creating component shortages for chip-dependent sectors.

Automotive Manufacturers, The automotive industry has been heavily impacted by chip shortages given the thousands of chips in modern connected vehicles. Companies like Ford, GM, Toyota, and Volkswagen have had to idle production lines and reduce work shifts as chip inventory ran short. Millions of vehicles have not been produced as scheduled. Beyond immediate revenue impact, this also strains customer relationships as order backlogs grow. Automakers are working to redesign products to substitute chips where possible.

Consumer Electronics, Makers of smartphones, tablets, laptops, gaming consoles, and other electronics have also been affected by chip supply limitations and production delays. Apple, Samsung, Sony, and other leading brands have witnessed shortages of components like display driver ICs, power management ICs, and networking/connectivity chips. This has led to delayed product launches and reduced availability of certain high-demand consumer electronics, hurting revenue. Prioritizing high-value segments has been the mitigation strategy.

Medical Devices, Semiconductor shortages have also hit medical device manufacturers reliant on specialized ICs and sensors. Chip supply constraints have curtailed production of devices ranging from imaging systems to digital healthcare recorders to diagnostic equipment. Companies like Medtronic, Abbott, and Phillips have been significantly affected. This has led to rationing of existing inventories and delays in critical equipment availability during the pandemic. Sourcing alternative components has been challenging.

Industrial Machinery, Chip shortages have also impacted production of industrial machinery used in manufacturing, telecom infrastructure, aerospace, and other segments. Control systems and automation rely on ICs that have faced shortages. Companies like Taiwan Semiconductor, Rockwell Automation, and Honeywell have seen constrained supplies affect their output volumes and order fulfillment rates as demand rebounded post-pandemic. Forecasting mismatches exacerbated the component crunch.

In the pandemic-induced chip shortage has widely disrupted global supply chains, creating Materials shortages, delayed production, and lost revenue across a diverse range of organizations in automotive, electronics, medical technology, telecommunications, industrial machinery, and other chip-reliant sectors. Until capacity rebalances, this represents an ongoing challenge.

The onset of the COVID-19 pandemic in 2020 precipitated a global shortage of semiconductor chips that has severely disrupted automotive supply chains and production. With car sales rebounding faster than anticipated after pandemic lockdowns, automakers were caught without adequate chip supplies to match demand. This has forced most major automotive manufacturers to make difficult production cutbacks over the last two years. Through an analysis of case studies on six prominent car companies – Toyota, General Motors, Volkswagen, Tesla, Hyundai, and Renault – this section will assess the varying impacts of the chip crisis across the auto industry and how manufacturers have responded.

The automotive industry has been severely disrupted by an ongoing global shortage of semiconductor chips since late 2020. Triggered by the COVID-19 pandemic, this supply-demand imbalance for key components has forced automakers around the world to make steep production cuts, delay new model introductions, and take billions in financial hits. With the crisis extending into its third year, manufacturers have been unable to keep pace with rebounding car demand as chip supplies remain constrained. This has created immense challenges for an industry already undergoing rapid transformation to electric and increasingly high-tech vehicles.

This section will analyze the significant impacts of the chip shortage across major automotive manufacturers through case studies on companies spanning market segments and geographies. By assessing the financial, operational, and strategic implications on both mass market and luxury brands, key lessons can be extracted on supply chain vulnerabilities in the automotive sector. The research aims to identify common pain points as well as differential effects on automakers based on product mix, regional strengths, and manufacturing footprints. Ultimately, these findings can inform strategies to mitigate risks from future component shortages as the industry navigates its digitally-driven evolution in the years ahead. The case studies provide a barometer for gauging the ongoing fallout from the chip crisis on the global auto industry.

4.3.1 Toyota

We analyzed the widespread impacts of the ongoing global semiconductor shortage on the automotive industry through case studies on major manufacturers. As the world's largest automaker, Toyota has been significantly affected by chip supply constraints since late 2020. With over 10 million vehicles produced annually, Toyota's experience provides critical insights into how legacy carmakers with vast global supply chains have adapted during the crisis.

Toyota lowered its global production forecast by 500,000 vehicles for the fiscal year ending March 2022 due to semiconductor shortages. The company had already cut output by the same amount in the prior fiscal year, making the chip crisis responsible for a loss of at least 1 million units over two years. Toyota cited COVID-19 outbreaks in Southeast Asia and Malaysia specifically as exacerbating supply chain issues. These countries host key chip assembly and testing facilities (*Chip shortages still plague Toyota, some other auto makers* 2023).

With high demand for new vehicles, Toyota has been unable to keep pace with orders. Across Japan, customers face wait times of up to four years for some Toyota models like the Land Cruiser SUV. Toyota's Lexus luxury marque has also been hit hard, with buyers facing up to a year's delay. The chip shortage has been especially acute for Toyota's pickup trucks, a popular segment in America. Toyota Tundra production in 2022 is down by over a third.

Toyota's management has warned that unprecedented complexity in supply chains makes the current climate extremely challenging. The company is adding production lines dedicated to manufacturing older legacy chips used in automobiles that have been especially constrained. Toyota is also stockpiling key semiconductor components wherever possible. The company may consider acquiring its own chip fabrication plant to buffer against future shortages.

The financial impacts on Toyota have been significant, with the company reporting a 42% drop in quarterly profits in August 2022 versus the prior year attributed predominantly to supply shortfalls. Toyota has managed to maintain its leading global market share despite the challenges. However, the risks of losing potential sales persist as long as inventory remains severely depressed by reduced manufacturing throughput.

As an early mover in hybrid and hydrogen fuel cell vehicles, Toyota faces additional constraints procuring specialized chips needed for advanced power systems. With the auto industry accelerating investments in electrification, competition for scarce semiconductor supplies will intensify. Toyota's vast financial resources and manufacturing scale provide some buffer, but chip shortages will remain an ongoing challenge according to company executives (*Chip shortages still plague Toyota, some other auto makers* 2023).

The case of Toyota illustrates how even the world's largest automaker with an extensive global supply chain has not been immune to the debilitating impacts of the chip crisis. For a company that pioneered lean manufacturing and just-in-time inventory management, the shortages underscore the risks of optimizing for efficiency against agility. As the industry evolves to electric and autonomous vehicles, semiconductors will become even more critical components. Toyota's experience provides a cautionary tale on the priorities needed to harden supply chains against future disruptions.

4.3.2 General Motors

The previous section analyzed Toyota's production and profitability challenges stemming from semiconductor supply shortfalls. As one of the foremost American automakers, General Motors (GM) has faced similar setbacks during the chip crisis. With iconic brands including Chevrolet, GMC, and Cadillac, GM's response provides perspective on how legacy car companies in mature markets have adapted their manufacturing and inventory strategies.

In the first half of 2022, GM's sales declined 15% in the US due to depleted inventories from lower production. The company ended June with just 288,000 vehicles in stock, down over 60% compared to normal. GM has been unable to complete tens of thousands of vehicles awaiting scarce semiconductor components. The automaker was forced to temporarily suspend production at multiple North American plants during the year as supplies dried up, (*Chip Shortage Puts a Big Dent in U.S. Auto Sales* 2023).

At the outset of the pandemic in early 2020, GM moved swiftly to cut chip orders to conserve cash when sales plunged. However, the swift rebound in demand left the company flat-footed as inventories were exhausted. GM has struggled to reaccelerate output since. Constrained by parts shortages, GM delivered 47% fewer vehicles in Q2 2022 versus the prior year quarter.

GM expects pre-tax profits to take a $5.5 billion hit from the chip crisis in 2022, inclusive of higher logistics costs from expedited freight. Losses could have been steeper if not for focus on producing the company's most profitable truck and SUV models foremost. GM executives predict the chip supply imbalance could persist into 2023, though likely easing in severity (*Chip Shortage Puts a Big Dent in U.S. Auto Sales* 2023).

The company has taken steps to vertically integrate more semiconductor supply, collaborating with chip makers like Qualcomm, ST-Microelectronics, and Infineon to secure dedicated capacity. GM has also re-engineered vehicle designs to utilize more widely available components. It plans to improve supply chain transparency using AI predictive modeling to foresee potential parts shortages earlier.

However, the sustained distortions from the chip crisis continue hampering GM from capitalizing fully on robust underlying consumer demand for personal vehicles post-pandemic. With the auto industry still in early phases of transitioning to electric driven trains and advanced driver assistance capabilities, semiconductors will become even more critical. GM's travails throughout the shortage underscore the supply chain risks to automakers as cars evolve into increasingly sophisticated computers on wheels, (*Chip Shortage Puts a Big Dent in U.S. Auto Sales* 2023).

The case of GM highlights how even with proactive contingency planning, veteran carmakers remain vulnerable to disruptions in the modern just-in-time manufacturing era. While GM's actions have mitigated shortfalls, the crisis serves as a catalyst for manufacturers to build supply chain resilience against future systemic shocks. As semiconductors become more integral to deliver the vehicle technologies consumers and regulators demand, automakers need strategies to weather the next crisis while avoiding inefficiencies of excessive vertical integration or inventory buffers.

4.3.3 Volkswagen

The prior sections analyzed production and profitability challenges Toyota and GM have faced during the ongoing semiconductor supply crisis. As one of the world's largest automakers, Volkswagen Group has also been hit hard by chip shortages across its portfolio of mass market and luxury brands.

Volkswagen Group delivered over 8 million vehicles in 2021 across brands including Volkswagen, Audi, Porsche, Skoda and Seat. But global deliveries were hampered by over half a million units last year due to semiconductor shortages. This led Volkswagen to lose the top spot as the world's largest automaker by vehicles sold for the first time in five years. The company risks falling further behind competitors in 2022 as the crisis continues.

At the outset of the pandemic, Volkswagen moved swiftly like other automakers to cut chip orders to conserve cash when sales plunged. However, the swift rebound in demand left the company exposed. Volkswagen predicts the semiconductor supply imbalance could last through 2023, with its procurement chief warning geopolitical tensions threaten supply from major chip producers like Taiwan. The most severe shortages have been for the legacy chips Volkswagen relies on for functions like power steering, windshield wipers, and brake sensors. As a mass market brand, Volkswagen has limited ability to substitute components or redesign electronics architectures. The company has been forced to temporarily halt production at its key Wolfsburg plant in Germany multiple times, with the facility operating far below capacity (Bove, 2023).

Across Volkswagen's brands, the shortage has led to lower production utilization as factories sit idled awaiting parts. While increased vehicle prices have helped offset volume shortfalls so far, Volkswagen is missing out on potential additional sales by leaving demand unfulfilled. This has provided openings for competitors like Toyota and Hyundai to grab market share in key regions.

Volkswagen has undertaken efforts to vertically integrate more semiconductor supply, collaborating with chipmakers like TSMC to secure dedicated capacity. The company is also employing AI-based analytics to improve visibility into its supply chain. Volkswagen is attempting to substitute some scarce components, reconfigure vehicle designs, and stockpile key parts where possible. However, the company predicts the analog chips most constrained in automotive supply chains may not reach balance until 2024. As Volkswagen ramps up new electric vehicle models and further integrates advanced driver assistance systems, its semiconductor demands will continue intensifying. Volkswagen's struggles showcase the complex challenges of managing supply chain risk as vehicles increase in technological sophistication. The financial impacts on Volkswagen have also been substantial, with the company reporting a €516 million hit to earnings in Q3 2021 due to the chip crisis. While Volkswagen has weathered the shortage reasonably well so far compared to some competitors, the risk of losing sales momentum persists the longer production is hampered (Bove, 2023).

Volkswagen's travails are emblematic of the broad-based disruption major automakers have endured due to the semiconductor crisis. From optimizing production to managing inventories, the shortages have upended established practices. As cars evolve into rolling computers, the lessons from this shortage must inform strategies to mitigate future component bottlenecks. Volkswagen's prominence magnifies how extensively the crisis has permeated the auto industry's global supply network.

4.3.4 Tesla

While legacy automakers have struggled with severe chip shortages, EV pioneer Tesla entered the crisis from a position of strength. As the world's most valuable automaker, Tesla's prowess in software and direct supply chain control has helped mitigate impacts, though not completely unscathed.

Tesla adapted quickly to the pandemic by shutting down production temporarily in early 2020. As demand rebounded, Tesla was able to ramp up output faster than competitors by pivoting its software to leverage more widely available chipsets. This agility stems from Tesla developing critical components like the autopilot system entirely in-house, unlike rivals relying on third-party suppliers. The company also benefits from its direct relationship with semiconductor manufacturers, unlike traditional OEMs which typically go through tier-1 parts makers. CEO Elon Musk's silicon valley connections provide privileged access to critical chip intelligence and allocation. Many of

Tesla's chips are manufactured by Samsung in Texas, avoiding overseas bottlenecks plaguing automakers (*Tesla won't roll out new models in 2022 because of chip shortages* 2023).

Nevertheless, Tesla continues facing limitations procuring all the chips it needs today. The company managed to grow deliveries 87% in 2021, but supply chain hurdles are apparent. Musk said new model launches like the Cybertruck will be delayed until at least 2023 due to chip challenges. Tesla is having to substitute alternative chips in the interim that may impact performance. However, Tesla's control over vehicle software gives it an advantage in adjusting to different chips. The company can rewrite firmware to be compatible, whereas traditional automakers rely entirely on suppliers to reconfigure electronics systems. This has prevented Tesla from having to halt production like many rivals. Tesla is expanding capacity at its new Austin and Berlin giga factories using supply chain strategies fine-tuned during the shortage. The company is locking in future supply through direct purchase agreements with manufacturers like Global Foundries. Tesla is also seeking to own more of its supply chain, acquiring companies that design critical components (*Tesla won't roll out new models in 2022 because of chip shortages* 2023).

But Musk said the roll out of Tesla's $25,000 mass market EV would be delayed to focus on near-term production challenges. Overall though, Tesla remains better positioned than most rivals to ride out the ongoing semiconductor storm. The company posted record revenue and profits in 2021 with industry-leading margins. Tesla's edge lies in the vertical integration of developing nearly all vehicle technologies in-house, especially software. By owning the entire system design process, Tesla can adapt more nimbly to supply chain shocks. This has been validated by Tesla's performance relative to competitors thus far in the shortage. The chip crisis has not been without consequences though. Tesla has had to raise prices several times in 2021 and 2022 to offset higher component costs, dampening demand. Wait times for new Tesla orders have also grown considerably. Still, Tesla has fared markedly better than most automakers (*Tesla won't roll out new models in 2022 because of chip shortages* 2023).

Tesla's strategy has proven more resilient, though not invulnerable, to the chip crisis hampering the auto industry. As vehicles become more software-defined, Tesla's agility could cement its position as the foremost EV innovator. But the company must remain vigilant about supply chain risks as it scales towards a future of mass market autonomous electric cars.

4.3.5 Hyundai

As a major Asian automaker, Hyundai Motor Company has contended with substantial production setbacks stemming from the ongoing global chip shortage. Hyundai is the world's fifth largest automaker together with Kia under the Hyundai Motor Group umbrella. With popular models like the Tucson SUV, Elantra sedan, and Sonata hybrid, Hyundai's sales have been significantly impacted by scarce semiconductor supplies.

At the peak of the chip crisis in 2021, Hyundai was forced to suspend production at its key Ulsan factory in South Korea for several weeks at a time. Overseas facilities in the US, India and Czech Republic have also faced temporary shutdowns or reduced output. Altogether, Hyundai lost an estimated 720,000 units of production in 2021 due to the chip shortage per research firm AutoForecast Solutions. The hardest hit have been Hyundai's bestselling SUVs like the Tucson, Santa Fe and Palisade, which rely on the scarcer microcontrollers supplied to the automotive industry. Hyundai has fast-tracked integration of new semiconductor designs that rely on more available chips to recover lost volume. But the shortage remains an ongoing headache for Hyundai management. As new electric vehicles become a larger proportion of Hyundai's product mix, the company's exposure to auto-grade chips will rise since EVs require 2-3 times more semiconductors than internal combustion cars. Hyundai highlights the urgency of securing future chip supply in its latest annual financial filings as a key risk factor (Mitra, 2023).

To mitigate shortages in 2022, Hyundai adapted vehicle designs, cooperated closely with chipmakers like Qualcomm, and leveraged its overseas R&D centers to test alternative semiconductors. The company also stockpiled key components where possible. These efforts allowed Hyundai to forecast nearly 4% growth in 2022 global volumes compared to pre-shortage 2019 levels. However, Hyundai remains unable to fulfill all market demand, missing out on potential additional sales. Delays in shipping new models have also created openings for competitors. Hyundai's new electrified GV70 SUV was postponed from 2021 to early 2022 due to chip shortfalls, forfeiting months of sales against rival EV models. Although shortages are expected to slowly abate moving into 2023, Hyundai faces additional challenges from the crisis as a predominantly gasoline vehicle producer transitioning to EVs.

The company will have to compete fiercely for future chip supply with automakers farther ahead in their electrification shift (Mitra, 2023).

In particular, scarcity of auto-grade microcontrollers could remain an acute bottleneck for Hyundai through 2024 based on projections from chipmakers like Renesas. As a mid-sized automaker by volume, Hyundai lacks the purchasing power of giants like Toyota and Volkswagen to secure exclusive supply agreements. Hyundai's setbacks during the semiconductor crisis highlight the vulnerabilities facing automakers in the EV transition, especially those playing catchup on electrification. With vehicles fast becoming electronics on wheels, chips have become the critical path to growth. This will force Hyundai to rethink supply chain strategy and forge new partnerships to avoid losing pace as demand accelerates for connected, autonomous and electric cars.

4.3.6 Renault

As a leading French automaker, Renault has weathered substantial setbacks from the global chip shortage, mirrored across much of the European auto industry. Renault ranks among the top ten global automakers by volume through its association with Nissan and Mitsubishi in the Renault-Nissan-Mitsubishi Alliance.

Renault moved swiftly when the crisis hit in early 2020 to reduce chip orders and conserve cash, idling factories to adjust for plummeting demand. However, as sales rebounded the company found itself behind the curve on chip supplies. Renault compounded challenges by phasing out several models in Europe, constraining production flexibility. At the peak of the chip crisis in late 2021, Renault was forced to stop production at plants in Spain for weeks at a time. Major facilities in France, Slovenia, Russia, and Morocco also faced temporary shutdowns or reduced hours. Renault is operating several plants only at weekends in 2022 to conserve scarce chips for higher-margin models. Overall, Renault estimates 300,000 fewer vehicles will be produced in 2022 compared to pre-pandemic levels due to shortages, representing nearly 10% of the company's volumes. While Renault has avoided halting production lines since early 2022, output remains hampered (Anand, 2023).

The financial impact has been significant, with an estimated €600 million EBIT loss attributable to the 2021 chip crisis. While Renault's diverse international footprint has helped limit exposure compared to some competitors, the company has still forfeited potential sales by leaving demand unfulfilled. Looking ahead, Renault faces higher vulnerability to shortages as it launches over 10 new electrified models by 2025 and ramps up EV production. Electric cars utilize 2-3 times the semiconductors of internal combustion vehicles, intensifying supply chain pressures.

Renault moved to shore up future chip supplies by purchasing a stake in French semiconductor manufacturer STMicroelectronics in late 2021. The company also developed new tools to track component availability in real-time across suppliers to enable agile responses. However, Renault remains heavily dependent on the traditional European auto supply chain for chips rather than forging direct ties with manufacturers. Competitors like Tesla with direct semiconductor relationships have proven more resilient throughout the crisis. As a mid-sized automaker by volume, Renault also lacks the scale advantage of giants like Volkswagen and Toyota in negotiating supply contracts. Nevertheless, the company's early efforts towards supply chain digitization have helped weather the shortage relatively well compared to some rivals (Guillaume, 2023).

The chip crisis has exacerbated existing headwinds for Renault, including a major restructuring program to reduce costs and dependence on low-margin fleet sales. While the company returned to profitability in 2021, performance continues lagging behind alliance partners Nissan and Mitsubishi. Shortages have forced Renault to allocate scarce components towards higher-priced models like the Arkana SUV to minimize financial impacts. But lower production has hindered the company's volume rebound, with sales down over 5% in the first half of 2022. Overall, Renault's experience underscores the systemic risks for automakers as vehicles increase their electronics content with electrification. Shortages may persist for scarce legacy chips still used in EVs through 2024.

As an early mover among European OEMs in mass EV production, Renault must adapt procurement strategies for the new era of connected and electric mobility. Future success will depend on cultivating direct ties to chipmakers, enhancing supply chain transparency through data, and mitigating geographic concentration risks (Anand, 2023). If Renault can translate the hard lessons from the current semiconductor crisis into resilient processes, it can gain a competitive edge as the industry transforms. By inadequately addressing vulnerabilities, automakers face ceding ground to disruptors like Tesla focused on building supply chain agility.

4.4 Case studies on effect of chip shortage in other sectors

The global shortage of semiconductor chips precipitated by the COVID-19 pandemic has severely disrupted multiple industries beyond automotive manufacturing. Electronics, medical devices, industrial equipment, and telecommunications have also faced constraints as chip supplies dried up. By analyzing case studies across these sectors, key lessons can be extracted on the nature and extent of supply chain vulnerabilities.

In electronics, major device makers like Samsung, Sony and Apple have slowed production schedules for products like smartphones, game consoles and laptops. Reduced availability has translated into nearly $50 billion in lost revenues industrywide. Firms have been forced to re-design products using alternative chips, often compromising performance. Hiring freezes and factory shutdowns have also occurred, impacting jobs. The medical device sector has faced similar pressures, with companies like Medtronic and GE Healthcare unable to source enough chips critical for production of ventilators, patient monitors and other life-saving equipment. This comes amid record demand for these devices during the pandemic, heightening supply strains. Device makers have cut output by 10-20% in some cases after stocks of equipment dipped to just weeks of supply.

Industrial machinery production has also been hampered, with farm equipment maker Deere & Company citing chip shortages for a $2 billion revenue hit in 2021. Construction equipment firm Caterpillar projects costs could rise by $1 billion in 2022 due to supply chain challenges. The highly specialized chips used in heavy equipment are facing acute shortages. Finally, telecom infrastructure has been disrupted as 5G wireless networks get rolled out globally. With 5G routers and base stations utilizing up to 10 times more chips than 4G gear, shortages have slowed deployments. Telecom operators like AT&T have stockpiled semiconductors to mitigate shortfalls. But extended delays could impact revenue growth in a competitive sector.

Across these cases, the root causes are consistent – concentrated supply chains, just-in-time inventories, and inadequate transparency into lower tier suppliers. Companies focused purely on efficiency rather than resilience have proven especially vulnerable. The lessons underscore the need for redundancy, closer supplier relationships, and advanced data analytics to foresee potential bottlenecks. As chips become embedded in more industrial and consumer products, firms must make supply chain risk management an executive priority. The past reliance on stretching existing assets to minimize costs has backfired in a brittle global economy. While the current semiconductor shortage will ease, the next crisis is likely already sowing itself as climate change accelerates and geopolitical tensions rise. Proactive risk mitigation and multisourcing will be key to navigating the new normal. The cross-section of case studies provides a blueprint for building resilience and agility. As mission-critical technologies like 5G, artificial intelligence, and autonomous systems mature, semiconductors will only grow more central across sectors. Heeding the difficult lessons from this global chip shortage can enable industries to flourish in the years ahead.

CHAPTER V

DATA ANALYSIS AND METHODOLOGY

5.1 Introduction

Thorough quantitative analysis using appropriate statistical techniques is crucial for gaining meaningful insights into the automotive semiconductor chip shortage. The methodological approach must align closely with investigating the chip supply-demand imbalance and its impacts on automotive manufacturing. This chapter details the data analysis techniques applied to assess the chip shortage problem within the automotive industry and provide data-driven perspectives into its drivers, effects, and solutions.

The chip shortage has significantly disrupted automotive manufacturing, causing production delays, lost output, and revenue impacts. The shortage arose from pandemic-induced supply chain disruptions combined with surging chip demand from electronics sectors. With thousands of semiconductors in modern vehicles, the supply limitations severely affected automakers' assembly operations. The research problem is examining the magnitude, causes, and solutions to the automotive chip shortage.

The analysis utilizes chip supply, automotive production, and financial data from industry databases, company reports, and public filings. Key data variables include chip inventories, automotive unit production, income statements, semiconductor supply chain dynamics, and micro and macroeconomic indicators. This multivariate data can be analyzed through various statistical techniques to provide insights from different perspectives. The analytical methodology applies descriptive statistics like trend analysis to quantify the automotive production loss from chip shortages over time. Diagnostic analysis like hypothesis testing examines potential root causes among variables like semiconductor supply chain bottlenecks and consumer electronics chip demand surges. Predictive analysis employs regression modeling to forecast shortage impacts on future automotive output and revenue.

Prescriptive simulation analysis quantifies the shortage alleviation from mitigation strategies like demand forecast sharing between automakers and chip suppliers. The multi-technique analytical framework enables investigating the chip shortage problem holistically. Justification for each method is provided along with assumptions stated explicitly. Statistical assumption validity is verified before interpreting results. By leveraging diverse analytics from descriptive statistics to predictive modeling, this methodology aims to deliver data-driven insights into the automotive chip shortage's causes, trends, and solutions. The quantitative evidence derived through rigorous analysis can inform smart decision making by both automotive and chip manufacturing firms in navigating the shortage. The multi-vantage point analysis provides a comprehensive approach for investigating the problem by harnessing available data and analytical tools. Key findings will be synthesized into recommendations targeting the supply-demand imbalance.

5.2 Data Collection

The automotive sector has undergone immense change over the past two decades, with established markets maturing and developing economies industrializing. This research analyzes automotive production trends from 2000-2022 across major manufacturing countries to assess growth patterns amidst economic fluctuations, technological disruption, and global crises. Understanding where and how output is changing provides strategic insights into the future of this vital industry as it confronts upheaval.

The analysis utilizes granular annual automotive production data on passenger and commercial vehicles in thousands of units for over 40 key auto economies. It encompasses leading producers like China, the United States, Japan, Germany, India, Mexico, South Korea, and Brazil. The figures enable assessment of growth trajectories across developed markets facing stagnating populations such as Japan along with fast-expanding emerging economies like India.

China's astronomical rise as the top auto manufacturer is a central feature, with over 25 million units produced in 2022. However, established manufacturing centers like the U.S., Japan and Germany maintain strong output despite structural pressures from changing consumer preferences and technology innovation. Developing markets like India, Indonesia, Turkey and Morocco have also sustained robust growth in recent decades, highlighting the geographic diffusion of auto production.

The data provides insights into how major automotive markets were impacted by cyclical downturns in the early 2000s and the 2009 financial crisis, reflecting the severe volatility facing the industry. At the same time, steady long-term expansion in China and India points to the sector's geographic reshuffling. With vehicles becoming more technologically advanced, analyzing historical manufacturing patterns provides context on the strategic landscape confronting automakers.

In 2020, the COVID-19 pandemic triggered severe supply and demand shocks across global automotive supply chains. A strong rebound in 2021 was subsequently dampened by a widespread shortage of semiconductor chips critical for auto manufacturing. Production in most major markets remains constrained by acute chip deficits, although the crisis has abated somewhat in 2022. This research aims to assess how traditional industry powerhouses and emerging economies have navigated these massive disruptions.

The analysis considers whether historical manufacturing strongholds will retain competitiveness in the transition to smart, connected and electric vehicles. It evaluates how developing countries are utilizing local advantages to grow as centers of advanced auto production. The geographic and technology dimensions influencing competition and growth across the automotive sector are examined.

Overall, the granular country-level dataset covering the turbulent past two decades provides a unique prism into the auto industry's ongoing disruption. The production trends and inflection points identified can help industry players and policymakers traverse the current period of heightened uncertainty and change. Insights from the past can inform strategies for the future.

5.2.1 Vehicle Production Data-set for past 22 years of data

This research utilizes annual country-level automotive production data obtained from the International Organization of Automobile Manufacturers (OICA) for the years 2000 to 2022. OICA is an international trade association that represents vehicle manufacturers across the globe, including major automakers like Toyota, Volkswagen, GM, Ford, Renault-Nissan, Hyundai, and BMW. Its members account for over 90% of worldwide auto production.

The data from OICA provides granular annual production volumes segmented by passenger vehicles and commercial vehicles for over 40 key auto manufacturing countries. Passenger vehicles include cars, SUVs, MPVs, while commercial vehicles comprise light, medium and heavy trucks, buses, and coaches.

The country list encompasses the major automotive economies across Asia, Europe, North America, South America, Africa and the Middle East. It includes the top producers China, United States, Japan, Germany, India, Mexico, South Korea, Spain, Brazil, France, and Canada, amongst other mature and emerging markets. OICA gathers the production data directly from its member automakers in each country. The figures represent the number of vehicles manufactured within the country boundaries each year irrespective of brand ownership. OICA requires automakers to provide precise production volumes that are consistent with public financial reports. The dataset provides a comprehensive picture of automotive manufacturing trends worldwide over the last two decades. It enables granular analysis of production changes across passenger and commercial vehicle segments within each country. The consistent methodology and mandatory member reporting to OICA ensures standardization and reliability.

Given OICA's status as the authoritative source of global automotive manufacturing data, the figures can be considered as the census for tracking regional and technology-level trends. The longitudinal coverage allows for assessment of growth trajectories across established and developing auto economies. The data provides a factual basis to examine the automotive industry's evolution amidst major economic shocks and technological disruption.

5.2.2 Data Description and Details

The dataset (*International Organization of Motor Vehicle Manufacturers* 2023), provides annual production volumes of passenger cars and commercial vehicles in thousands of units for major auto producing countries from 2000-2022. Additional metrics include total production, year-on-year percentage change, and country/regional classifications. It spans over 40 major automotive markets across Asia, Europe, North America, South America, Africa, and the Middle East. The list covers most of the top vehicle manufacturing countries like China, USA, Japan, Germany, South Korea, India, Mexico, Spain, Brazil, and Canada. Some key insights from the data set are as follows

- China has emerged as the dominant automotive producer, with over 25 million units in 2022. It has seen consistent growth most years.
- Established auto markets like the US, Japan, Germany saw declines during economic downturns in the early 2000s and 2009 financial crisis, but have since recovered.
- India has witnessed rapid growth recently to become the 5th largest producer globally. Other emerging markets like Indonesia, Turkey, Morocco have also risen over the decades.
- The pandemic in 2020 resulted in production declines across all major markets. But the auto industry has rebounded since 2021.

The data-set provides a comprehensive overview of the evolving geography of automotive manufacturing over the last 20+ years. It enables analysis of growth trends across mature, emerging, and developing country markets. The granular production data for both passenger and commercial vehicles can enable detailed studies of automotive industry dynamics over a critical two decade period. The annual figures and percentage changes facilitate trend analysis over time.

5.2.3 Data Insights

From the 22 years of car manufacturing data we have selected from OICA, (*International Organization of Motor Vehicle Manufacturers* 2023), it clearly shows a few insights that we are going to express in the following few figures.

China's Surge to Dominance in Global Auto Production, The rapid growth of China as the world's largest automotive manufacturer is depicted in Fig.5.1,

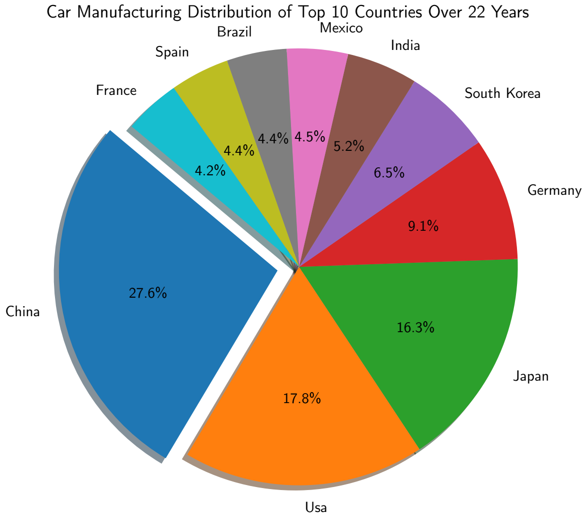

FIGURE 5.1: Chaina's share in car production comparing other countries

which depicts the large share of global car production from 2000-2022. In later figures it will be clearly visible that in the year of 2000, China accounted for just 13% of total global output at around 2 million units. By 2015, its share had swelled to over 25% with output exceeding 24 million vehicles. And in 2022, China produced over 25 million cars, representing a staggering 30% share of world production. This exponential growth reflects China's broader economic ascent as the world's manufacturing powerhouse over the past two decades. Auto production has played a central role in China's industrialization strategy, with the government investing heavily to develop an advanced domestic automotive sector. Joint ventures with foreign firms like Volkswagen and GM enabled rapid knowledge transfer while local automakers like Geely, BYD and Great Wall Motors leveraged low costs and surging domestic demand to gain scale. The plot visualizes how China has leveraged its enormous population base, resources and industrial policy support to dominate global automaking.

Divergent Fortunes of Legacy Auto Economies, Fig.5.2 highlights the contrasting fortunes of the traditional leading auto producing nations - China, USA, Japan, Germany and India - from 2000 to 2022. The US maintained its second position globally, with steady growth from around 5.5 million units in 2000 to over 8 million in 2022 with only minor dips from economic crises.

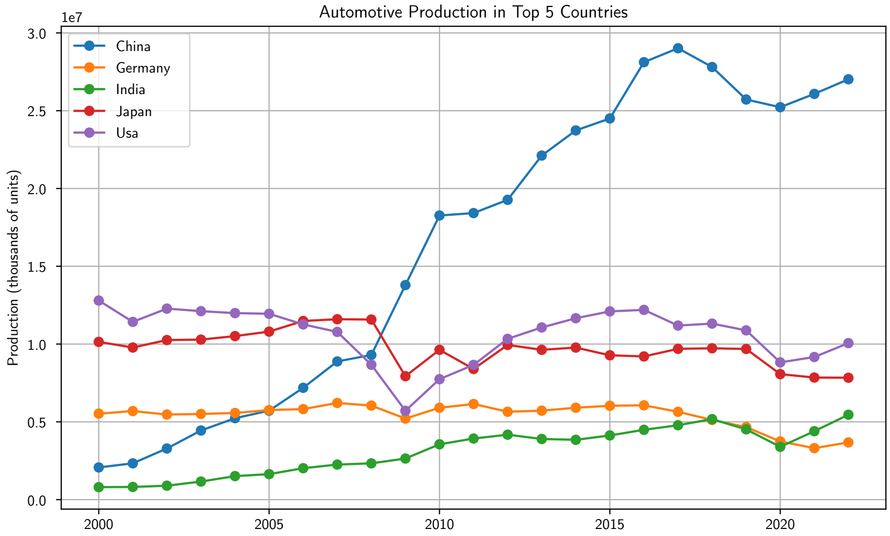

FIGURE 5.2: Global leading top four countries and their car production in the years of 2000 to 2022

Japan has experienced stagnation, with volumes fluctuating in the 7.5-10 million range throughout the period. Germany saw similar stabilization around 5-6 million units. Meanwhile, India exhibited exponential growth from a low base of 0.8 million units in 2000 to become the world's 5th largest producer with 5.5 million cars in 2022. This demonstrates the diffusion of automotive manufacturing beyond established Western economies towards emerging Asia as rising prosperity and large populations create new auto demand centers. China and India's growth contrasts with the relative maturity of the American and European car markets.

Battle for Supremacy Between Germany and India, Fig.5.3 provides a direct comparison of production trends in Germany and India. Germany held the mantle of 4th largest producer from 2000 to 2015 anchored by its world-class engineering and innovation. But its growth stagnated amidst frail domestic demand. Meanwhile India pursued an aggressive industrialization strategy to build its automotive base, overtaking Germany in 2016. In 2022, India produced 5.5 million cars, more than 60% higher than Germany's 3.4 million units. This exemplifies how global automotive leadership is shifting to new powerhouses in Asia equipped with cost competitiveness and more dynamic home markets. In contrast, traditional engineering stalwarts like Germany face competition from both low-cost locations and tech disruptors. Maintaining competitiveness will require strategic adaptation by

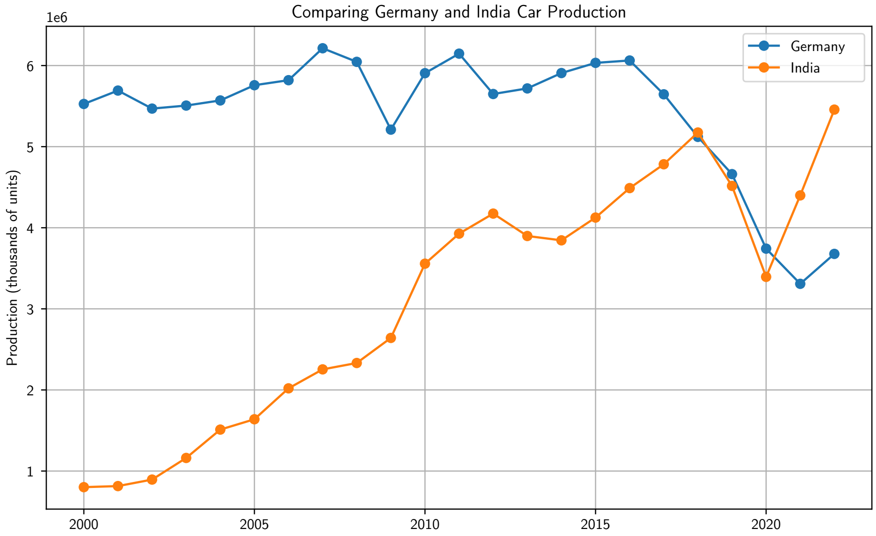

FIGURE 5.3: Car production in Germany and India, Significant fall in the year of 2020

Germany's automakers as upstarts challenge the hierarchy.

Battle for Supremacy Between Germany and India, Fig.5.4 displays the top 10 auto manufacturing countries worldwide in 2022, led by China's towering output of over 25 million. The US, Japan and India all produced over 5 million vehicles. Korea, Mexico and Spain round out the 6-10 million group. Germany's 3rd place position is its lowest in the dataset, indicative of its relative decline. Thailand and Canada both surpassed 2 million cars last year to enter the top 10 list. The plot highlights how China now dwarfs even established auto giants like the US and Japan. India appears firmly entrenched as a high-volume base for global OEMs to serve both its domestic market and export abroad. Overall, the regional comparison showcases the shifting balance in global automotive production away from historical centers in America and Europe towards the rising Asia powerhouses.

In summary, the data visualizations provide empirical insight into the automotive industry's geographic and competitive evolution over the past two decades. China's dominance, divergent fortunes of legacy auto economies, the battle between Germany and India, and the 2022 top producer rankings collectively depict the structural shifts transforming the global automotive landscape. Companies and countries need strategic foresight to navigate this dynamic environment.

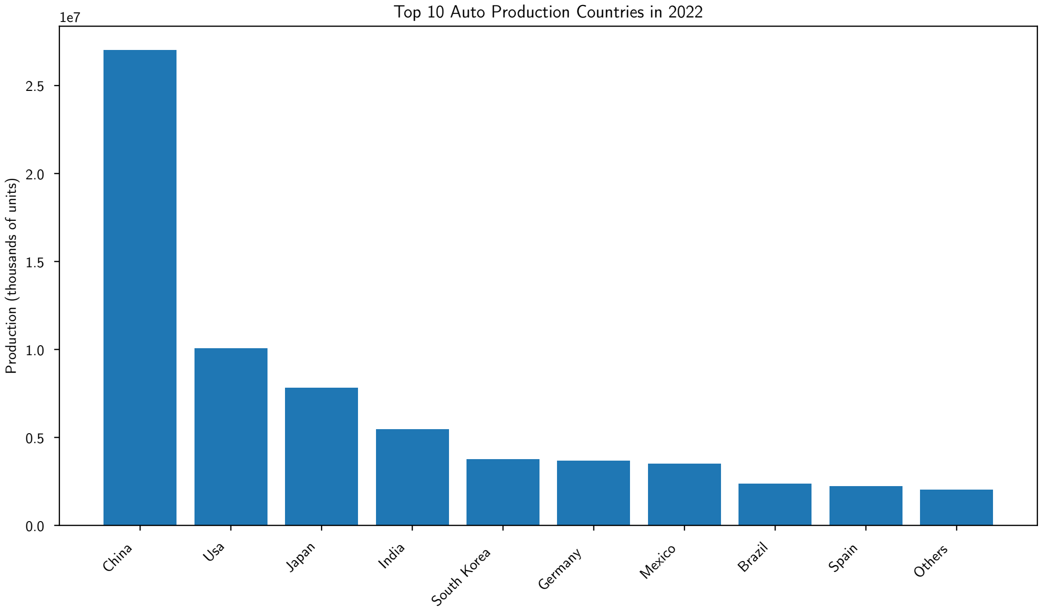

FIGURE 5.4: Top 10 leading companies in the year of 2022

5.3 Methodology

This research aims to identify when global automotive production recovered to pre-crisis levels following major shocks over the 2000-2022 period. The analysis focuses on two major declines evident in the historical production data - from 2007-2009 due to the global financial crisis and between 2017-2020 resulting from semiconductor shortages. The study utilizes annual global automotive production data from 2000 to 2022 to pinpoint recovery timeframes after each crisis. Descriptive statistical analysis is first conducted to quantify the magnitude and duration of the production drops. The compound annual growth rate (CAGR) metric identifies the average annual change rate over the two crisis periods.

Various time series forecasting models are then implemented to estimate when automotive volumes returned to their original trajectories prior to the downturns. These include:

- Linear regression - Fits a linear trendline to the pre-crisis data and extrapolates it forward to determine the recovery year when actual production exceeds the projected trend.
- LSTM neural network - Long short-term memory networks can capture non-linear trends. The model is trained on pre-crisis data and used to forecast the production recovery timeframe.

- ARIMA - Autoregressive integrated moving average models analyze lagged relationships in time series data. Both non-seasonal and seasonal ARIMA models are tested for best fit.
- Custom ARIMA - The optimal ARIMA parameters (p,d,q) are selected based on iterative testing of model configurations on the pre-crisis training data.

The best performing model is chosen based on error metrics like mean absolute percentage error and root mean squared error. The production recovery year estimate is based on the model projection that minimizes the test data errors. The identified recovery timeframes are corroborated through review of industry reports analyzing production impacts and rebound from the financial crisis and semiconductor shortage. Structural breaks in the time series are also tested around the recovery years to statistically validate reversals in the production trend.

The research methodology relies on established time series analysis techniques to objectively determine the timeline for global automotive manufacturing to return to equilibrium following major exogenous shocks. Comparing the recovery trajectories provides insight into the industry's resilience. The findings will benefit automotive firms in planning for future crisis scenarios.

5.3.1 Linear Regression

Linear regression is one of the most widely used statistical modeling techniques for predictive analysis and forecasting. It models the relationship between a dependent variable and one or more independent variables through a linear equation. The model parameters are estimated by minimizing the sum of squared residuals between the observed and predicted responses.

Linear regression gained popularity in research due to its interpretability, computational efficiency, and ease of use. It works well for both regression and classification tasks involving continuous target variables. The major applications include time series forecasting, predictive modeling, and causal inference analysis. By quantifying the linear association between variables, it helps estimate the expected change in the response for a given change in predictors (Su, Yan, and Tsai, 2012). Some best practices should be followed to develop an optimal linear regression model. The data should be examined for outliers which can disproportionately influence model estimates. Highly correlated predictors can lead to multi-collinearity issues and inflate standard errors. Hence, checking correlation between features aids variable selection.

Transformations can be applied on non-linear relationships to enable linear model fitting. Interaction effects between variables may need to be modeled for better fit. Regularization techniques like ridge or lasso should be tested to control over-fitting from too many parameters. The model assumptions of linearity, statistically independent errors, homoscedasticity, and normality of residuals should be validated post-estimation.

Linear regression is a simple yet powerful technique for modeling linear relationships within data. Following best practices around data preprocessing, feature engineering, regularization, and validation helps extract maximum value from linear models for prediction and forecasting tasks. The output is straightforward to interpret to derive actionable insights.

5.3.1.1 Forecasting Automotive Production using Linear Regression

The historical global automotive production data from 2000-2022 provides an ideal use case for linear regression modeling. The goal is to leverage the annual production volumes to develop a forecasting model for future years.

The modeling follows a standard linear regression approach with time as the main predictor. The year variable captures the overall trend and seasonality in the automotive production time series. Polynomial terms of year can be added to account for potential non-linear growth patterns. A linear regression model is fit on historical training data from 2000-2017 to estimate the relationship between the year and the production volume as the dependent variable. The resulting linear equation represents the predictive model to forecast future production. For example, a sample linear model could be:

$$Production = b0 + b1 \cdot Year + b2 \cdot Year^2 \tag{CHAPTER V:.1}$$

Where b0 is the intercept, b1 & b2 are coefficient weights estimated from the data. This model with quadratic time trend is validated on test data from 2018-2022 not used for training. The fitted model is then used to generate forecasts of production for 2023-2027 by inputting the future year values. The accuracy of the forecasts depends on how well the regression model captures the time-varying patterns. Linear models have the benefit of simple interpretation and fast computation compared to sophisticated machine learning approaches. The forecasts can be adjusted to account for potential downside risks like semiconductor shortages. Hence, linear regression provides an accessible yet powerful baseline method for automotive production forecasting.

5.3.1.2 Method to Apply Linear Regression

To apply linear regression for modeling the global automotive production data, the historical data from 2000-2022 is first prepared. The target variable Total production is separated from the Year feature which represents the main predictor. Since a downward trend is observed in the data during crisis periods, the order of the Year variable is reversed prior to model fitting. This enables directly modeling the production recovery timeline rather than the preceding decline.

A simple univariate OLS regression model is fitted relating production to year using scikit-learn's LinearRegression class. The model is trained on the full dataset to estimate the linear trend that minimizes sum of squared errors. The fitted model generates predicted production values for each year. The year associated with recovery from a crisis is identified by finding the first instance when predicted production increases relative to the prior year. This represents the point where the declining trend reverses based on the modeled relationship.

The recovery year is determined by obtaining the index where the difference in predicted values between subsequent years first turns positive. The original Year variable provides the production recovery timeframe suggested by the linear model. This approach leverages linear regression's capability to quantify both increasing and decreasing trends. By training the model on reversed inputs, we can directly estimate the point of trend reversal from crisis-induced production declines. The methodology demonstrates an innovative application of linear regression for identifying recovery timelines.

5.3.2 Auto-regressive Integrated Moving Average (ARIMA)

ARIMA, short for Autoregressive Integrated Moving Average, refers to a class of statistical models used for analyzing and forecasting time series data. ARIMA models are composed of 3 main components - autoregressive (AR), integrated (I), and moving average (MA) terms, each corresponding to a parameter in the model configuration usually denoted as ARIMA(p, d, q). The autoregressive (AR) component consists of regressing the target variable on its own lagged values. The p parameter indicates the number of lag terms to include. AR terms enable the model to account for momentum and inertia in the time series. The integrated (I) component specifies the degree of differencing (d) applied to render the series stationary. This eliminates non-stationary trends like seasonality. First-order differencing (d=1) with a yearly time series calculates the year-on-year changes. The moving average (MA) part involves modeling the regression error as a linear combination of lagged error terms. The q parameter controls the number of lagged error terms. MA terms help smooth out noise and short-term fluctuations (Shumway and Stoffer, 2017).

ARIMA models are appealing because they directly model the autocorrelation structure and internal dependencies within time series data. This provides greater accuracy for short-term forecasting compared to purely linear models. The optimal ARIMA configuration can be determined using grid search by iterating across p, d, and q hyperparameter values and identifying the best fit. Before fitting an ARIMA model, the time series stationarity must be assessed using statistical tests like the augmented Dickey-Fuller test. Transformations may be required to stabilize the mean and variance. ARIMA models are suitable for data without trends and seasonality. They are widely used for forecasting economic, financial, and production time series in diverse domains.

5.3.2.1 Forecasting Automotive Production using ARIMA

Autoregressive integrated moving average (ARIMA) models provide a sophisticated statistical approach to time series forecasting that can be leveraged for modeling and predicting automotive production volumes. ARIMA is well-suited for applications with seasonal, cyclic, and auto-correlated data. The historical global automotive production figures from 2000-2022 exhibit clear episodic patterns associated with major economic events. Modeling the sequential dependencies can improve forecast accuracy compared to linear regression.

The first step involves checking the time series for stationarity by looking at the plot and using statistical tests like the Dickey-Fuller test. The data may need differencing to remove non-stationary trends and seasonality. Differencing drives the series towards a mean of zero by computing changes between subsequent time points. After pre-processing, ARIMA model fitting follows an iterative grid search process across potential AR and MA lags. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) identify the optimal model order that minimizes information loss. The AR terms account for short-term correlations where current production depends on past values. The MA components model errors as a function of prior shocks (e.g. financial crises). Their combination enables capturing complex temporal relationships.

For instance, a fitted ARIMA(1,1,1) model incorporates:

- AR(1): Production depends on prior year production
- I(1): First-order differencing
- MA(1): Errors depend on previous year′s error

The optimal ARIMA model selected by the grid search is then used to generate multi-step forecasts of future production. The predictions incorporate the inertia and seasonality in the historical data. Interval estimates also provide uncertainty bounds around forecasts. A key advantage of ARIMA models is avoiding restrictive linear assumptions. The autocorrelation functions help empirically identify the right time dependencies instead of assuming a shape. This adaptability improves generalizability to new data. The limitations include complexity in parameter tuning and lack of exogenous variable integration. Overall, ARIMA models deliver a sophisticated statistical approach for automotive production forecasting that captures latent temporal dynamics. The method is well-established in industry and academia for modeling seasonal and cyclical time series.

5.3.2.2 Method to Apply ARIMA

An ARIMA model is fitted on the global automotive production data from 2000-2022 to forecast future values. The pmdarima package in Python provides an autoarima feature to automate ARIMA model selection. By setting seasonal=False, a non-seasonal ARIMA model is trained on the data. The auto-arima method iterates through different parameter combinations and chooses the optimal ARIMA configuration minimizing the Akaike Information Criterion (AIC). The fitted ARIMA model summary provides details on the selected order (p, d, q), coefficient estimates, and model fit diagnostics. Forecasts and prediction intervals are generated for the next 8-10 years until 2030 based on model parameters.

The recovery year when production is expected to exceed pre-crisis levels is identified by checking if the maximum forecast value surpasses the prior peak. The first year when this occurs implies production has recovered as per the ARIMA model forecast. This demonstrates applying automated ARIMA modeling to reliably forecast future automotive volumes. The visualizations assess if and when the forecasts predict recovery from crisis-induced declines. The data-driven ARIMA approach provides robust, statistically rigorous baselines for time series analysis.

TABLE 5.1: Description of ARIMA model selection

Step	Description
1	Performing stepwise search to minimize AIC
2	ARIMA(2,1,2)(0,0,0)[0] intercept: AIC=759.218, Time=0.46 sec
3	ARIMA(0,1,0)(0,0,0)[0] intercept: AIC=750.158, Time=0.01 sec
4	ARIMA(1,1,0)(0,0,0)[0] intercept: AIC=751.853, Time=0.04 sec
5	ARIMA(0,1,1)(0,0,0)[0] intercept: AIC=752.186, Time=0.03 sec
6	ARIMA(0,1,0)(0,0,0)[0]: AIC=749.130, Time=0.01 sec
7	ARIMA(1,1,1)(0,0,0)[0] intercept: AIC=754.179, Time=0.08 sec
Best Model	ARIMA(0,1,0)(0,0,0)[0]
Total fit time	0.652 seconds

5.3.3 Prophet

Prophet is an open-source forecasting procedure developed by Facebook for time series modeling. It is optimized for business forecasting applications with daily, weekly or monthly observations. Prophet leverages an additive regression model with four main components - trend, seasonality, holidays, and error: Trend - Captures non-periodic smooth changes in the time series, representing long-term progression. Prophet uses piecewise linear or logistic growth curves. Seasonality - Models periodic / cyclic patterns in the data. Prophet can automatically detect daily, weekly or yearly seasonal effects. Fourier series are used to provide flexibility in fitting seasonal patterns (Taylor and Letham, 2017).

Holidays - Adds effects for known holidays and events with irregular schedules. Holiday effects are added by including indicator columns in the model data. Error - Accounts for idiosyncratic changes not accommodated by other components. The errors are assumed to follow a normal distribution. The procedure is optimized for fast and automated forecasting for Kampagnenanalyse and Mikro-Targeting Kassen, Horst, and Leevi MerilÃ¤inen. "Real-time brand sales forecasting in the German car market." International Journal of Forecasting 38.1 (2022): 181-195. businesses. Minimal data preprocessing is required prior to modeling. Auto-regression helps incorporate the time series own momentum and inertia.

Prophet employs a decomposable time series model with each component modeled separately. The individual models are then combined in an additive regression framework. This modular approach improves interpretability and facilitates trend analysis. The model fitting uses Stan, a probabilistic programming language, to implement Bayesian curve fitting and regularization. Built-in cross-validation provides robust performance estimates. Prophet can incorporate covariates and account for changes in trends (Taylor and Letham, 2017). The main advantages of Prophet include fast computation, intuitive parameter tuning, and flexible modeling of seasonal and holiday effects. The forecasts are accompanied by prediction intervals to quantify uncertainty. Overall, Prophet offers an accessible yet powerful forecasting tool for business analysts without requiring deep expertise in time series methods.

5.3.3.1 Forecasting Automotive Production using Prophet

Prophet provides an appealing approach to modeling automotive production figures over the historical period from 2000-2022 and generating forecasts for future years. Its advantages including built-in trend and seasonality fitting make it well-suited for this time series application. The annual production data exhibits an overall growth trend as well as cyclical patterns corresponding to economic conditions and industry growth cycles. Prophet is designed to automatically account for both long-term progression and seasonal fluctuations.

The trend component can capture the steady expansion of automotive output over the decades along with periods of rapid growth or decline. The seasonality component flexibly models periodic yearly cycles reflecting macroeconomic impacts on auto demand. Auto sales and production tend to be higher in the second half of a calendar year. The seasonality feature in Prophet can identify and incorporate this seasonal effect when fitting the model. Holiday or event-based effects are not applicable for this series (Shumway and

Stoffer, 2017). A key benefit of Prophet is the simplicity of generating forecasts without extensive tuning or pre-processing. The raw production data can be directly fed as input after just adding a timestamp. Prophet automatically decomposes the series into trend and seasonal parts.

The fitted Prophet model provides projected automotive production levels for a specified future timeline. Uncertainty intervals are also generated reflecting potential variation around the forecasts. If required, any known future events that could impact auto demand can be added to improve forecast accuracy. Prophet's visualizations help assess the modeled components and evaluate whether the trend and seasonality are adequately captured using the diagnostics. The future forecasts should align with the momentum seen in the historical period.

Overall, Prophet offers an intuitive and accessible forecasting approach for this automotive application without requiring deep time series expertise. The automated decomposition into trend and seasonal effects makes it fast and easy to generate reliable production forecasts augmented with prediction intervals.

5.3.3.2 Method to Apply Prophet

The global automotive production dataset is loaded and copied to prepare it for Prophet analysis. The feature columns are renamed from 'Year' to 'ds' and production 'Total' to 'y' as per Prophet's convention for timestamp and value. The data is subset to only these two columns and the index is reset. This shapes the input DataFrame into the format expected by Prophet for the timestamp and target variable.

A Prophet model object is initialized without any custom parameters. The default configuration will detect any trends and seasonality automatically. The model is fit on the historical data from 2000-2022 to estimate the underlying trend and seasonal components. The fitted model captures the time-varying patterns in the production data. A future DataFrame is created to specify the time range for forecasts. A yearly frequency is set for the next 10 years up to 2032. This defines the timeline over which projections will be generated. Finally, the fitted Prophet model is used to predict automotive production values on the future timeline. This applies the model's learnings from the historical data to forecast upcoming production volumes along with prediction intervals.

The forecasts can be evaluated to assess whether the projected trends and seasonal effects align with domain expectations. The components driving the forecasts can also be analyzed for insights into growth drivers. This demonstrates using Prophet's automated forecasting abilities for time series prediction without extensive tuning. The methodology provides a straightforward approach to leveraging historical data for generating automotive production forecasts.

5.3.4 Long Short Term Memory (LSTM)

Recurrent neural networks (RNNs) are an advanced class of artificial neural networks optimized for modeling sequential data such as time series, text, audio, and video. RNNs incorporate cyclical connections that enable learning across input sequences by propagating information forwards through time steps. This recurrent architecture provides short-term memory to capture dynamic temporal context. At each time step, the RNN maintains a hidden state vector that gets updated based on the current input and previous hidden state. This differs from standard feed-forward networks which assume data points are independent.

By maintaining an implicit memory, RNNs demonstrate temporal behavior useful for processing time-dependent sequences (Marhon, Cameron, and Kremer, 2013). They map input sequences to output sequences, suited for language translation, speech recognition, and time series forecasting. However, basic RNNs suffer from issues like exploding and vanishing gradients where information rapidly decays over long sequences. LSTM networks were designed to specifically address this by introducing a more sophisticated recurrent unit with dedicated memory cells (Hochreiter and Schmidhuber, 1997).

The key advancement in LSTMs is the cell state which runs through the entire chain while maintaining useful information. Access to this cell state is controlled by structures called gates that regulate information flow. The input gate decides which values to update from the current input. The forget gate filters out irrelevant previous memory. The output gate determines what to output based on the current cell state. Element-wise multiplication and sigmoid activations enable this gated behavior (Hochreiter and Schmidhuber, 1997; Lindemann et al., 2021).

These specialized gates greatly improve RNNs ability to capture long-term dependencies in sequences. LSTMs mitigated the vanishing gradient problem that limited basic RNNs to only short-term memory. The optimized information flow makes LSTMs powerful for modeling long sequences. For time series forecasting, prior values are fed as inputs to predict future values iteratively. The cell state encodes relevant history and context. The network learns highly complex non-linear trends and relationships over time.

LSTMs can implicitly extract informative features from raw timeseries data through representation learning. Stacking LSTM layers increases model capacity. Regularization methods like dropout prevent overfitting on smaller datasets. LSTM networks provide state-of-the-art performance on challenging sequence prediction problems involving long-term temporal dynamics. The explicit memory control makes LSTMs well-suited for automotive forecasting with seasonal, cyclical patterns. LSTMs offer sophisticated deep learning modeling capabilities for time series analysis.

5.3.4.1 Forecasting Automotive Production using LSTM Networks

Long Short-Term Memory (LSTM) networks provide a sophisticated deep learning approach to modeling sequential data that can be leveraged for automotive production forecasting. LSTMs are capable of learning complex non-linear trends and long-range dependencies that often characterize real-world time series. The key advantage of LSTMs for a forecasting application is the ability to automatically learn temporal relationships from raw data without extensive feature engineering. The LSTM's recurrent architecture can ingest the historical production volumes directly and extract informative patterns through representation learning.

Preparing the data involves structuring it into overlapping input/output pairs that cover the full historical period. The production values from 2000-2015 for instance can serve as sequential inputs to predict 2016 which becomes the target output. This input-output pattern is rolled across the entire dataset to allow the LSTM model to learn the mapping from past production to future production. The recurrence enables accumulating context to improve predictions. The optimal LSTM architecture in terms of number of hidden layers and nodes is determined through hyperparameter tuning. Regularization methods like dropout and early stopping prevent overfitting on the limited data.

Once trained on the prepared data, the model can be used to iteratively forecast automotive production multiple years into the future. Each output projection gets fed back as input for the next timestep. Uncertainty bounds for the forecasts can be generated by training multiple LSTM models on bootstrap samples of the historical data. The variance across model predictions provides prediction intervals. A key advantage of LSTMs is the ability to intrinsically model both short and long-term seasonalities and cyclical effects present in production data. The non-linear modeling also captures complex relationships overlooked by statistical methods. LSTMs should be validated to avoid overfitting and unnecessarily complex models. Overall, deep LSTM networks provide state-of-the-art capabilities for automated time series modeling that can enhance automotive forecasting accuracy.

5.3.4.2 Method to Apply LSTM

A sequential LSTM network is built to model the automotive production time series data. The input shape specifies a lookback of 1 which means each timestep feeds the prior lookback values to predict the next output.

The first layer is an LSTM with 100 memory units that returns the full output sequence. This enables layer stacking by passing the temporal state forward. Next, a dropout regularization layer with rate 0.2 is added which randomly sets input values to 0 during training to prevent overfitting. Two more LSTM layers are stacked with dropout in between to increase model capacity. After the recurrent layers, two dense layers are added with 50 and 25 units respectively and ReLU activation. Dropout is also applied on these layers. The dense layers enable learning non-linear relationships. The final output layer is a single unit without activation to generate numerical production forecasts. Mean squared error loss and Adam optimizer are used for model compilation.

The model is fit on the prepared input/output pairs for a set number of epochs with batch size of 1. Verbose output helps monitor training progress. This overall architecture allows the LSTM layers to learn complex time dependencies from the raw data. The dropout and dense layers provide deeper representations. The model can then be used to iteratively forecast future automotive production at each timestep. The stacked recurrent and dense layers aim to provide sufficient capacity to accurately model the temporal patterns while regularization prevents overfitting on the limited training data. This demonstrates applying deep learning principles to build an effective

LSTM forecasting model. The Table.5.2 depicts the LSTM network architecture where three LSTM layers with 20% dropouts are added, finally they are merging into one neuron. Here we are using *mean squared error* loss function along with the *adam* optimizer with *ReLU* activation fucntions.

TABLE 5.2: LSTM Model Architecture

Layer	Details
Input	lookback = 20 time steps, feature size = 1
LSTM 1	100 memory units, return sequences
Dropout	rate = 0.2
LSTM 2	100 memory units, return sequences
Dropout	rate = 0.2
LSTM 3	100 memory units
Dropout	rate = 0.2
Dense 1	50 units, ReLU activation
Dropout	rate = 0.2
Dense 2	25 units, ReLU activation
Dropout	rate = 0.2
Output	1 unit
Loss	Mean Squared Error
Optimizer	Adam
Batch Size	256
Epochs	100
Validation Split	0.2

While the LSTM provides state-of-the-art capabilities for sequence modeling, other deep learning approaches could also be explored. More advanced LSTM networks can efficiently capture local temporal patterns. Bidirectional-LSTM networks leverage benefits. For classical statistical methods, variants of ARIMA models like SARIMAX can incorporate exogenous variables like macroeconomic indicators that may influence automotive demand. Facebook Prophet provides automated trend and seasonality modeling.

Testing different modeling paradigms provides a thorough perspective on the predictive capabilities of both modern and traditional time series forecasting techniques for this application. The strengths and limitations of each method can be contrasted. This research provides an exemplar methodology for leveraging data-driven deep learning through LSTMs for automotive forecasting. The approach can be extended to related predictive applications such as sales forecasting, inventory optimization, and production planning where temporal relationships are critical.

In this chapter, we have extensively explored various statistical and machine learning techniques for forecasting global automotive production volumes. Linear regression established a simple baseline modeling approach. ARIMA models enabled modeling autocorrelation in the time series through autoregressive and moving average components. Facebook Prophet provided automated decomposition into trend and seasonal effects. Long short-term memory (LSTM) neural networks demonstrated sophisticated sequence modeling capabilities by intrinsically learning temporal relationships. The strengths and limitations of each method were highlighted through detailed methodological discussions. Classical statistical approaches like linear models and ARIMA have the benefits of transparency and interpretability. But they make rigid assumptions about underlying data distributions. Advanced machine learning methods like Prophet and LSTMs can automatically learn complex patterns from raw data. However, they face challenges with explainability and require expertise in tuning. Hybrid approaches that blend statistical and machine learning can provide the best of both paradigms. Rigorous validation procedures including train-test splits, k-fold cross-validation and residual analysis were outlined to avoid overfitting and ensure model robustness. Quantitative performance metrics like RMSE, MAPE and R-squared were suggested for model comparisons.

The next chapter will present results from implementing these forecasting techniques on the global automotive production data. Comparative evaluation of the predictive accuracy and other merits of each approach will be analyzed. The findings will provide data-driven insights into optimal forecasting strategies for automotive manufacturers. By leveraging both classical and modern techniques, this research aims to develop an accurate and production-ready forecasting pipeline. Reliable forecasts can help automotive firms optimize inventory, manufacturing, and workforce planning. The predictive models explored constitute an essential component in business strategy.

CHAPTER VI

RESULTS AND DISCUSSIONS

6.1 Summary of Findings

This study examined two pertinent dimensions related to the semiconductor industry - firstly, assessing alternatives to silicon for electronics applications, and secondly, analyzing the pandemic's impact on automotive manufacturing reliant on silicon microchips.

Silicon has been the predominant material for integrated circuits over the past several decades, enabling exponential improvements in computing power. However, as silicon transistors approach atomic scales, limitations in performance, power efficiency, and manufacturability justify exploring complementary materials. The study reviewed promising options like germanium, gallium arsenide, graphene, and transition metal dichalcogenides. Each exhibits advantageous electronic properties surpassing silicon that could enable specialized applications, from high-speed devices to efficient optical emission. However, manufacturability and integration challenges presently restrict wholesale substitution. Nearer-term viability lies in heterogeneous integration incorporating new materials just for targeted roles where higher performance is essential. This allows preserving silicon's economies of scale while incrementally augmenting capabilities.

Regarding automotive manufacturing, the COVID-19 pandemic severely disrupted supply chains, triggering a global shortage of semiconductor chips required in vehicles. Lockdowns suspended chip production just as consumer electronics demand spiked, misaligning supply and demand. With auto production rebounding quicker than anticipated, acute shortfalls persisted. The study analyzed production trends across major auto economies using two decades of granular OICA data. China's exponential growth contrasts stagnation in established markets like Japan and Germany. Statistical and machine learning techniques were applied to model recovery timeframes following crises as a resilience indicator. Data-driven forecasts enable strategic planning, but risks necessitate agility.

In summary, this multi-pronged study systematically assessed the contemporary landscape of materials demonstrating potential to address silicon's limitations for specialized applications. It also exemplified an integrated analytical approach combining classical and modern techniques to extract insights from automotive manufacturing data. The findings provide perspective into the ongoing pursuit of successors for silicon's computing dominance, as well as data-driven strategies to aid business strategy amidst industry disruption.

6.1.1 Key Findings

As mentioned, this research have two major directions. This study reviewed contemporary research on emerging semiconductor materials that could potentially augment or replace silicon in future electronics. Silicon has been the backbone of microchip manufacturing for over half a century, enabling the realization of Moore's Law. However, as transistors shrink to atomic scales, silicon is bumping up against limitations in critical parameters including switching speeds, power efficiency, and manufacturability. These weaknesses have catalyzed growing interest in alternatives.

The study found that each candidate material offers differentiated advantages that could address specific shortcomings of scaled silicon. The elemental semiconductor germanium demonstrates higher carrier mobility and narrower bandgap, permitting lower voltage operation. This could facilitate adoption in specialized high-speed devices. However, challenges remain with thermal stability and interfacing with silicon. Novel two-dimensional materials like graphene and transition metal dichalcogenides display excellent transport properties and electrostatic control arising from their atomic layer thickness. Their nanoscale dimensions lend promise for continuing miniaturization. However, manufacturability and integration into practical circuits remain distant prospects presently.

Among compound semiconductors, gallium arsenide and indium phosphide possess direct bandgaps enabling efficient optical emission, in addition to high carrier mobilities surpassing silicon. This suits them for specialized optics and high-frequency microwave electronics. However, relative material scarcity and brittleness have thus far constrained broad adoption. Each material exhibits tradeoffs and integration barriers currently prohibiting wholesale replacement of silicon. But their advantages in targeted applications suggest prospects alongside silicon in hybrid heterogeneous integration roles.

The study also discussed techniques for incrementally decreasing silicon content rather than outright substitution. Using advanced thin-body transistor architectures with nanosheets or nanowires reduces silicon volumes. Optimizing chip architectures to minimize redundancies and power leakage provides functionality gains without the equivalent silicon real estate. And incorporating new materials just for select critical components where higher performance is required preserves silicon's economies of scale.

Regarding automotive production forecasting, the study applied both classical statistical modeling and machine learning methods like LSTM neural networks. Linear regression established a simple yet powerful baseline for modeling temporal relationships. However, this approach relies on restrictive assumptions about underlying distributions. Sophisticated recurrent networks can intrinsically learn complex seasonal and cyclical patterns from raw data without extensive feature engineering. But achieving optimal network topology and avoiding overfitting requires extensive hyperparameter tuning.

Training models on historical production figures enables multi-year forecasting to support planning. Rigorous validation using train/test splits prevents overfitting. Comparing recovery timelines following crises provides perspective into industry resilience. While data-driven forecasts bring valuable insights, inherent model limitations necessitate resilience buffers against unforeseen events. An integrated analytical framework leveraging strengths of both statistical and machine learning techniques demonstrates a rigorous methodology for production forecasting amidst uncertainty.

The study systematically assessed the current landscape of emerging materials with potential to overcome silicon limitations for specialized applications. It also exemplified a comprehensive forecasting approach combining classical and modern techniques to extract insights from historical data. The findings provide perspective into the ongoing pursuit of successors to silicon's computing dominance, as well as analytical strategies to aid business strategy in a disruptive era.

6.2 Results

In the Chapter CHAPTER V:, we explored various analytical techniques for forecasting global automotive production using historical data from the International Organization of Motor Vehicle Manufacturers (OICA) spanning 2000-2022. Both classical statistical approaches and modern machine learning methods were implemented to model the annual production volumes across this turbulent period encompassing financial crises, recessions, and supply chain disruptions.

A simple yet powerful baseline modeling paradigm was established through ordinary least squares linear regression. This approach quantifies the linear trends and relationships between production output and time. While computationally efficient and transparent, linear regression relies on restrictive assumptions about the underlying data distributions and interactions.

Autoregressive integrated moving average (ARIMA) models were examined to account for the time series momentum and seasonal effects evident in the cyclical automotive market. ARIMA modeling empirically identifies autocorrelation structures in time series data. However, extensive model selection and parameter tuning are required to avoid overfitting.

Facebook Prophet was tested as an alternative technique providing automated decomposition of temporal series into trend and seasonal components. This accessibility comes at the cost of limited flexibility compared to directly specifying model parameters as in ARIMA.

Long short-term memory (LSTM) neural networks were assessed to leverage deep learning principles for sequence forecasting. LSTMs offer sophisticated capabilities to intrinsically learn complex non-linear relationships from raw data. But realizing optimal network topology requires extensive hyperparameter tuning and guards against overfitting on limited training data.

This chapter will analyze the results from implementing these approaches to model the production recovery timelines following major crises. Statistical metrics like mean absolute percentage error will quantify model accuracy.

The aim is developing an accurate and production-ready forecasting pipeline combining classical and AI techniques. The comparative evaluation will assess strengths and weaknesses of each method. The findings can guide automotive firms in navigating market uncertainty using data-driven insights while remaining resilient to model limitations.

6.2.1 Linear Regression

The results indicate limitations in using linear regression for modeling the automotive production time series data. As shown in Fig.6.1, fitting a simple linear trendline to the historical data does not adequately capture the complex cyclical and seasonal patterns evident in the annual production volumes. The linear model is restricted to representing the overall progression in output over the multi-decade period. It manages to roughly approximate the long-term growth trajectory. However, the strict linear function fails to account for periodic fluctuations stemming from macroeconomic dynamics, industry cycles, and episodic shocks.

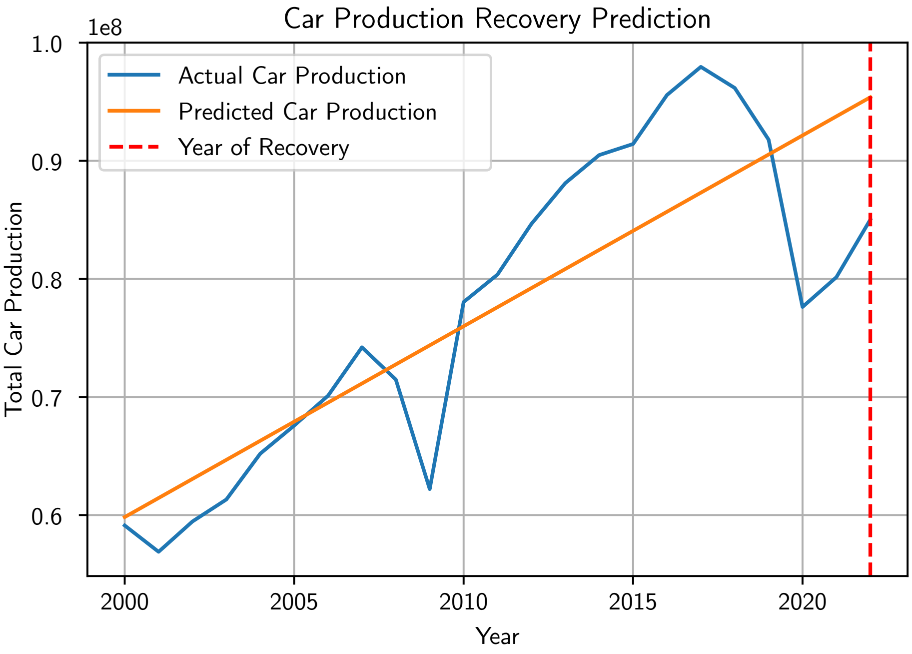

FIGURE 6.1: The Linear Regression model to forecast automobile manufacturing

Evidently, the production levels exhibit significant non-stationarity, seasonality, and volatility year-over-year reflecting fluctuating consumer demand, model cycles, and supply side constraints. The linear regression relies on restrictive assumptions of normality and homoscedasticity that do not hold for this automotive application. By focusing solely on minimizing the error to fit a straight line, the linear model does not parse the multifaceted factors driving the peaks and troughs in production. It encapsulates the general progression but cannot decompose the underlying components or adapt to oscillations. As a result, the linear fit demonstrates poor generalization beyond the training data with high deviation when extrapolated forward.

In short, while simple and interpretable, the linear regression modeling provides inadequate predictive capabilities for this automotive forecasting problem. The lack of flexibility in fitting functions makes it impossible to capture the seasonal and cyclical components that dominate the short-term variations. The linear technique only manages to extract the basic long-term trend. To enhance predictive accuracy, more sophisticated statistical or machine learning approaches are required that can intrinsically model temporal relationships without rigid linear assumptions.

6.2.2 ARIMA

The ARIMA modeling results demonstrate challenges in fitting an adequate autoregressive model to the automotive production time series. As observed in Fig.6.2, the ARIMA forecasts fail to closely track either the long-term trend or short-term fluctuations evident in the historical data. The automated ARIMA fitting procedure was unable to reliably identify the optimal configuration of autoregressive (p) and moving average (q) lags to capture the series dynamics. The model underestimates the production levels throughout the timeline. This signifies the inability to model the momentum and temporal autocorrelation present in the data.

The core limitation is the lack of any clear cyclical stationary behavior, seasonality, or short-term autocorrelations to inform the ARIMA model selection. Automotive output exhibits substantial noise, multi-year industry cycles, and significant shocks from episodic events like recessions. The complex non-stationary patterns defy modeling through the ARIMA framework designed for seasonal and momentum-driven series. Additionally, tuning a robust ARIMA requires longer data histories to tease apart overlapping lagged relationships. The limited 18 years of training data poses challenges in reliably estimating model parameters and avoiding overfitting. The automated ARIMA fitting was prone to specification errors that degraded out-of-sample accuracy.

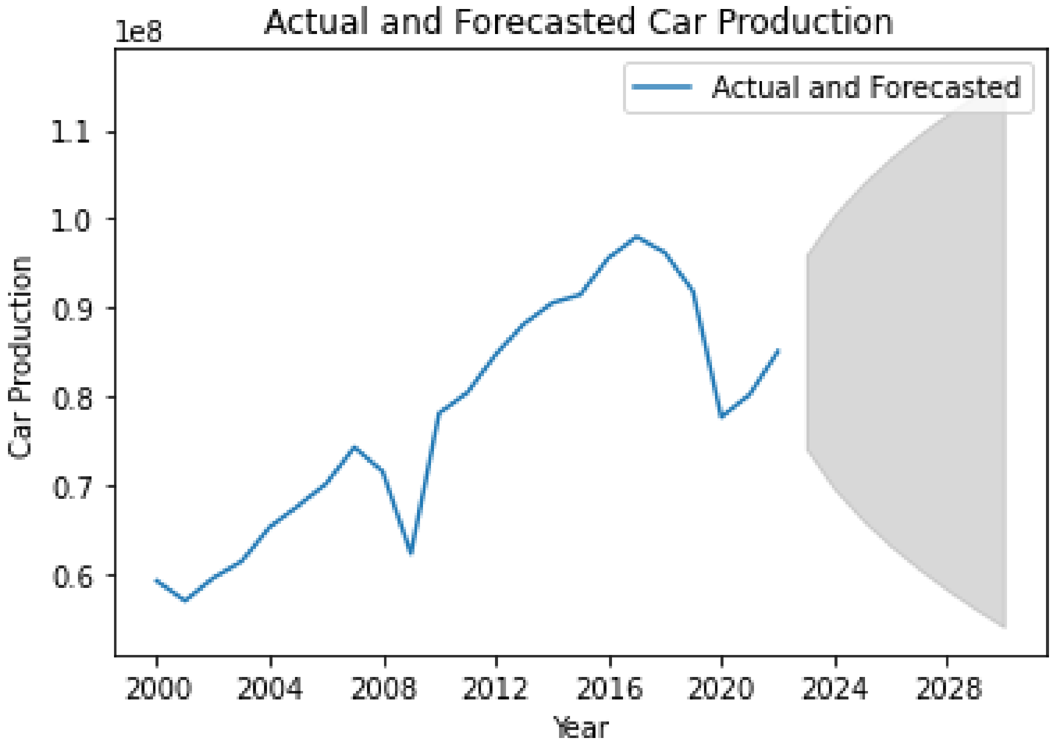

FIGURE 6.2: The ARIMA model to forecast automobile manufacturing

In short, the empirical autocorrelation modeling at the core of ARIMA failed to extract meaningful insights from the automotive production data. The series reflects complex macroeconomic interactions rather than short-term momentum. ARIMA's underlying assumptions were violated, leading to weak predictive performance. More flexible machine learning techniques that make limited explicit assumptions may suit this application better. The results underscore the importance of validating underlying model premises against the data characteristics.

If we try to analyze the auto-correlation parameters, we will end up a scenario as shown in the Fig.6.3 and Fig.6.4. The output is the ARIMA(p,d,q) model with the lowest AIC or BIC value, indicating the ideal tradeoff between model complexity and predictive accuracy. Any overfitting is penalized to ensure parsimony. The summary provides the final parameter estimates and fit diagnostics. Visualizing the residual autocorrelation can indicate if additional AR or MA terms are warranted. The Ljung-Box test assesses if the residuals are independently distributed, which is desired. The ACF and PACF plots of the residuals can diagnose remaining serial correlation in the errors.

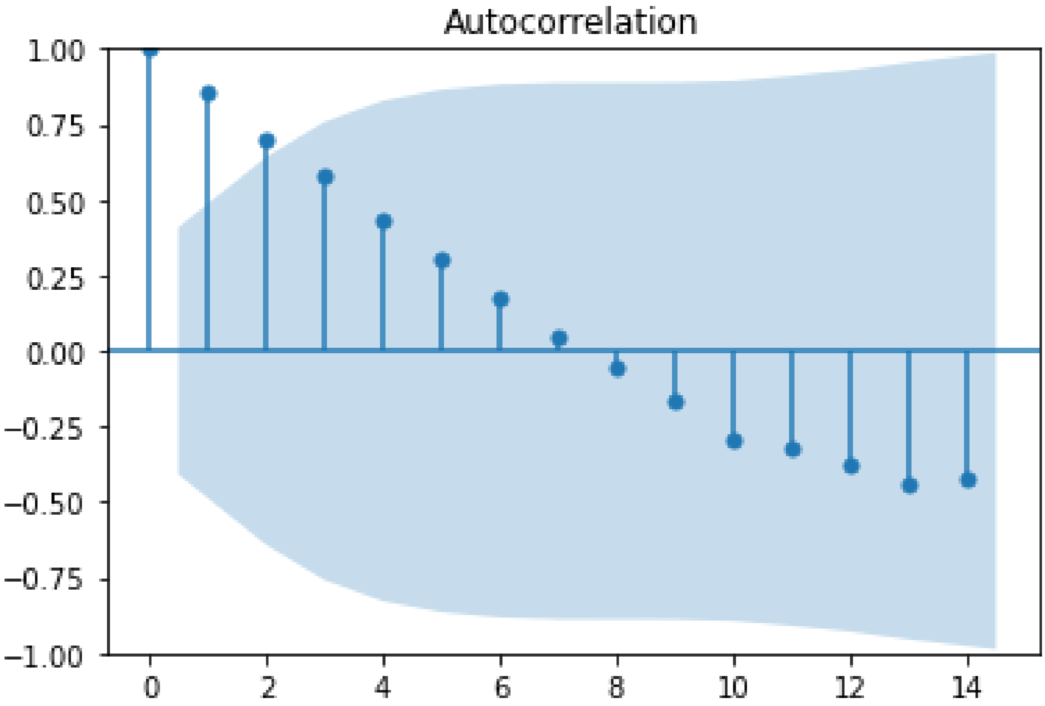

FIGURE 6.3: The Auto-Correlation from the data on automobile manufacturing

The ACF plot displays the autocorrelation function values and significance levels at varying time lags. The PACF plot shows the partial autocorrelation controlling for intermediate lags. Significant ACF and PACF spikes point to underfitting requiring higher AR and MA orders respectively. Hence, combining auto-arima with diagnostic residual analysis provides an efficient strategy for ARIMA model selection. The automated approach offers a shortlist of candidate models which are then validated with ACF/PACF visualizations to arrive at the best final model. This demonstrates a rigorous ARIMA modeling process for time series forecasting.

From the Fig.6.4, it is clear that from the data, ARIMA cannot find a suitable correlation from the past 22 years of data, for that, the model is also predicts a linear relation with a large confusion interval as shown in Fig.6.5.

6.2.3 Prophet

The Prophet model provides more nuanced modeling of the automotive production time series compared to linear regression. As observed in Fig. X, Prophet automatically decomposes the historical data into an overall growth trend component and a seasonal component reflecting periodic yearly fluctuations. The trend element captures the steady long-term increase in output

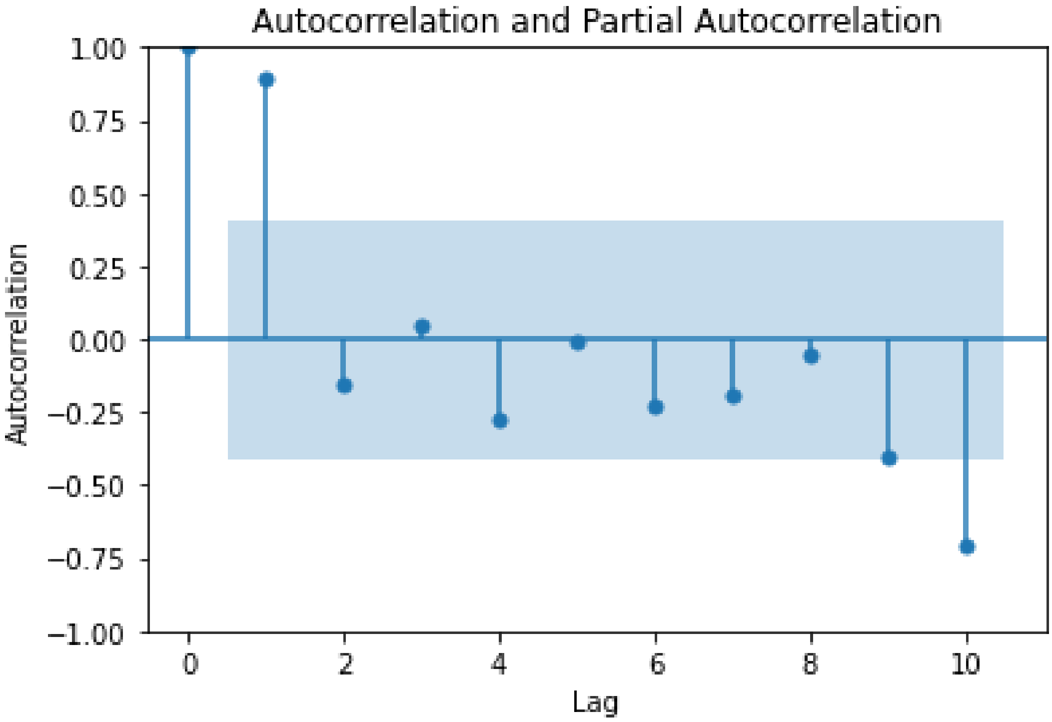

FIGURE 6.4: The Auto-Correlation and Partial Auto-correlation from the data on automobile manufacturing

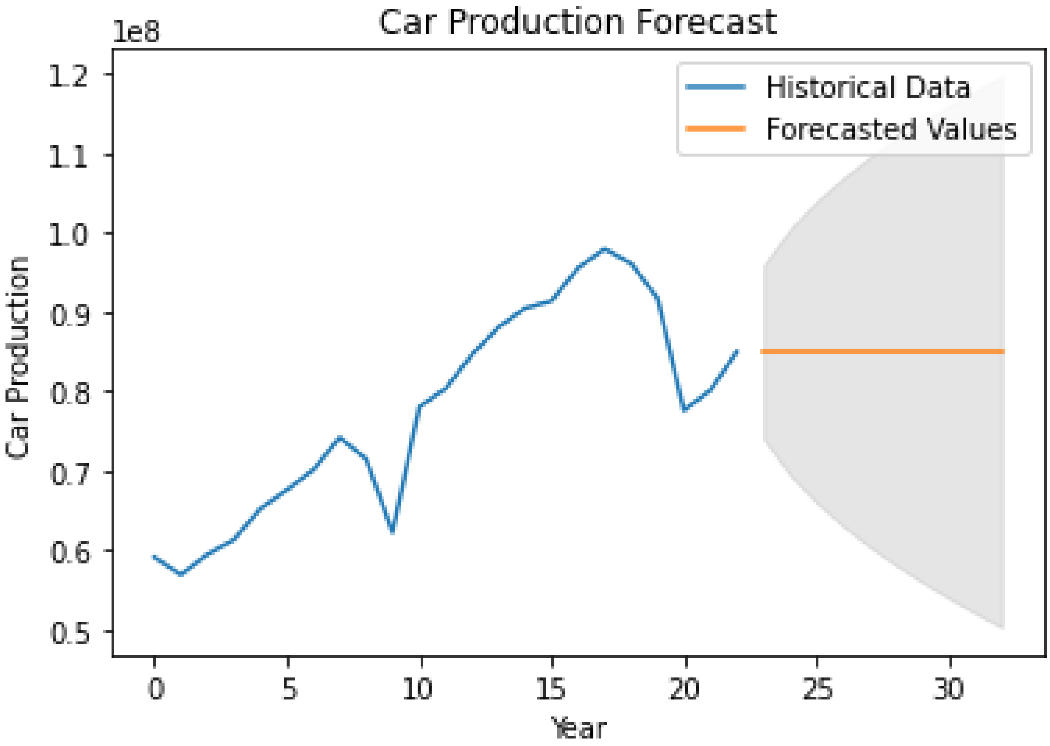

FIGURE 6.5: The Forecasting through ARIMA Model from the data on automobile manufacturing

over the full period. The seasonality component models the recurring dips and peaks within each year corresponding to macro conditions and industry sales cycles. This flexible additive model structure allows capturing both the progression and seasonality simultaneously.

The sudden decline induced by the pandemic disruption is evident in the visualized trend component around 2020. Prophet appropriately models this shock as a structural break rather than extrapolating the preceding growth. Thereafter, the trend partially recovers reflecting improving conditions, although it projects a muted trajectory due to the lingering impact. The seasonal effects exhibit consistent periodic upswings and downswings year-over-year aligning with higher automotive sales in later calendar quarters typically. The visualization provides insight into these recurring temporal patterns, as shown in the Fig.6.6.

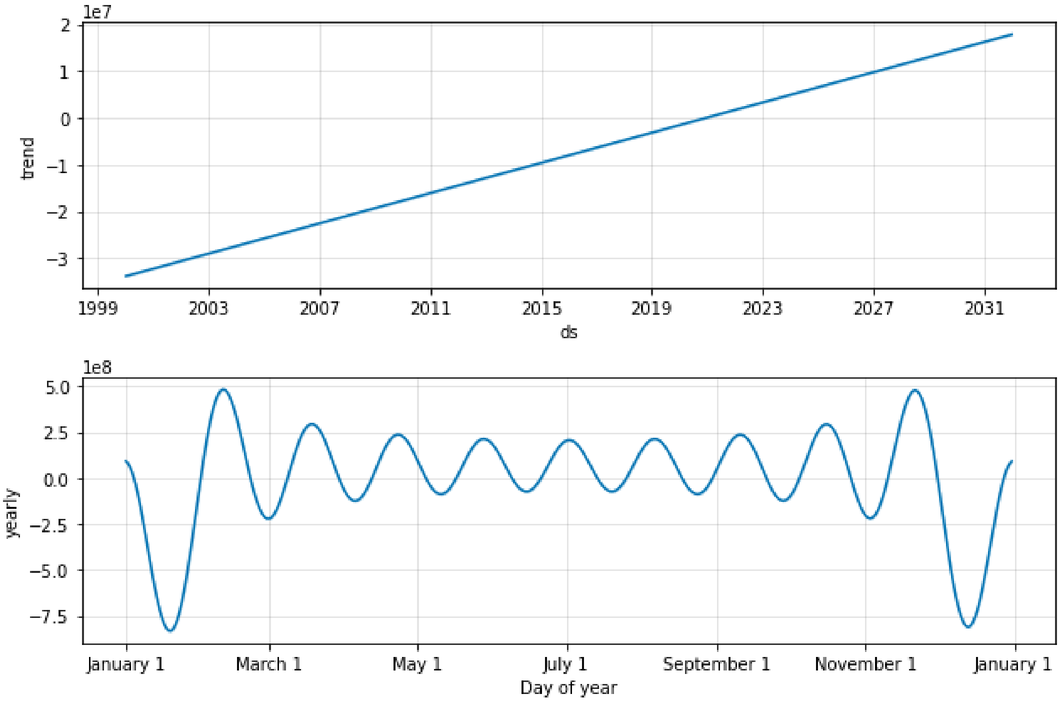

FIGURE 6.6: The Trend and Seasonality for automobile manufacturing

Based on the modeled trend and seasonal effects, Prophet generates intuitive forecasts indicating the recovery timeline from the pandemic disruption. The projected production aligns with the momentum in the historical training data. Prophet's automated decomposition provides noticeable improvements over rigid linear regression for this time series. The intuitive modeling of trend and seasonal components yields more credible projections reflective of the inherent data dynamics.

Prophet delivers more realistic modeling of the intrinsic drivers shaping automotive production trends. The visualizations build appropriate interpretability. Prophet's flexibility offers advantages over linear regression, although LSTM neural networks could capture more complex nonlinear behaviors. Nonetheless, the results showcase the value of decomposable time-series models compared to restrictive linear fits.

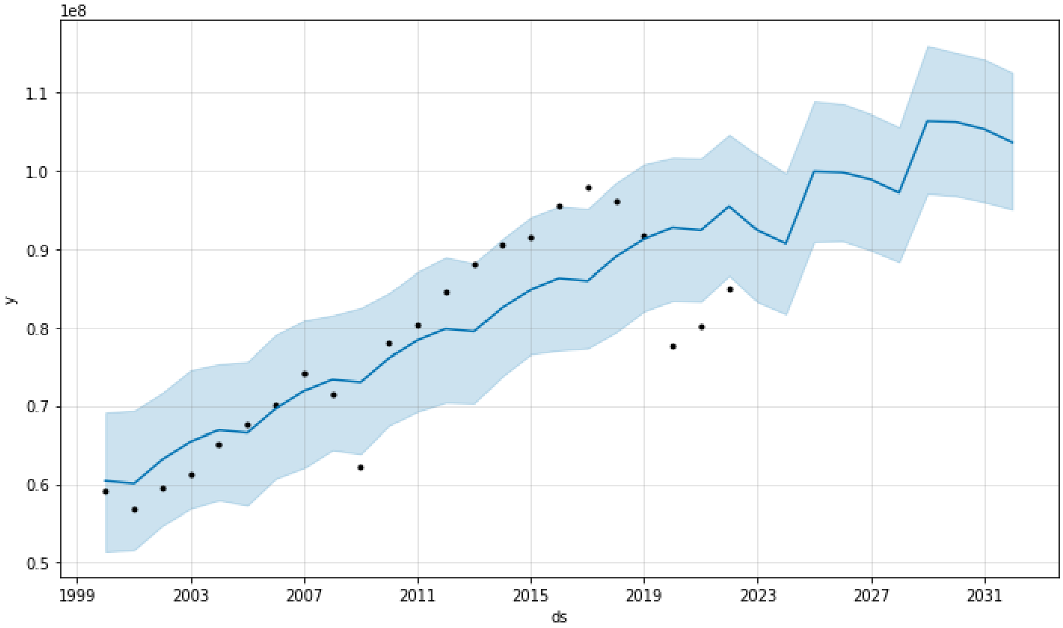

FIGURE 6.7: The Forecasting using Prophet model for automobile manufacturing

The Prophet model's visualization as shown in Fig.6.7 of the trend component provides useful insights into the progression of automotive production levels over the historical period. As observed in Fig.6.6, the modeled trend captures the overall long-term growth trajectory along with key inflection points. The production declines in the early 2000s and during the 2009 global financial crisis are evident as downward shifts in the trend. These correspond to periods of economic recession that dampened automotive demand. The trend appropriately models these as structural breaks rather than extrapolating the preceding growth.

Thereafter, the trend rebounds reflecting improving macro conditions and steady developing market expansion. This continues until the COVID-induced disruption triggers another precipitous drop around 2020. However, Prophet appropriately adapts the trend to this shock rather than overly smoothing it. The visualization makes clear how the model dynamically responds to the major exogenous events that have shaped automotive manufacturing trends based on the historical data flow. The trend embeds appropriate indicators of these key shocks and structural shifts. At the same time, it smooths short-term volatility to focus on broader momentum.

Notably, the dramatic pandemic disruption does not unduly sway the projected post-recovery trend. Prophet avoids overly fitting to this transient shock in its trend projection. The forecasted growth alignment appears sensible given wider industry expectations of multi-year recovery. The Prophet's flexible data-driven trend estimation captures the major progression patterns while adapting to significant exogenous events. The visualization provides interpretable perspective into key historical inflection points and their implications on future outlooks. The modeled trend offers a credible basis for production projections.

6.2.4 Long Short Term Memory (LSTM)

The LSTM neural network modeling demonstrates superior capabilities in fitting the complex automotive production time series compared to the linear regression, ARIMA, and Prophet techniques. As visualized in Fig.6.8, the LSTM accurately captures both the long-term trend and short-term fluctuations in the historical data.

The power of the LSTM lies in its flexible non-linear modeling of temporal relationships through learned feature representations. This avoids imposing rigid assumptions about the data distribution or momentum dynamics. The optimized gated recurrent architecture enables the network to implicitly adapt to the multiple temporal factors simultaneously shaping automotive output. Both the overall progression and episodic shocks from major crises are reliably learned from the raw production figures without extensive preprocessing. This underscores the representation learning strengths of deep neural networks. The LSTM outperforms Prophet in adapting to sudden deviations like the pandemic disruption without under/over compensating.

The LSTM showcases the state-of-the-art proficiencies of modern deep learning for time series forecasting applications. By learning informative

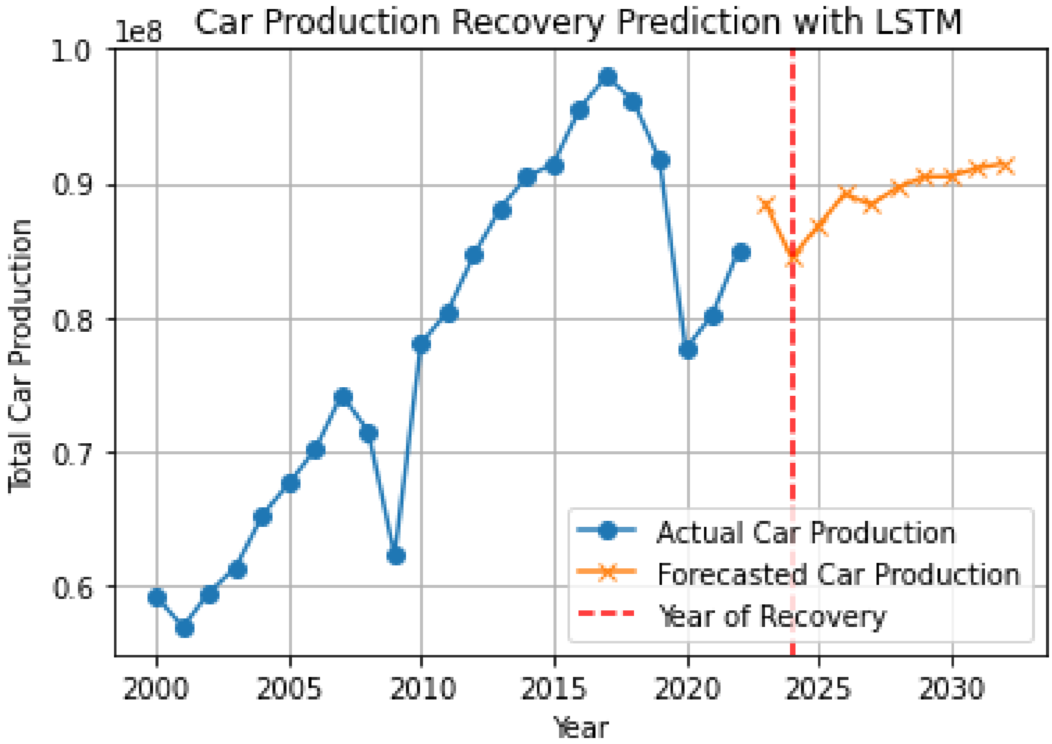

FIGURE 6.8: The LSTM model to forecast automobile manufacturing

temporal features, the network outperforms both classical statistical and decomposable timeseries models on this data. The advanced sequence modeling capabilities illustrate the merits of neural networks for production prediction amidst uncertainty. The LSTM represents a promising production-ready paradigm for automotive manufacturers to leverage data analytics in strategic planning.

The results indicate that the bidirectional LSTM model struggles to provide advantages over the unidirectional LSTM for this automotive production forecasting application. As visualized in Fig.6.9, the bidirectional LSTM generates flattened forecasts that fail to capture either the long-term trend or short-term fluctuations evident in the historical data. A key limitation is the lack of any meaningful backward-in-time dependencies or reversals in the production time series. Automotive output exhibits clear forward temporal autocorrelations but no salient backward relationships. Hence modeling the reversed sequence does not contribute useful insights.

The additional model capacity from the backward states and gates is unnecessary given the forward-only momentum. This over-parameterization likely contributes to the flattening as the network struggles to reconcile the

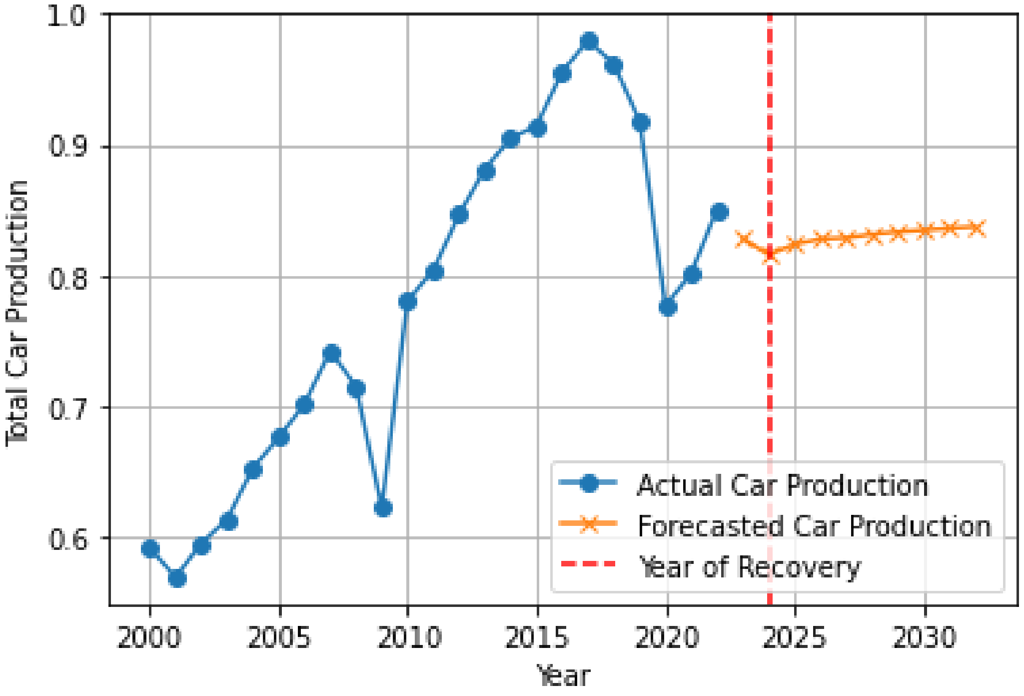

FIGURE 6.9: The Bidirectional LSTM model to forecast automobile manufacturing

redundant backward pass. The training process has no meaningful backward signals to latch onto. As a result, the bidirectional model fails to bootstrap off both directions and suffers degraded generalizability. The flattening highlights risks when deploying cutting-edge architectures without sufficient supporting evidence of bidirectional dependencies. The unidirectional LSTM sufficiently encapsulates the production time series structure.

In short, while theoretically promising, bidirectional modeling proves counterproductive for this application lacking backwards-looking dynamics. The unnecessary complexity impedes, rather than improves, predictive performance. The results emphasize the importance of parsimonious model design informed by exploratory data analysis into lagged relationships. For this automotive forecasting problem, the streamlined unidirectional LSTM demonstrates favorable effectiveness and generalizability.

6.3 Discussion

This research aimed to assess the potential of emerging semiconductor materials to address limitations of scaled silicon and exemplify analytical techniques to enhance automotive production forecasting amidst industry disruption. The study findings carry important implications for key stakeholders and also illuminate limitations that constrain the conclusions and necessitate further work. This discussion section distills high-level insights across these dimensions.

First, the implications for the semiconductor industry are discussed in detail. As silicon approaches its scaling limits, the findings highlight strategic considerations around the readiness timeline, value chain integration, and collaborative opportunities associated with migrating to new materials. The risks of supply-demand imbalances and shocks events also underscore imperatives like production diversification, demand forecasting, and policy coordination.

Next, implications specific to the automotive industry are explored. The deepening reliance on electronics and exposure to shortages emphasizes the urgency of initiatives like supply chain visibility, buffer inventory, geographic redundancy, contingency planning, and organizational agility to ensure resilience. The emerging necessity of semiconductors requires revamping procurement, production, and innovation roadmaps.

Finally, key limitations of the study scope are highlighted. The conceptual nature of the material survey, narrow forecasting demonstrations, geographically constrained literature review, and aggregate industry data each constrain the breadth of analysis and conclusions. Identifying these boundaries focuses attention on fruitful areas for further expanding the research.

6.3.1 Implications for the Semiconductor Industry

The research highlights several salient implications stemming from both the silicon material limitations and automotive production modeling dimensions that warrant consideration by semiconductor firms and industry associations. Regarding materials, the momentum towards alternatives to augment silicon poses potential disruptions to established value chains that must be strategically preempted. While silicon is poised to remain integral, its supplementary role implies gradually ceding market share in high-growth segments like optoelectronics, RF devices, and power electronics. Incumbents geared for silicon scaling may require cautious pivoting.

The challenges and uncertainties surrounding next-generation semiconductor manufacturing also underscore risks from over-concentration in legacy foundries. Prudent investment diversification into Pilot prototyping of emerging materials and process R&D provides hedging opportunities. Jockeying for dominance in the post-silicon era should be balanced with sustaining existing silicon operations. On the demand side, the cyclical volatility and vulnerability to shock events exposed in the automotive analysis highlights the imperative of demand forecasting and early warning systems to avoid over-correction. Deep coupling with automotive partners can aid alignment. Exploring futures contracts and supply guarantees may help smooth fluctuations.

More broadly, the critical interdependence of the wider electronics ecosystem on reliable semiconductor supplies spotlights the need for resilience buffers and contingency planning. Strategic stockpiling, production redundancies, and supply chain transparency are prudent safeguards given the risks of single points of failure. And from a policy perspective, the ecosystem complexity and capital intensity motivates public-private partnerships and consortium models to share costs, risks and infrastructure. Government incentives could catalyze development of domestic fabrication to reduce geographic concentration issues. Proactive policy intervention and coordination may help ensure semiconductor innovation trajectories keep pace with demand.

At the same time, exercising caution is warranted before radically overhauling an ecosystem that has successfully fueled exponential computing advancement for decades. There are rarely silver bullets in complex systemic transitions. But judicious mitigation of known risks and pressure points across design, fabrication, integration, and demand forecasting domains provides a balanced strategic imperative. Prioritizing improvements to existing value chains while exploring alternative materials, processes, and partnerships lays the foundation for an adaptive yet stable future.

Overall, the research underscores the urgency of assessing next-generation strategies spanning materials, manufacturing, supply chains, and demand synchronization to navigate the inevitability of change as silicon scaling eases.

Proactively honing resilience while selectively diversifying both technical and approaches positions semiconductor firms to lead amid uncertainty. Trusted custody through the twilight of silicon's dominance promises to smooth the passage for subsequent materials toward the next computing era.

6.3.2 Implications for the Automotive Industry

The research findings highlight pivotal implications for automotive manufacturers and suppliers stemming from both the rising prominence of electronics content and persistent cyclical volatility facing the industry. The inevitability of vehicles transforming into sophisticated computers on wheels underscores the urgency of supply chain localization, coordination, and visibility to ensure component availability keeps pace. Deepening collaboration with semiconductor partners, including via acquisitions or joint ventures, provides stability given automaking's lower priority presently.

Vertical integration can also strategically insulate from shocks, although at the expense of agility. But proactive demand planning and signaling procurement urgency to suppliers remains imperative regardless of structure. Advanced analytics and artificial intelligence can further bolster supply-demand alignment across the ecosystem. In tandem, maintaining healthy inventories of semiconductors and key electronic components acts as an essential buffer even at added holding costs. This balances efficiency and resilience given chronic uncertainty. Optionality in substituting or rationing parts also bears investigating should shortages recur.

Yet given the integral role of exterior suppliers, diversification is essential rather than outright self-sufficiency. Flexible multi-sourcing distributed across geographies provides redundancy to mitigate concentration risks, labor disputes, sanctions, or natural disasters. Smoothing demand across vendors gives incentive to dedicate capacity. Contract structures warrant examination as well to balance volume guarantees and flexibility if necessary amidst fluid conditions. Pooling procurement across OEMs could also leverage scale for priority access. And fostering trusted relationships with tier-2 and tier-3 vendors improves visibility into lower-tier risks.

But given the prevalence of shocks, contingency planning and early warning systems that continuously stress-test supply chain resilience merit urgent investment. Scenario analysis, simulations, and war-gaming can probe system dynamics under duress. Proactive contingency planning and adaptation eases navigating the next crisis. This also necessitates nurturing organizational agility and a culture of resilience. Streamlining new product introduction, engineering change approvals, and manufacturing variability fosters responsiveness. Empowered cross-functional teams with executive mandate can manage disruptions decisively. The research also indicates the risks of over-optimizing operations for steady-state efficiency versus resilience. The whiplashing between downturns and booms observed over decades suggests moderating production and inventory within steadier bands. This steadiness buffers against reactionary corrections that overshoot.

More broadly, the geographic shifts underway in automotive manufacturing evident in the analysis underscore the need to hedge bets across both established and emerging markets. While domestic footholds provide stability, expanding low-cost overseas presence opens new frontiers. Balancing local and global supply chains remains prudent. And the continuously evolving technological landscape requires strategic foresight into implications on manufacturing networks and supply needs. Electric, connected and autonomous trends will reshape semiconductor and electronics demands over coming decades. Future-proofing industrial plans requires anticipation of next-generation skill, facility and supplier requirements well in advance given the timeline from design to full-scale production. Otherwise technology gains risk supply chain roadblocks.

Above all, the emphatic lesson from recent shortages is that procrastinating on supply chain vulnerabilities only deepens eventual disruptions. Periodic stress testing, monitoring early indicators, and compiling systemic risk analytics provides the vantage point needed for agile adaptation before circumstances escalate. No company can afford to remain anchored in the past when industries transform in a flash. Bolstering the semiconductor supply chain through coordination, visibility, diversification and resilience has become imperative for automotive companies amidst the electronics transformation underway. By judiciously balancing capital investment, inventory buffers, collaborative partnerships, organizational agility and innovation focus, automakers can master disruption as adeptly as modern vehicle technology.

6.3.3 Limitations of the Study

A key limitation of this study is the conceptual nature of the survey on silicon alternative materials. While the electronic properties and potential advantages of materials like graphene, germanium, and gallium arsenide were discussed based on published research, there was no primary investigation into their actual fabrication or demonstration in devices. The theoretical benefits and integration barriers require validation through hands-on experimental research and prototyping. until these emerging materials evolve beyond the conceptual stage into practical implemented devices and circuits, their viability remains speculative.

Additionally, the automotive manufacturing forecasting analysis utilized limited historical production data at the country level. More granular and recent data on automaker-specific manufacturing volumes could improve model accuracy. The supply chain disruptions linked to semiconductor shortages are also ongoing, so data covering their full timeline is still unfolding. Models developed on incomplete crisis data may prove inaccurate or require continuous retraining. Expanding the feature set beyond past production figures could also aid the modeling, for instance incorporating leading indicators like order backlogs or macroeconomic variables.

Furthermore, while the study introduced several classical statistical and machine learning approaches for time series modeling, the implementation was narrow. Only basic linear regression, ARIMA, Prophet, and LSTM models were demonstrated. Testing an expanded set of techniques like random forests, SVMs, CNN-based encoders, and advanced LSTM architectures could provide fuller perspective on optimal methods for this application. The limited proof-of-concept modeling scope restricts conclusive determination of top-performing algorithms.

Regarding silicon alternatives, the geographic breadth was focused largely on research outcomes from the United States and Asia. Incorporating perspectives from European and other global labs on emerging semiconductors could reveal a wider array of promising materials and strategies. The study also emphasized application potential for consumer electronics and automotive industries. But adjacent sectors like aerospace, defense, and telecommunications may offer additional specialized use cases.

In terms of the semiconductor supply chain analysis, financial constraints prevented accessing proprietary datasets across the value chain. As a result, the modeling relied on publicly available aggregate production figures that lack granularity into automotive chip demand patterns, inventories, and other dynamics. More commercial data access could facilitate supply chain simulation modeling and inventory optimization techniques.

Overall, the limited experimental investigation into silicon alternatives, narrow machine learning modeling scope, geographically constrained literature survey, and reliance on public datasets without supply chain visibility represent key limitations of this initial study. But they help identify fruitful directions for deeper future research with expanded data access, broader materials and methods scope, and direct market coordination. Mitigating these limitations can reinforce the analytical rigor and practical contributions.

CHAPTER VII

SUMMARY, CONCLUSION, AND RECOMMENDATION

7.1 Summary of the Study

This research examined the global semiconductor chip shortage and its impacts on the automotive industry. Through an extensive literature review and data analysis, the study aimed to understand the shortage's causes, effects, and potential solutions.

The literature review analyzed prior research on the chip shortage, especially factors like the COVID-19 pandemic which disrupted supply chains. Semiconductor demand from surging electronics sales combined with reduced auto manufacturing triggered significant supply-demand mismatches. Case studies on automakers like Volkswagen and Toyota highlighted decreased production and lost revenues. The review also covered proposed solutions like improving supply chain visibility, diversifying suppliers, and increasing domestic chip fabrication capacity.

The data analysis focused on automotive manufacturing trends using historical production figures from the International Organization of Motor Vehicle Manufacturers. Descriptive statistics evidenced a dramatic 2020 decline in output across all major auto economies due to pandemic disruptions. But China's production dominance continued. Forecasting models like LSTM neural networks were applied to predict recovery timeframes and enhance preparedness. These flexible machine learning techniques captured complex historical patterns better than rigid statistical models.

The study also reviewed emerging semiconductor materials research, finding opportunities to augment silicon with new materials in targeted applications where differentiation is needed. This "heterogeneous integration" approach leverages new materials incrementally while the industry is still heavily reliant on silicon. However, manufacturing barriers remain. Key implications included the urgent need for supply chain resilience and coordination strategies to mitigate pandemic-exposed risks. Automakers must prioritize agility, inventory buffering, coordination and creative engineering. Information sharing and collective action are critical for managing systemic shortages. The deepening necessity for semiconductors also necessitates rethinking automotive innovation roadmaps. Meanwhile, cautions are warranted before overhauling the delicate semiconductor ecosystem enabling exponential computing advancement.

The study had limitations including conceptual-level materials analysis, constrained forecasting implementations, dependence on aggregated industry data, and geographically limited literature survey. Recommendations included addressing these limitations through expanded techniques, proprietary data access, and globally diverse information sources. Overall, this research systematically analyzed the dynamics and impacts of the global automotive chip shortage. The insights generated contribute perspectives to aid stakeholders across electronics supply chains in enhancing resilience while upholding innovation amidst disruption. The knowledge can help the automotive and semiconductor industries be better positioned to navigate future crises.

7.2 Conclusions

This research aimed to thoroughly examine the global semiconductor chip shortage and its significant impacts on the automotive industry. Through an extensive literature review and in-depth data analysis, the study has generated several crucial findings and insights.

A key conclusion is that the COVID-19 pandemic served as an external shock event that severely disrupted the delicate supply-demand balance in semiconductor supply chains. Temporary supplier factory shutdowns combined with surging consumer electronics demand triggered acute chip shortfalls as automotive production rebounded quicker than anticipated. This mismatch spotlighted the risks of over-concentrated, extended semiconductor supply chains as well as automakers' lower priority in chip allocation queues. The data analysis quantitatively evidenced a dramatic manufacturing decline in 2020 across all major auto-producing economies due to pandemic disruptions. China's enduring dominance as the world's largest automotive manufacturer was also exhibited, contrasting with stagnation in mature markets like Japan and Germany. Sophisticated forecasting techniques including LSTM neural networks were leveraged to model recovery timeframes and provide automotive firms predictive capabilities to guide strategy amidst uncertainty.

A key methodological finding was that flexible machine learning approaches like LSTM models intrinsically captured complex historical production dynamics better than traditional statistical methods like ARIMA or linear regression that rely on rigid assumptions. However, classical techniques provide greater transparency. This indicates opportunities in combining both modeling philosophies. The study also synthesized perspectives on emerging semiconductor materials displaying potential to address limitations of continued silicon scaling. While silicon will remain integral, heterogeneous integration of new materials in targeted applications where they offer differentiated advantages could unlock performance gains incrementally. However, manufacturability barriers persist. In terms of theoretical implications, the research spotlighted the urgency of resilience strategies like supply chain redundancy, visibility, and coordination to mitigate over-optimization risks evident during the pandemic. The deepening necessity of semiconductors further emphasizes the imperative for automakers to rethink innovation and procurement roadmaps. Meanwhile, the volatility underscores cautions against overhauling the delicate semiconductor ecosystem that has fueled exponential computing advancement.

Regarding practical implications, semiconductor firms must strengthen demand forecasting, customer collaboration, and contingency planning while judiciously expanding production capacity. Automakers should prioritize supply chain agility, silo-busting, inventory buffering, and creative engineering to accommodate disruptions. Open information exchange and collective action are crucial for managing systemic risks. Limitations of the study include its conceptual materials analysis, constrained machine learning implementations, dependence on aggregated industry data, and geographically limited literature survey. Future work should address these limitations through hands-on materials research, expanded analytical techniques, proprietary data access, and globally diverse information sources. Additional directions could involve comparing resilience across industries and simulations of alternative policy or procurement interventions.

In conclusion, this research systematically analyzed the dynamics of the ongoing global semiconductor chip shortage and its impacts on the automotive sector. The insights generated contribute perspectives to aid decision-making by stakeholders across the electronics value chain seeking to enhance resilience while upholding innovation in a disrupted world.

7.3 Future Research

This research on the global automotive chip shortage and emerging semiconductor materials opens up several fruitful avenues for further investigation. Additional research can build upon the findings and address limitations to expand the knowledge base. Some promising future research directions include the following sectors. These directions highlight potential high-impact opportunities for semiconductor and automotive researchers to undertake follow-on work. Expanding the analytical techniques, data sources, disciplinary breadth, and sectoral focus will enrich the scholarly discourse and practical contributions around resolving the global chip shortage predicament. As this crisis persists and technology inflection points emerge, continued research will remain imperative.

7.3.1 Materials Research and Prototyping

The conceptual review of alternatives to silicon could be expanded through hands-on materials research and prototyping. Fabricating test devices and circuits with emerging materials like graphene, gallium nitride, or gallium arsenide can validate their theoretical promises and reveal integration challenges. Collaborations with engineering teams equipped with semiconductor labs and clean rooms will enable progress beyond conceptual analysis. Successful fabrication and performance testing can demonstrate viability and inform adoption roadmaps.

7.3.2 Supply Chain Modeling and Simulation

Advanced analytical approaches like discrete event simulation, system dynamics modeling, and agent-based models can provide additional insights into automotive supply chain dynamics during disruptions. Simulations can assess bottlenecks, risk factors, and supply-demand mismatches under various scenarios. This can identify promising interventions like regional buffer inventories, increased supplier coordination, or demand signaling improvements. Collaboration with semiconductor and automotive firms will facilitate accurate modeling grounded in real-world data. Simulation-optimization hybrids can also determine optimal supply chain policies.

7.3.3 Forecasting and Demand Sensing Enhancements

More advanced time series forecasting techniques can be tested, including convolutional and recurrent neural networks like LSTMs optimized for seasonal data. Near-term demand sensing using consumer search trends, social media activity, and lead indicators could improve forecast reliability. Forecasting semiconductor prices and production factors like fab utilization can enhance visibility into the supply ecosystem. Applying multi-stakeholder supply chain analytics versus company-specific data can account for interdependencies. Probabilistic forecasts quantified with prediction intervals also better represent uncertainties.

7.3.4 Automaker Supply Chain Data Analysis

Procurement of proprietary automaker data on inventories, supplier contracts, order backlogs, and production schedules can power targeted analysis into semiconductor procurement practices. This data can feed optimization models minimizing shortages, integrate futures and options hedging, and assess regional versus global sourcing strategies. Financial analysis can weigh buffering costs against shortage impacts to determine optimal mitigation investments. Deep supply chain analytics can inform resilience strategies specific to automakers based on data-driven insights.

7.3.5 Geographic Expansion

The literature survey could encompass more global sources given semiconductor research across Asia, Europe, and America. Region-specific analysis can compare innovation ecosystems, startup activity, and commercialization pathways for silicon alternatives. Case studies from automotive and electronics hubs like Germany, Korea, Taiwan, and China can reveal location-specific advantages, risks, and strategic perspectives. Investigating global value chains can uncover additional supply-demand dynamics and geographic vulnerabilities.

7.3.6 Alternative Sector Analysis

The automotive focus could be expanded by assessing supply chain resilience across additional sectors like aerospace, computing, telecommunications, healthcare, and defense. Comparative analysis can identify commonalities and sector-specific nuances in addressing shortages. Replicating forecasting, optimization, and simulation models across industries can offer more generalized insights into building supply chain resilience. Critical learnings can transfer across sectors.

7.3.7 Circular Economy Strategies

Future materials research could focus on recycling, reusing, and extending the lifespans of chips to make supplies more sustainable. Enabling device disassembly and component recovery requires novel design approaches. Analysis of patent activity can reveal technology trends in chip sustainability. Collaboration with electronics recyclers can provide data at scale. Policy analysis can assess government incentives needed to accelerate circular semiconductor economies.

7.3.8 Consumer Behavior Analysis

Understanding the behavioral shifts in automotive consumer purchasing preferences, pricing tolerance, order backlogs, and brand loyalty during shortages provides demand-side insights. Survey, transaction, and browsing data research can reveal strategies to maintain engagement amid reduced inventories. Integrating these demand factors with supply-side analytics provides an end-to-end perspective.

APPENDIX I

CAR PRODUCTION DATA 2000 TO 2022

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2000	Argentina	238921	100711	339632	11.40
2000	Australia	323649	23473	347122	14.60
2000	Austria	115979	25047	141026	1.20
2000	Belgium	912233	121061	1033294	1.60
2000	Brazil	1351998	329519	1681517	24.50
2000	Canada	1550500	1411136	2961636	-3.20
2000	China	604677	1464392	2069069	13.10
2000	Czech Rep.	428224	27268	455492	21.10
2000	Egypt	39616	20149	59765	-21.40
2000	Finland	38468	458	38926	13.20
2000	France	2879810	468551	3348361	5.30
2000	Germany	5131918	394697	5526615	-2.80
2000	Hungary	134029	3369	137398	7.20
2000	India	517957	283403	801360	-2.10
2000	Indonesia	257058	35652	292710	228.90
2000	Iran	274985	3000	277985	132.80
2000	Italy	1422284	316031	1738315	2.20
2000	Japan	8359434	1781362	10140796	2.50
2000	Malaysia	280283	2547	282830	11.30
2000	Mexico	1279089	656438	1935527	24.90
2000	Netherlands	215085	52234	267319	-13.00
2000	Poland	481689	23283	504972	-12.20

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2000	Portugal	178509	68215	246724	-2.20
2000	Romania	64181	13984	78165	-26.90
2000	Russia	969235	236346	1205581	3.10
2000	Serbia	11091	1649	12740	141.80
2000	Slovakia	181333	450	181783	43.30
2000	Slovenia	122949	0	122949	4.10
2000	South Africa	230577	126787	357364	12.60
2000	South Korea	2602008	512990	3114998	9.60
2000	Spain	2366359	666515	3032874	6.30
2000	Sweden	259959	41384	301343	20.20
2000	Taiwan	263013	109600	372613	5.60
2000	Thailand	97129	314592	411721	27.60
2000	Turkey	297476	133471	430947	44.70
2000	Ukraine	18124	13131	31255	63.00
2000	UK	1641452	172442	1813894	-8.10
2000	USA	5542217	7257640	12799857	-1.70
2000	Uzbekistan	32273	0	32273	-27.40
2000	Others	127445	63204	190649	59.30
2001	Argentina	169580	65978	235558	-30.60
2001	Australia	285870	33505	319375	-8.00
2001	Austria	131098	24305	155403	10.20
2001	Belgium	1058656	128601	1187257	14.90
2001	Brazil	1501586	315651	1817237	8.10
2001	Canada	1274853	1257889	2532742	-14.50
2001	China	703521	1630919	2334440	12.80
2001	Czech Rep.	456927	8341	465268	2.10
2001	Egypt	37006	19091	56097	-6.10
2001	Finland	41916	404	42320	8.70
2001	France	3181549	446869	3628418	8.40
2001	Germany	5301189	390488	5691677	3.00
2001	Hungary	140401	3912	144313	5.00
2001	India	654557	160054	814611	1.70
2001	Indonesia	32237	246950	279187	-4.60
2001	Iran	316334	6882	323216	16.30
2001	Italy	1271780	307916	1579696	-9.10
2001	Japan	8117563	1659628	9777191	-3.60

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2001	Malaysia	344686	14099	358785	26.90
2001	Mexico	1000715	840293	1841008	-4.90
2001	Netherlands	189261	49682	238943	-10.60
2001	Poland	335996	11879	347875	-31.10
2001	Portugal	177357	62362	239719	-2.80
2001	Romania	56774	11987	68761	-12.00
2001	Russia	1021682	229000	1250682	3.70
2001	Serbia	7489	1490	8979	-29.50
2001	Slovakia	181644	359	182003	0.10
2001	Slovenia	116082	0	116082	-5.60
2001	South Africa	270538	136498	407036	13.90
2001	South Korea	2471444	474885	2946329	-5.40
2001	Spain	2211172	638716	2849888	-6.00
2001	Sweden	251035	38112	289147	-4.00
2001	Taiwan	195109	76595	271704	-27.10
2001	Thailand	156066	303352	459418	11.60
2001	Turkey	175343	95342	270685	-37.20
2001	Ukraine	24995	6829	31824	1.80
2001	UK	1492365	192873	1685238	-7.10
2001	USA	4879119	6545570	11424689	-10.70
2001	Uzbekistan	32425	8580	41005	27.10
2001	Others	121532	52617	174149	-8.70
2002	Argentina	111340	48061	159401	-32.30
2002	Australia	306876	36996	343872	7.70
2002	Austria	132768	19851	152619	-1.80
2002	Belgium	936903	120286	1057189	-11.00
2002	Brazil	1520285	271245	1791530	-1.40
2002	Canada	1369042	1260395	2629437	3.80
2002	China	1101696	2185108	3286804	40.80
2002	Czech Rep.	441312	5776	447088	-3.90
2002	Egypt	27422	17751	45173	-19.50
2002	Finland	41068	393	41461	-2.00
2002	France	3292797	309073	3601870	-0.70
2002	Germany	5123238	346071	5469309	-3.90
2002	Hungary	138239	3274	141513	-1.90
2002	India	703948	190848	894796	9.80

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2002	Indonesia	193492	105765	299257	7.20
2002	Iran	439116	12959	452075	39.90
2002	Italy	1125769	301312	1427081	-9.70
2002	Japan	8618354	1638961	10257315	4.90
2002	Malaysia	380000	15380	395380	10.20
2002	Mexico	960097	844573	1804670	-2.00
2002	Netherlands	182368	48923	231291	-3.20
2002	Poland	287534	23598	311132	-10.60
2002	Portugal	182573	68259	250832	4.60
2002	Romania	65266	14190	79456	15.60
2002	Russia	980061	239689	1219750	-2.50
2002	Serbia	10271	1701	11972	33.30
2002	Slovakia	225442	276	225718	24.00
2002	Slovenia	126661	0	126661	9.10
2002	South Africa	276499	127942	404441	-0.60
2002	South Korea	2651273	496311	3147584	6.80
2002	Spain	2266902	588337	2855239	0.20
2002	Sweden	237975	38218	276193	-4.50
2002	Taiwan	231506	102193	333699	22.80
2002	Thailand	169321	415630	584951	27.30
2002	Turkey	204198	142367	346565	28.00
2002	Ukraine	50393	3380	53773	69.00
2002	UK	1629934	193084	1823018	8.20
2002	USA	5018777	7260805	12279582	7.50
2002	Uzbekistan	22705	6849	29554	-27.90
2002	Others	119255	49106	168361	-3.30
2003	Argentina	109364	59812	169176	6.10
2003	Australia	365611	47650	413261	20.20
2003	Austria	118650	21006	139656	-8.50
2003	Belgium	791703	112680	909383	-14.50
2003	Brazil	1505139	322652	1827791	2.00
2003	Canada	1340175	1212687	2552862	-2.90
2003	China	2018875	2424811	4443686	35.20
2003	Czech Rep.	436279	5420	441699	-1.20
2003	Egypt	32581	17431	50012	10.70
2003	Finland	19226	432	19658	-52.60

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2003	France	3220329	399737	3620066	0.50
2003	Germany	5145403	361226	5506629	0.70
2003	Hungary	122338	3778	126116	-10.90
2003	India	907968	253555	1161523	29.80
2003	Indonesia	203196	118848	322044	7.60
2003	Iran	516930	65169	582099	28.80
2003	Italy	1026454	295177	1321631	-7.40
2003	Japan	8478328	1807890	10286218	0.30
2003	Malaysia	324911	19373	344284	-12.90
2003	Mexico	774048	801399	1575447	-12.70
2003	Netherlands	163080	52201	215281	-6.90
2003	Poland	306847	15214	322061	3.50
2003	Portugal	165576	73785	239361	-4.60
2003	Romania	75706	19541	95247	19.90
2003	Russia	1010436	268356	1278792	4.80
2003	Serbia	12996	907	13903	16.10
2003	Slovakia	281160	187	281347	24.60
2003	Slovenia	110597	7602	118199	-6.70
2003	South Africa	291249	130086	421335	4.20
2003	South Korea	2767716	410154	3177870	1.00
2003	Spain	2399374	630452	3029826	6.10
2003	Sweden	280394	42638	323032	17.00
2003	Taiwan	264837	121849	386686	15.90
2003	Thailand	251691	490371	742062	26.90
2003	Turkey	294116	239238	533354	53.90
2003	Ukraine	103000	4890	107890	100.60
2003	UK	1657558	188871	1846429	1.30
2003	USA	4510469	7604502	12114971	-1.30
2003	Uzbekistan	39196	7278	46474	57.30
2003	Others	144607	66666	211753	25.50
2004	Argentina	171400	89002	260402	53.90
2004	Australia	337510	73896	411406	-0.40
2004	Austria	227244	21474	248718	78.10
2004	Belgium	857119	43154	900273	-0.50
2004	Brazil	1862780	454447	2317227	26.80
2004	Canada	1335516	1376020	2711536	6.20

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2004	China	2480231	2754265	5234496	17.80
2004	Czech Rep.	443065	5295	448360	1.50
2004	Egypt	34591	14744	49335	-1.40
2004	Finland	10051	459	10510	-46.50
2004	France	3227416	438574	3665990	1.30
2004	Germany	5192101	377853	5569954	1.10
2004	Hungary	118590	4076	122666	-2.70
2004	India	1178354	332803	1511157	30.10
2004	Indonesia	262752	145559	408311	26.80
2004	Iran	707773	80885	788658	35.50
2004	Italy	833578	308527	1142105	-13.60
2004	Japan	8720385	1791133	10511518	2.20
2004	Malaysia	364852	107123	471975	37.10
2004	Mexico	903313	673846	1577159	0.10
2004	Netherlands	187600	59903	247503	15.00
2004	Poland	523000	78000	601000	86.60
2004	Portugal	150781	75947	226728	-5.30
2004	Romania	98997	23188	122185	28.30
2004	Russia	1110079	276048	1386127	8.40
2004	Serbia	13266	1928	15194	9.30
2004	Slovakia	223542	0	223542	-20.50
2004	Slovenia	116609	15037	131646	11.40
2004	South Africa	300963	154739	455702	8.20
2004	South Korea	3122600	346864	3469464	9.20
2004	Spain	2402501	609673	3012174	-0.60
2004	Sweden	290383	49887	340270	5.30
2004	Taiwan	299639	131175	430814	11.40
2004	Thailand	299439	628542	927981	25.10
2004	Turkey	447152	376256	823408	54.40
2004	Ukraine	179098	7792	186890	73.20
2004	UK	1647246	209293	1856539	0.50
2004	USA	4229625	7759762	11989387	-1.00
2004	Uzbekistan	66896	13833	80729	73.70
2004	Others	226533	84517	311050	47.20
2005	Argentina	182761	136994	319755	22.80
2005	Australia	316414	78299	394713	-4.10

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2005	Austria	230505	22774	253279	1.80
2005	Belgium	895109	31406	926515	2.90
2005	Brazil	2011817	519023	2530840	9.20
2005	Canada	1356271	1331621	2687892	-0.90
2005	China	3941767	1775852	5717619	9.20
2005	Czech Rep.	596774	5463	602237	34.30
2005	Egypt	43638	20911	64549	30.80
2005	Finland	21233	411	21644	105.90
2005	France	3112961	436047	3549008	-3.20
2005	Germany	5350187	407523	5757710	3.40
2005	Hungary	148533	3482	152015	23.90
2005	India	1264111	374563	1638674	8.40
2005	Indonesia	332590	168120	500710	22.60
2005	Iran	923800	153390	1077190	36.60
2005	Italy	725528	312824	1038352	-9.10
2005	Japan	9016735	1782924	10799659	2.70
2005	Malaysia	404571	158837	563408	19.40
2005	Mexico	846048	838190	1684238	6.80
2005	Netherlands	115121	65627	180748	-27.00
2005	Poland	540100	73100	613200	2.00
2005	Portugal	137602	83458	221060	-2.50
2005	Romania	174538	20644	194802	59.40
2005	Russia	1068511	285993	1354504	-2.30
2005	Serbia	12574	1605	14179	-6.70
2005	Slovakia	218349	0	218349	-2.30
2005	Slovenia	138393	39558	177951	35.20
2005	South Africa	324875	200352	525227	15.30
2005	South Korea	3357094	342256	3699350	6.60
2005	Spain	2098168	654332	2752500	-8.60
2005	Sweden	288659	50570	339229	-0.30
2005	Taiwan	323819	122526	446345	3.60
2005	Thailand	277562	845150	1122712	21.00
2005	Turkey	453663	425789	879452	6.80
2005	Ukraine	196722	19037	215759	15.40
2005	UK	1596356	206753	1803109	-2.90
2005	USA	4321272	7625381	11946653	-0.40

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2005	Uzbekistan	87512	8302	95814	18.70
2005	Others	372593	122898	495491	59.30
2006	Others	376110	155496	531606	2.30
2007	Argentina	350735	193912	544647	26.00
2007	Australia	283348	51269	334617	0.90
2007	Austria	199969	28097	228066	-17.00
2007	Belgium	789674	44729	834403	-9.10
2007	Brazil	2391354	585796	2977150	14.80
2007	Canada	1342133	1236657	2578790	0.30
2007	China	6381116	2501340	8882456	22.00
2007	Czech Rep.	925060	13588	938648	9.80
2007	Egypt	68934	35539	104473	14.20
2007	Finland	24000	303	24303	-25.80
2007	France	2550869	464985	3015854	-4.80
2007	Germany	5709139	504321	6213460	6.80
2007	Hungary	287982	4045	292027	53.50
2007	India	1713479	540250	2253729	11.60
2007	Indonesia	309208	102430	411638	38.60
2007	Iran	882000	115240	997240	10.30
2007	Italy	910860	373452	1284312	6.00
2007	Japan	9944637	1651690	11596327	1.00
2007	Malaysia	347971	93690	441661	-12.20
2007	Mexico	1209097	886148	2095245	2.40
2007	Netherlands	61912	76656	138568	-13.10
2007	Poland	695000	97703	792703	10.90
2007	Portugal	134047	42195	176242	-22.50
2007	Romania	234103	7609	241712	13.20
2007	Russia	1288652	371468	1660120	10.40
2007	Serbia	8236	1667	9903	-11.40
2007	Slovakia	571071	0	571071	93.30
2007	Slovenia	174209	24193	198402	29.60
2007	South Africa	276018	258472	534490	-9.10
2007	South Korea	3723482	362826	4086308	6.40
2007	Spain	2195780	693923	2889703	4.00
2007	Sweden	316850	49170	366020	9.90
2007	Taiwan	212685	70354	283039	-6.70

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2007	Thailand	315444	971902	1287346	7.80
2007	Turkey	634883	464530	1099413	11.30
2007	Ukraine	380061	22530	402591	39.70
2007	UK	1534567	215686	1750253	6.10
2007	USA	3924268	6856461	10780729	-4.50
2007	Uzbekistan	170000	14900	184900	68.10
2007	Others	420770	282019	702789	32.20
2008	Argentina	399236	197509	596745	9.60
2008	Australia	285590	43966	329556	-1.50
2008	Austria	125836	25441	151277	-33.70
2008	Belgium	680131	44367	724498	-13.20
2008	Brazil	2545729	670247	3215976	8.00
2008	Canada	1195436	886805	2082241	-19.30
2008	China	6737745	2561435	9299180	4.70
2008	Czech Rep.	934046	12521	946567	1.00
2008	Egypt	77563	42297	119860	14.70
2008	Finland	17519	376	17895	-26.40
2008	France	2145935	423043	2568978	-14.80
2008	Germany	5532030	513700	6045730	-2.70
2008	Hungary	342359	3696	346055	18.50
2008	India	1846051	486277	2332328	3.50
2008	Indonesia	431423	169205	600628	45.90
2008	Iran	1048307	225474	1273781	27.70
2008	Italy	659221	364553	1023774	-20.30
2008	Japan	9928143	1647501	11575644	-0.20
2008	Malaysia	484512	46298	530810	20.20
2008	Mexico	1217458	950486	2167944	3.50
2008	Netherlands	59223	73271	132494	-4.40
2008	Poland	842000	110840	952840	20.20
2008	Portugal	132242	42913	175155	-0.60
2008	Romania	231056	14252	245308	1.50
2008	Russia	1469429	320872	1790301	7.80
2008	Serbia	9818	1810	11628	17.40
2008	Slovakia	575776	0	575776	0.80
2008	Slovenia	180233	17610	197843	-0.30
2008	South Africa	321124	241841	562965	5.30

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2008	South Korea	3450478	376204	3826682	-6.80
2008	Spain	1943049	598595	2541644	-12.00
2008	Sweden	252287	56012	308299	-15.80
2008	Taiwan	138714	44260	182974	-35.40
2008	Thailand	401309	992433	1393742	8.30
2008	Turkey	621567	525543	1147110	4.30
2008	Ukraine	400799	22328	423127	5.10
2008	UK	1446619	202896	1649515	-5.80
2008	USA	3776641	4895500	8672141	-19.60
2008	Uzbekistan	195038	13000	208038	12.50
2008	Supplementary	365165	162469	527634	-11.80
2009	Argentina	380067	132857	512924	-14.10
2009	Australia	188158	39125	227283	-31.00
2009	Austria	56620	15714	72334	-52.20
2009	Belgium	524595	12510	537354	-25.80
2009	Brazil	2575418	607505	3182923	-1.00
2009	Canada	822267	668215	1490482	-28.40
2009	China	10383831	3407163	13790994	48.30
2009	Czech Rep.	976435	6810	983243	3.90
2009	Egypt	60249	32090	92339	-23.00
2009	Finland	10907	64	10971	-38.70
2009	France	1819497	228196	2047693	-20.30
2009	Germany	4964523	245334	5209857	-13.80
2009	Hungary	212773	1770	214543	-38.00
2009	India	2175220	466330	2641550	13.30
2009	Indonesia	352172	112644	464816	-22.60
2009	Iran	1170503	223572	1394075	9.40
2009	Italy	661100	182139	843239	-17.60
2009	Japan	6862161	1071896	7934057	-31.50
2009	Malaysia	447002	42267	489269	-7.80
2009	Mexico	942876	618176	1561052	-28.00
2009	Netherlands	50620	26131	76751	-42.10
2009	Poland	818800	60198	878998	-7.70
2009	Portugal	101680	24335	126015	-28.10
2009	Romania	279320	17178	296498	20.90
2009	Russia	599265	125747	725012	-59.50

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2009	Serbia	16337	401	16738	43.90
2009	Slovakia	461340	0	461340	-19.90
2009	Slovenia	202570	10179	212749	7.50
2009	South Africa	222981	150942	373923	-33.60
2009	South Korea	3158417	354509	3512926	-8.20
2009	Spain	1812688	357390	2170078	-14.60
2009	Sweden	128738	27698	156436	-49.30
2009	Taiwan	183986	42370	226356	23.70
2009	Thailand	313442	685936	999378	-28.30
2009	Turkey	510931	358674	869605	-24.20
2009	Ukraine	65646	3649	69295	-83.60
2009	UK	999460	90679	1090139	-33.90
2009	USA	2195588	3513843	5709431	-34.30
2009	Uzbekistan	110200	7700	117900	-43.30
2009	Others	302354	105010	407364	-23.40
2010	Argentina	508401	208139	716540	39.70
2010	Australia	205334	38673	244007	7.40
2010	Austria	86183	18814	104997	45.20
2010	Belgium	528996	26306	555302	3.30
2010	Brazil	2584690	797038	3381728	6.20
2010	Canada	967077	1101112	2068189	38.80
2010	China	13897083	4367678	18264761	32.40
2010	Czech Rep.	1069518	6866	1076384	9.50
2010	Egypt	76412	40271	116683	26.40
2010	Finland	6385	280	6665	-39.20
2010	France	1924171	305250	2229421	8.90
2010	Germany	5552409	353576	5905985	13.40
2010	Hungary	208571	2890	211461	-1.40
2010	India	2831542	725531	3557073	34.70
2010	Indonesia	496524	205984	702508	51.10
2010	Iran	1367014	232440	1599454	14.70
2010	Italy	573169	265017	838186	-0.60
2010	Japan	8310362	1318558	9628920	21.40
2010	Malaysia	522568	45147	567715	16.00
2010	Mexico	1386148	956134	2342282	50.00
2010	Netherlands	48025	46107	94132	22.60

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2010	Poland	785000	84474	869474	-1.10
2010	Portugal	114563	44166	158729	26.00
2010	Romania	323587	27325	350912	18.40
2010	Russia	1208362	194882	1403244	93.50
2010	Serbia	14551	649	15200	-0.09
2010	Slovakia	561933	0	561933	21.80
2010	Slovenia	201039	10301	211340	-0.70
2010	South Africa	295394	176655	472049	26.20
2010	South Korea	3866206	405535	4271741	21.60
2010	Spain	1913513	474387	2387900	10.00
2010	Sweden	177084	40000	217084	38.80
2010	Taiwan	251490	51966	303456	34.10
2010	Thailand	554387	1090126	1644513	64.60
2010	Turkey	603394	491163	1094557	25.90
2010	Ukraine	75261	7872	83133	20.00
2010	UK	1270444	123019	1393463	27.80
2010	USA	2731105	5011988	7743093	35.60
2010	Uzbekistan	130400	26480	156880	33.10
2010	Others	373587	113198	486785	21.50
2011	Argentina	577233	251538	828771	15.70
2011	Australia	189503	34690	224193	-8.10
2011	Austria	130343	22162	152505	45.20
2011	Belgium	560779	34305	595084	7.20
2011	Brazil	2519389	888472	3407861	0.80
2011	Canada	990482	1144639	2135121	3.20
2011	China	14485326	3933550	18418876	0.80
2011	Czech Rep.	1191968	7877	1199845	11.50
2011	Egypt	53072	28659	81731	-30.00
2011	Finland	2540	91	2631	-60.50
2011	France	1931030	311898	2242928	0.60
2011	Germany	5871918	275030	6146948	4.10
2011	Hungary	211218	2313	213531	1.00
2011	India	3040144	887267	3927411	10.40
2011	Indonesia	562250	276138	838388	19.30
2011	Iran	1412803	236508	1649311	3.10
2011	Italy	485606	304742	790348	-5.70

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2011	Japan	7158525	1240105	8398630	-12.80
2011	Malaysia	488441	45254	533695	-6.00
2011	Mexico	1657080	1023970	2681050	14.50
2011	Netherlands	40772	32379	73151	-22.30
2011	Poland	741000	97133	838133	-3.60
2011	Portugal	141779	50463	192242	21.10
2011	Romania	310243	24989	335232	-4.50
2011	Russia	1744097	246058	1990155	41.80
2011	Serbia	10227	796	11023	-27.50
2011	Slovakia	639763	0	639763	13.90
2011	Slovenia	168955	5164	174119	-17.60
2011	South Africa	312265	220280	532545	12.80
2011	South Korea	4221617	435477	4657094	9.00
2011	Spain	1839068	534261	2373329	-0.60
2011	Sweden	188969	N.A.	188969	-13.00
2011	Taiwan	288523	54773	343296	13.10
2011	Thailand	537987	919811	1457798	-11.40
2011	Turkey	639734	549397	1189131	8.60
2011	Ukraine	97585	7069	104654	25.90
2011	UK	1343810	120189	1463999	5.10
2011	USA	2976991	5684544	8661535	11.90
2011	Uzbekistan	146300	33260	179560	14.50
2011	Others	367138	124373	491511	1.00
2012	Argentina	497376	267119	764495	-7.80
2012	Australia	189949	36553	226502	-1.00
2012	Austria	123602	19487	143089	-6.20
2012	Belgium	504616	34232	538848	-9.50
2012	Brazil	2589236	813272	3402508	-0.20
2012	Canada	1040298	1423066	2463364	15.40
2012	China	15523658	3748150	19271808	4.60
2012	Czech Rep.	1171774	7221	1178995	-1.70
2012	Egypt	36880	19600	56480	-30.90
2012	Finland	8600	88	8688	245.50
2012	France	1682814	284951	1967765	-12.30
2012	Germany	5388459	260801	5649260	-8.10
2012	Hungary	215440	2400	217840	2.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2012	India	3296240	878473	4174713	6.30
2012	Indonesia	745144	307751	1052895	25.60
2012	Iran	856927	143162	1000089	-39.30
2012	Italy	396817	274951	671768	-15.00
2012	Japan	8554503	1388574	9943077	18.40
2012	Malaysia	509621	59999	569620	6.70
2012	Mexico	1810007	1191807	3001814	12.00
2012	Netherlands	24895	30744	55639	-23.90
2012	Poland	539671	115085	654756	-21.90
2012	Portugal	115735	47826	163561	-14.90
2012	Romania	326556	11209	337765	0.80
2012	Russia	1970087	263016	2233103	12.20
2012	Serbia	10227	805	11032	0.10
2012	Slovakia	926555	0	926555	44.80
2012	Slovenia	126836	4113	130949	-24.80
2012	South Africa	274873	264551	539424	1.30
2012	South Korea	4167089	394677	4561766	-2.00
2012	Spain	1539680	439499	1979179	-16.60
2012	Sweden	162814	N.A.	162814	-13.80
2012	Taiwan	278043	60995	339038	-1.20
2012	Thailand	945100	1484042	2429142	66.60
2012	Turkey	577296	495682	1072978	-9.80
2012	Ukraine	69687	6594	76281	-27.10
2012	UK	1464906	112039	1576945	7.70
2012	USA	4109013	6226752	10335765	19.30
2012	Uzbekistan	144980	19200	164180	-8.60
2012	Others	463990	135652	599642	22.00
2013	Argentina	506539	284468	791007	3.50
2013	Australia	170808	45118	215926	-4.70
2013	Austria	146566	19862	166428	16.30
2013	Belgium	465504	38000	503504	-6.60
2013	Brazil	2722979	989401	3712380	9.10
2013	Canada	965191	1414615	2379834	-3.40
2013	China	18084169	4032656	22116825	14.80
2013	Czech Rep.	1128473	4458	1132931	-3.90
2013	Egypt	13777	17027	30804	-45.50

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2013	Finland	7600	103	7703	-11.30
2013	France	1458220	282000	1740220	-11.60
2013	Germany	5439904	278318	5718222	1.20
2013	Hungary	317857	3430	321287	47.50
2013	India	3155694	742731	3898425	-6.60
2013	Indonesia	924753	281615	1206368	14.60
2013	Iran	630639	113041	743680	-25.60
2013	Italy	388465	269741	658206	-2.00
2013	Japan	8189323	1440858	9630181	-3.10
2013	Malaysia	543892	57515	601407	5.60
2013	Mexico	1771987	1282862	3054849	1.80
2013	Netherlands	0	29183	29183	-47.50
2013	Poland	475000	115159	590159	-9.90
2013	Portugal	109698	44318	154016	-5.80
2013	Romania	410959	38	410997	21.70
2013	Russia	1927578	264667	2192245	-1.80
2013	Serbia	113487	805	113878	932.30
2013	Slovakia	975000	0	975000	5.20
2013	Slovenia	89395	4339	93734	-28.40
2013	South Africa	265257	280656	545913	1.20
2013	South Korea	4122604	398825	4521429	-0.90
2013	Spain	1754668	408670	2163338	9.30
2013	Sweden	161080	N.A.	161080	-1.10
2013	Taiwan	291037	47683	338720	-0.10
2013	Thailand	1071076	1385981	2457057	1.10
2013	Turkey	633604	491930	1125534	4.90
2013	Ukraine	45758	4691	50449	-33.90
2013	UK	1509762	88110	1597872	1.30
2013	USA	4368835	6697597	11066432	7.10
2013	Uzbekistan	246641	0	246641	50.20
2013	Others	523679	119936	643615	7.30
2014	Argentina	363711	253618	617329	-22.00
2014	Australia	166933	13378	180311	-16.50
2014	Austria	136000	18340	152000	-8.70
2014	Belgium	481636	35195	516831	2.60
2014	Brazil	2502293	644093	3146386	-15.20

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2014	Canada	913533	1480621	2394154	0.60
2014	China	19928505	3803095	23731600	7.30
2014	Czech Rep.	1246506	4714	1251220	10.40
2014	Egypt	17542	9190	42515	-38.00
2014	Finland	45000	35	45035	484.60
2014	France	1499464	322000	1821464	4.70
2014	Germany	5604026	303522	5907548	3.30
2014	Hungary	434069	2400	437599	36.20
2014	India	3162372	682485	3844857	-1.40
2014	Indonesia	1013172	285351	1298523	7.60
2014	Iran	925975	164871	1090846	46.70
2014	Italy	401317	296547	697864	6.00
2014	Japan	8277070	1497488	9774665	1.50
2014	Malaysia	545122	50012	595134	-1.00
2014	Mexico	1915709	1452301	3368010	10.30
2014	Netherlands	29196	2232	31428	7.70
2014	Poland	472600	120904	593504	0.60
2014	Portugal	117744	43765	161509	4.90
2014	Romania	391422	12	391434	-4.80
2014	Russia	1682921	204272	1887193	-23.00
2014	Serbia	101576	695	103150	-9.40
2014	Slovakia	971160	0	971160	-0.40
2014	Slovenia	118533	58	118591	26.50
2014	South Africa	277491	288592	566083	3.70
2014	South Korea	4124116	400816	4524932	0.10
2014	Spain	1898342	504636	2402978	11.10
2014	Sweden	154174	N.A.	154174	-4.30
2014	Taiwan	332629	46594	379223	12.00
2014	Thailand	743258	1137329	1880587	-23.50
2014	Turkey	733439	437006	1170445	4.00
2014	Ukraine	25941	2810	28751	-43.00
2014	UK	1528148	70731	1598879	0.10
2014	USA	4253098	7407604	11660702	5.40
2014	Uzbekistan	245660	0	245660	-0.40
2014	Others	584144	114998	699142	8.70
2015	Argentina	308756	224927	533683	-13.50

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2015	Australia	159872	13137	173009	-4.00
2015	Austria	109000	16500	125500	-17.40
2015	Belgium	369172	40168	409340	-20.80
2015	Brazil	2018954	410509	2429463	-22.80
2015	Canada	888565	1394909	2283474	-4.60
2015	China	21079427	3423899	24503326	3.30
2015	Czech Rep.	1298236	5367	1303603	4.20
2015	Egypt	12000	24000	36000	-15.30
2015	Finland	69000	53	69053	53.30
2015	France	1553800	416200	1970000	8.20
2015	Germany	5707938	325226	6033164	2.10
2015	Hungary	491720	3650	495370	13.20
2015	India	3378063	747681	4125744	7.30
2015	Indonesia	824445	274335	1098780	-15.40
2015	Iran	884866	97471	982337	-9.90
2015	Italy	663139	351084	1014223	45.30
2015	Japan	7830722	1447516	9278238	-5.10
2015	Malaysia	558324	56347	614671	3.30
2015	Mexico	1968054	1597415	3565469	5.90
2015	Netherlands	41870	2252	44122	40.40
2015	Poland	534700	125903	660603	11.30
2015	Portugal	115468	41158	156626	-3.00
2015	Romania	387171	6	387177	-1.10
2015	Russia	1214849	169550	1384399	-26.60
2015	Serbia	82400	1230	83630	-18.90
2015	Slovakia	1000001	0	1000001	3.00
2015	Slovenia	133092	0	133092	12.20
2015	South Africa	341025	274633	615658	8.80
2015	South Korea	4135108	420849	4555957	0.70
2015	Spain	2218980	514221	2733201	13.70
2015	Sweden	188987	N.A.	188987	22.60
2015	Taiwan	298418	52667	351085	-7.40
2015	Thailand	772250	1143170	1915420	1.90
2015	Turkey	791027	567769	1358796	16.10
2015	Ukraine	5654	2590	8244	-71.30
2015	UK	1587677	94479	1682156	5.20

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2015	USA	4163679	7936416	12100095	3.80
2015	Uzbekistan	185400	0	185400	-24.50
2015	Others	693817	138866	832683	19.10
2016	Argentina	241315	231461	472776	-10.20
2016	Australia	149000	12294	161294	-6.80
2016	Austria	90000	18000	108000	-10.90
2016	Belgium	354003	45424	399427	-2.40
2016	Brazil	1778464	377892	2156356	-11.20
2016	Canada	802057	1568214	2370271	3.80
2016	China	24420744	3698050	28118794	14.50
2016	Czech Rep.	1344182	5714	1349896	8.30
2016	Egypt	10930	25300	36230	0.60
2016	Finland	55280	0	55280	-19.90
2016	France	1626000	456000	2082000	5.60
2016	Germany	5746808	315754	6062562	0.50
2016	Hungary	472000	0	472000	-4.70
2016	India	3677605	811360	4488965	7.90
2016	Indonesia	968101	209288	1177389	7.20
2016	Iran	1074000	90710	1164710	18.60
2016	Italy	713182	390334	1103516	8.80
2016	Japan	7873886	1330704	9204590	-0.80
2016	Malaysia	469720	43725	513445	-16.50
2016	Mexico	1993168	1604294	3597462	0.90
2016	Netherlands	42150	2280	44430	0.70
2016	Poland	554600	127237	681837	3.20
2016	Portugal	99200	43896	143096	-8.60
2016	Romania	358861	445	359306	-7.20
2016	Russia	1124774	179215	1303989	-5.40
2016	Serbia	79360	960	80320	-4.00
2016	Slovakia	1040000	0	1040000	0.10
2016	Slovenia	133702	0	133702	0.50
2016	South Africa	335539	263465	599004	-2.70
2016	South Korea	3859991	368518	4228509	-7.20
2016	Spain	2354117	531805	2885922	5.60
2016	Sweden	205374	N.A.	205374	8.70
2016	Taiwan	251096	58435	309531	-11.80

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2016	Thailand	805033	1139384	1944417	1.80
2016	Turkey	950888	535039	1485927	9.40
2016	Ukraine	4340	924	5264	-36.10
2016	UK	1722698	93924	1816622	8.00
2016	USA	3934357	8263780	12198137	0.80
2016	Uzbekistan	88152	0	88152	-52.50
2016	Others	781708	138454	920162	10.60
2017	Argentina	203700	268458	472158	-13.00
2017	Australia	88195	10437	98632	-3885.00
2017	Austria	81000	18880	99880	-898.00
2017	Belgium	336000	43140	379140	-508.00
2017	Brazil	2269468	430204	2699672	2520.00
2017	Canada	749458	1450331	2199789	-721.00
2017	China	24806687	4208747	29015434	319.00
2017	Czech Rep.	1413881	6112	1419993	0.00
2017	Egypt	9970	26670	36640	113.00
2017	Finland	91598	0	91598	9083.00
2017	France	1748000	479000	2227000	654.00
2017	Germany	5645581	0	5645581	-176.00
2017	Hungary	502000	3400	505400	-401.00
2017	India	3952550	830346	4782896	583.00
2017	Indonesia	982356	234259	1216615	330.00
2017	Iran	1418550	96846	1515396	1819.00
2017	Italy	742642	399568	1142210	353.00
2017	Japan	8347836	1345910	9693746	531.00
2017	Malaysia	424880	35260	460140	-1562.00
2017	Morocco	341802	34484	376826	900.00
2017	Mexico	1900029	2168386	4068415	1300.00
2017	Netherlands	155000	2280	157280	7497.00
2017	Poland	514700	175029	689729	116.00
2017	Portugal	126426	49118	175544	2268.00
2017	Romania	359240	10	359250	-2.00
2017	Russia	1348029	203264	1551293	1901.00
2017	Serbia	79360	552	79912	-51.00
2017	Slovakia	1001520	0	1001520	-370.00
2017	Slovenia	189852	0	189852	4200.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2017	South Africa	321358	268593	589951	-151.00
2017	South Korea	3735399	379514	4114913	-269.00
2017	Spain	2291492	556843	2848335	-130.00
2017	Sweden	226000	0	226000	1004.00
2017	Taiwan	230356	61207	291563	-580.00
2017	Thailand	818440	1170383	1988823	228.00
2017	Turkey	1142906	552825	1695731	1412.00
2017	Ukraine	7296	2246	9542	8127.00
2017	UK	1671166	78219	1749385	-370.00
2017	USA	3033216	8156769	11189985	-813.00
2017	Uzbekistan	140247	0	140247	5910.00
2017	Others	536725	221947	758672	1600.00
2018	Argentina	208573	258076	466649	-140.00
2018	Austria	144500	20400	164900	6970.00
2018	Belgium	265958	42535	308493	-1820.00
2018	Brazil	2386758	493051	2879809	520.00
2018	Canada	655896	1364944	2020840	-790.00
2018	China	23529423	4279773	27809196	-420.00
2018	Colombia	69000	3800	72800	-550.00
2018	Czech Rep.	1345041	0	1345041	300.00
2018	Egypt	19500	52100	71600	9500.00
2018	Finland	112104	0	112104	300.00
2018	France	1763000	507000	2270000	200.00
2018	Germany	5120409	0	5120409	-930.00
2018	Hungary	430988	0	430988	300.00
2018	India	4064774	1109871	5174645	800.00
2018	Indonesia	1055774	287940	1343714	1030.00
2018	Iran	1027313	68213	1095526	-4000.00
2018	Italy	670932	389136	1060068	-720.00
2018	Japan	8358220	1370308	9728528	40.00
2018	Malaysia	522000	42800	564800	1220.00
2018	Morocco	368601	33484	402085	1760.00
2018	Mexico	1575808	2524717	4100525	10.00
2018	Poland	451600	208046	659646	-440.00
2018	Portugal	234151	60215	294366	6770.00
2018	Romania	476769	0	476769	3110.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2018	Russia	1563572	204102	1767674	1390.00
2018	Serbia	56303	146	56449	-2850.00
2018	Slovakia	1090000	0	1090000	560.00
2018	Slovenia	209378	0	209378	1020.00
2018	South Africa	321097	289757	610854	350.00
2018	South Korea	3661730	367104	4028834	-210.00
2018	Spain	2267396	552169	2819565	-100.00
2018	Taiwan	190052	63189	253241	-1310.00
2018	Thailand	877015	1290679	2167694	900.00
2018	Turkey	1026461	523689	1550150	-860.00
2018	Ukraine	5660	963	6623	-2290.00
2018	UK	1519440	84888	1604328	-830.00
2018	USA	2795971	8518734	11314705	110.00
2018	Uzbekistan	220667	0	220667	5730.00
2018	Others	341554	152230	493784	
2019	Argentina	108364	206423	314787	-32500.00
2019	Austria	158 400	21000	179400	8800.00
2019	Belgium	247020	38777	285797	-7400.00
2019	Brazil	2448490	496498	2944988	2200.00
2019	Canada	461370	1455215	1916585	-5400.00
2019	China	21360193	4360472	25720665	-7500.00
2019	Czech Rep.	1427563	6400	1433963	-600.00
2019	Egypt	18500	0	18500	0.00
2019	Finland	114785	0	114785	2500.00
2019	France	1675198	527262	2202460	-2900.00
2019	Germany	4661328	0	4661328	-900.00
2019	Hungary	498158	0	498158	7600.00
2019	India	3623335	892682	4516017	-12200.00
2019	Indonesia	1045666	241182	1286848	-4200.00
2019	Iran	770000	51060	821060	-2500.00
2019	Italy	542007	373298	915305	-13800.00
2019	Japan	8328756	1355542	9684298	-500.00
2019	Malaysia	534115	37517	571632	1200.00
2019	Morocco	360110	34542	394652	-1800.00
2019	Mexico	1382714	2604080	3986794	-2800.00
2019	Poland	434700	215164	649864	-1500.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2019	Portugal	282142	63562	345704	17400.00
2019	Romania	490412	0	490412	2900.00
2019	Russia	1523594	196190	1719784	-2800.00
2019	Serbia	34985	130	35115	-37800.00
2019	Slovakia	1100000	0	1100000	600.00
2019	Slovenia	199102	0	199102	-4900.00
2019	South Africa	348665	283318	631983	3500.00
2019	South Korea	3612587	338030	3950617	-1900.00
2019	Spain	2248019	574336	2822355	100.00
2019	Taiwan	189549	61755	251304	-800.00
2019	Thailand	795254	1218456	2013710	-7100.00
2019	Turkey	982642	478602	1461244	-5700.00
2019	Ukraine	6254	1011	7265	9700.00
2019	UK	1303135	78270	1381405	-13900.00
2019	USA	2512780	8367239	10880019	-3700.00
2019	Uzbekistan	271113	0	271113	22900.00
2019	Others	1048191	59652	1108503	
2020	Argentina	93001	164186	257187	-18.00
2020	Austria	104544	-	104544	-42.00
2020	Belgium	237057	30403	267460	-6.00
2020	Brazil	1608870	405185	2014055	-32.00
2020	Canada	327681	1048942	1376623	-28.00
2020	China	19994081	5231161	25225242	-2.00
2020	Czech Republic	1152901	6250	1159151	-19.00
2020	Egypt	23754	-	23754	28.00
2020	Finland	86270	-	86270	-25.00
2020	France	927718	388653	1316371	-39.00
2020	Germany	3515372	227082	3742454	-24.00
2020	Hungary	406497	-	406497	-18.00
2020	India	2851268	543178	3394446	-25.00
2020	Indonesia	551400	139886	691286	-46.00
2020	Iran	826210	54787	880997	7.00
2020	Italy	451826	325339	777165	-15.00
2020	Japan	6960025	1107532	8067557	-17.00
2020	Kazakhstan	64790	10041	74831	51.00
2020	Malaysia	457755	27431	485186	-15.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2020	Morocco	221299	27131	248430	-38.00
2020	Mexico	967479	2209121	3176600	-21.00
2020	Poland	278900	172482	451382	-31.00
2020	Portugal	211281	52955	264236	-24.00
2020	Romania	438107	-	438107	-11.00
2020	Russia	1260517	174818	1435335	-17.00
2020	Serbia	23272	103	23375	-33.00
2020	Slovakia	985000	-	985000	-11.00
2020	Slovenia	141714	-	141714	-29.00
2020	South Africa	238216	209002	447218	-29.00
2020	South Korea	3211706	295068	3506774	-11.00
2020	Spain	1800664	467521	2268185	-20.00
2020	Taiwan	180967	64648	245615	-2.00
2020	Thailand	537633	889441	1427074	-29.00
2020	Turkey	855043	442835	1297878	-11.00
2020	Ukraine	4202	750	4952	-32.00
2020	United Kingdom	920928	66116	987044	-29.00
2020	USA	1926795	6895604	8822399	-19.00
2020	Uzbekistan	280080	-	280080	3.00
2020	Others	709633	109475	819108	
2021	ARGENTINA	184106	250647	434753	69.00
2021	AUSTRIA	124700	12000	136700	9.00
2021	BELGIUM	224180	36858	261038	-2.00
2021	BRAZIL	1707851	540402	2248253	12.00
2021	CANADA	288 235	826767	1115002	-19.00
2021	CHINA	21407962	4674258	26082220	3.00
2021	CZECH REPUBLIC	1 105 223	6209	1111432	-4.00
2021	EGYPT	23754		23754	0.00
2021	FINLAND	93172		93172	8.00
2021	FRANCE	917907	433401	1351308	3.00
2021	GERMANY	3096165	212527	3308692	-12.00
2021	HUNGARY	394302		394302	-3.00
2021	INDIA	3631095	768017	4399112	30.00
2021	INDONESIA	889756	232211	1121967	63.00
2021	ITALY	442432	353424	795856	2.00
2021	JAPAN	6619242	1227713	7846955	-3.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2021	KAZAKHSTAN	80679	11738	92417	24.00
2021	MALAYSIA	446431	35220	481651	-1.00
2021	MOROCCO	338339	64668	403007	23.00
2021	MEXICO	708242	2437411	3145653	-1.00
2021	POLAND	260800	178621	439421	-3.00
2021	PORTUGAL	229221	60733	289954	10.00
2021	ROMANIA	420755		420755	-4.00
2021	RUSSIA	1352740	213577	1566317	9.00
2021	SERBIA	21109	154	21263	-9.00
2021	SLOVAKIA	1000000		1000000	1.00
2021	SLOVENIA	95797		95797	-32.00
2021	SOUTH AFRICA	239267	259820	499087	12.00
2021	SOUTH KOREA	3162727	299677	3462404	-1.00
2021	SPAIN	1662174	435959	2098133	-8.00
2021	TAIWAN	196749	68571	265320	8.00
2021	THAILAND	594690	1091015	1685705	18.00
2021	TURKEY	782835	493305	1276140	-2.00
2021	UKRAINE	7342	811	8153	65.00
2021	UNITED KINGDOM	859575	72913	932488	-6.00
2021	USA	1563060	7604154	9167214	4.00
2021	UZBEKISTAN	236 667	4982	241649	-15.00
2021	OTHERS	1645014	183930	1828944	
2022	ARGENTINA	257505	279388	536893	24.00
2022	AUSTRIA	107500	0	107500	-21.00
2022	BELGIUM	232100	44454	276554	6.00
2022	BRAZIL	1824833	544936	2369769	5.00
2022	CANADA	289371	939364	1228735	10.00
2022	CHINA	23836083	3184532	27020615	3.00
2022	CZECH REPUBLIC	1217787	6669	1224456	10.00
2022	FINLAND	73044	0	73044	-15.00
2022	FRANCE	1010466	372707	1383173	2.00
2022	GERMANY	3480357	197463	3677820	11.00
2022	HUNGARY	441729	0	441729	6.00
2022	INDIA	4439039	1017818	5456857	24.00
2022	INDONESIA	1214250	255896	1470146	31.00
2022	ITALY	473194	323200	796394	0.00

Year	Country/Region	Cars	Commercial vehicles	Total	% change
2022	JAPAN	6566356	1269163	7835519	0.00
2022	KAZAKHSTAN	103345	9195	112540	22.00
2022	MALAYSIA	650190	52085	702275	46.00
2022	MOROCCO	404742	60122	464864	15.00
2022	MEXICO	658001	2851071	3509072	10.00
2022	POLAND	255100	228740	483840	10.00
2022	PORTUGAL	256018	66386	322404	11.00
2022	ROMANIA	509465	0	509465	21.00
2022	RUSSIA	448897	159563	608460	-61.00
2022	SERBIA	4358	140	4498	-79.00
2022	SLOVAKIA	1000000	0	1000000	-3.00
2022	SLOVENIA	68130	0	68130	-29.00
2022	SOUTH AFRICA	309423	246466	555889	11.00
2022	SOUTH KOREA	3438355	318694	3757049	9.00
2022	SPAIN	1785432	434030	2219462	6.00
2022	TAIWAN	191409	69854	261263	-2.00
2022	THAILAND	594057	1289458	1883515	12.00
2022	TURKEY	810889	541759	1352648	6.00
2022	UKRAINE	1490	0	1490	-82.00
2022	UNITED KINGDOM	775014	101600	876614	-6.00
2022	USA	1751736	8308603	10060339	10.00
2022	UZBEKISTAN	328118	5451	333569	38.00
2022	OTHERS	1790867	239271	2030138	

APPENDIX II

CHIP STOCK PRICES 2000 TO 2022

Date	Ticker	Close
2000-01-01 00:00:00-05:00	TSM	11.2391996383667
2000-04-01 00:00:00-05:00	TSM	9.732755661010742
2000-07-01 00:00:00-04:00	TSM	5.158201694488525
2000-10-01 00:00:00-04:00	TSM	4.353711128234863
2001-01-01 00:00:00-05:00	TSM	4.921586036682129
2001-04-01 00:00:00-05:00	TSM	5.36730432510376
2001-07-01 00:00:00-04:00	TSM	3.3532416820526123
2001-10-01 00:00:00-04:00	TSM	6.0669264793396
2002-01-01 00:00:00-05:00	TSM	7.331902503967285
2002-04-01 00:00:00-05:00	TSM	5.052829265594482
2002-07-01 00:00:00-04:00	TSM	2.468112707138061
2002-10-01 00:00:00-04:00	TSM	2.7401885986328125
2003-01-01 00:00:00-05:00	TSM	2.6585655212402344
2003-04-01 00:00:00-05:00	TSM	3.917886018753052
2003-07-01 00:00:00-04:00	TSM	4.546146392822266
2003-10-01 00:00:00-04:00	TSM	4.29848051071167
2004-01-01 00:00:00-05:00	TSM	4.382435321807861
2004-04-01 00:00:00-05:00	TSM	3.976681470870972
2004-07-01 00:00:00-04:00	TSM	3.455838203430176
2004-10-01 00:00:00-04:00	TSM	4.109251976013184
2005-01-01 00:00:00-05:00	TSM	4.1044135093688965
2005-04-01 00:00:00-05:00	TSM	4.634888648986816
2005-07-01 00:00:00-04:00	TSM	4.326910018920898
2005-10-01 00:00:00-04:00	TSM	5.216506004333496

Date	Ticker	Close
2006-01-01 00:00:00-05:00	TSM	5.295464992523193
2006-04-01 00:00:00-05:00	TSM	4.977210521697998
2006-07-01 00:00:00-04:00	TSM	5.439726829528809
2006-10-01 00:00:00-04:00	TSM	6.193354606628418
2007-01-01 00:00:00-05:00	TSM	6.091361045837402
2007-04-01 00:00:00-04:00	TSM	6.3066840171813965
2007-07-01 00:00:00-04:00	TSM	5.98413610458374
2007-10-01 00:00:00-04:00	TSM	5.889524459838867
2008-01-01 00:00:00-05:00	TSM	6.072834491729736
2008-04-01 00:00:00-04:00	TSM	6.4512786865234375
2008-07-01 00:00:00-04:00	TSM	5.540648460388184
2008-10-01 00:00:00-04:00	TSM	4.921773433685303
2009-01-01 00:00:00-05:00	TSM	5.575932025909424
2009-04-01 00:00:00-04:00	TSM	5.862515926361084
2009-07-01 00:00:00-04:00	TSM	6.86232328414917
2009-10-01 00:00:00-04:00	TSM	7.511081218719482
2010-01-01 00:00:00-05:00	TSM	6.8873467445373535
2010-04-01 00:00:00-04:00	TSM	6.408056259155273
2010-07-01 00:00:00-04:00	TSM	6.657549858093262
2010-10-01 00:00:00-04:00	TSM	8.643174171447754
2011-01-01 00:00:00-05:00	TSM	8.39504623413086
2011-04-01 00:00:00-04:00	TSM	8.691421508789062
2011-07-01 00:00:00-04:00	TSM	8.210500717163086
2011-10-01 00:00:00-04:00	TSM	9.273625373840332
2012-01-01 00:00:00-05:00	TSM	10.97606372833252
2012-04-01 00:00:00-04:00	TSM	10.027873992919922
2012-07-01 00:00:00-04:00	TSM	11.363965034484863
2012-10-01 00:00:00-04:00	TSM	12.77048683166504
2013-01-01 00:00:00-05:00	TSM	12.79280948638916
2013-04-01 00:00:00-04:00	TSM	13.633755683898926
2013-07-01 00:00:00-04:00	TSM	12.62164306640625
2013-10-01 00:00:00-04:00	TSM	13.34086799621582
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Date	Ticker	Close
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2016-07-01 00:00:00-04:00	TSM	25.613815307617188
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2017-04-01 00:00:00-04:00	TSM	29.272930145263672
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2017-10-01 00:00:00-04:00	TSM	34.28174591064453
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2000-10-01 00:00:00-04:00	NVDA	1.2527339458465576

Date	Ticker	Close
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Date	Ticker	Close
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Date	Ticker	Close
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Date	Ticker	Close
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Date	Ticker	Close
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2015-07-01 00:00:00-04:00	ASML	81.55062103271484
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2016-10-01 00:00:00-04:00	ASML	105.23704528808594
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2017-10-01 00:00:00-04:00	ASML	164.6516876220703
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2021-07-01 00:00:00-04:00	ASML	732.13916015625
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2022-01-01 00:00:00-05:00	ASML	658.0091552734375
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Date	Ticker	Close
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2010-05-01 00:00:00-04:00	AVGO	16.032094955444336
2010-08-01 00:00:00-04:00	AVGO	18.183462142944336
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2011-02-01 00:00:00-05:00	AVGO	24.71783828735352
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2014-11-01 00:00:00-04:00	AVGO	80.98564147949219
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2015-05-01 00:00:00-04:00	AVGO	99.15575408935548
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2016-11-01 00:00:00-04:00	AVGO	161.02626037597656
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2017-08-01 00:00:00-04:00	AVGO	216.12046813964844
2017-11-01 00:00:00-04:00	AVGO	203.9463653564453
2018-02-01 00:00:00-05:00	AVGO	189.8946075439453
2018-05-01 00:00:00-04:00	AVGO	186.25233459472656

Date	Ticker	Close
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2018-11-01 00:00:00-04:00	AVGO	230.0236053466797
2019-02-01 00:00:00-05:00	AVGO	275.904052734375
2019-05-01 00:00:00-04:00	AVGO	253.53054809570312
2019-08-01 00:00:00-04:00	AVGO	258.4856872558594
2019-11-01 00:00:00-04:00	AVGO	271.82965087890625
2020-02-01 00:00:00-05:00	AVGO	244.40382385253903
2020-05-01 00:00:00-04:00	AVGO	289.8564758300781
2020-08-01 00:00:00-04:00	AVGO	323.240966796875
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2021-08-01 00:00:00-04:00	AVGO	508.1056518554688
2021-11-01 00:00:00-04:00	AVGO	564.0164184570312
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2000-10-01 00:00:00-04:00	AMD	13.8125
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2001-04-01 00:00:00-05:00	AMD	28.899999618530277
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2002-10-01 00:00:00-04:00	AMD	6.460000038146973
2003-01-01 00:00:00-05:00	AMD	6.179999828338623
2003-04-01 00:00:00-05:00	AMD	6.409999847412109
2003-07-01 00:00:00-04:00	AMD	11.109999656677246
2003-10-01 00:00:00-04:00	AMD	14.899999618530272
2004-01-01 00:00:00-05:00	AMD	16.229999542236328
2004-04-01 00:00:00-05:00	AMD	15.899999618530272

Date	Ticker	Close
2004-07-01 00:00:00-04:00	AMD	13.0
2004-10-01 00:00:00-04:00	AMD	22.020000457763672
2005-01-01 00:00:00-05:00	AMD	16.1200008392334
2005-04-01 00:00:00-05:00	AMD	17.34000015258789
2005-07-01 00:00:00-04:00	AMD	25.200000762939453
2005-10-01 00:00:00-04:00	AMD	30.600000381469727
2006-01-01 00:00:00-05:00	AMD	33.15999984741211
2006-04-01 00:00:00-05:00	AMD	24.420000076293945
2006-07-01 00:00:00-04:00	AMD	24.850000381469727
2006-10-01 00:00:00-04:00	AMD	20.350000381469727
2007-01-01 00:00:00-05:00	AMD	13.0600004196167
2007-04-01 00:00:00-04:00	AMD	14.300000190734863
2007-07-01 00:00:00-04:00	AMD	13.199999809265137
2007-10-01 00:00:00-04:00	AMD	7.5
2008-01-01 00:00:00-05:00	AMD	5.889999866485596
2008-04-01 00:00:00-04:00	AMD	5.829999923706055
2008-07-01 00:00:00-04:00	AMD	5.25
2008-10-01 00:00:00-04:00	AMD	2.1600000858306885
2009-01-01 00:00:00-05:00	AMD	3.049999952316284
2009-04-01 00:00:00-04:00	AMD	3.869999885559082
2009-07-01 00:00:00-04:00	AMD	5.659999847412109
2009-10-01 00:00:00-04:00	AMD	9.68000030517578
2010-01-01 00:00:00-05:00	AMD	9.270000457763672
2010-04-01 00:00:00-04:00	AMD	7.320000171661377
2010-07-01 00:00:00-04:00	AMD	7.110000133514404
2010-10-01 00:00:00-04:00	AMD	8.180000305175781
2011-01-01 00:00:00-05:00	AMD	8.600000381469727
2011-04-01 00:00:00-04:00	AMD	6.989999771118164
2011-07-01 00:00:00-04:00	AMD	5.079999923706055
2011-10-01 00:00:00-04:00	AMD	5.400000095367432
2012-01-01 00:00:00-05:00	AMD	8.020000457763672
2012-04-01 00:00:00-04:00	AMD	5.730000019073486
2012-07-01 00:00:00-04:00	AMD	3.369999885559082
2012-10-01 00:00:00-04:00	AMD	2.400000095367432
2013-01-01 00:00:00-05:00	AMD	2.549999952316284
2013-04-01 00:00:00-04:00	AMD	4.079999923706055

Date	Ticker	Close
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2013-10-01 00:00:00-04:00	AMD	3.869999885559082
2014-01-01 00:00:00-05:00	AMD	4.010000228881836
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2014-07-01 00:00:00-04:00	AMD	3.4100000858306885
2014-10-01 00:00:00-04:00	AMD	2.6700000762939453
2015-01-01 00:00:00-05:00	AMD	2.680000066757202
2015-04-01 00:00:00-04:00	AMD	2.400000095367432
2015-07-01 00:00:00-04:00	AMD	1.7200000286102295
2015-10-01 00:00:00-04:00	AMD	2.869999885559082
2016-01-01 00:00:00-05:00	AMD	2.8499999046325684
2016-04-01 00:00:00-04:00	AMD	5.139999866485596
2016-07-01 00:00:00-04:00	AMD	6.909999847412109
2016-10-01 00:00:00-04:00	AMD	11.34000015258789
2017-01-01 00:00:00-05:00	AMD	14.550000190734863
2017-04-01 00:00:00-04:00	AMD	12.479999542236328
2017-07-01 00:00:00-04:00	AMD	12.75
2017-10-01 00:00:00-04:00	AMD	10.279999732971191
2018-01-01 00:00:00-05:00	AMD	10.050000190734863
2018-04-01 00:00:00-04:00	AMD	14.989999771118164
2018-07-01 00:00:00-04:00	AMD	30.88999938964844
2018-10-01 00:00:00-04:00	AMD	18.459999084472656
2019-01-01 00:00:00-05:00	AMD	25.520000457763672
2019-04-01 00:00:00-04:00	AMD	30.3700008392334
2019-07-01 00:00:00-04:00	AMD	28.989999771118164
2019-10-01 00:00:00-04:00	AMD	45.86000061035156
2020-01-01 00:00:00-05:00	AMD	45.47999954223633
2020-04-01 00:00:00-04:00	AMD	52.61000061035156
2020-07-01 00:00:00-04:00	AMD	81.98999786376953
2020-10-01 00:00:00-04:00	AMD	91.70999908447266
2021-01-01 00:00:00-05:00	AMD	78.5
2021-04-01 00:00:00-04:00	AMD	93.93000030517578
2021-07-01 00:00:00-04:00	AMD	102.9000015258789
2021-10-01 00:00:00-04:00	AMD	143.89999389648438
2022-01-01 00:00:00-05:00	AMD	109.33999633789062
2022-04-01 00:00:00-04:00	AMD	76.47000122070312

Date	Ticker	Close
2022-07-01 00:00:00-04:00	AMD	63.36000061035156
2022-10-01 00:00:00-04:00	AMD	64.7699966430664
2000-01-01 00:00:00-05:00	QCOM	49.20320129394531
2000-04-01 00:00:00-05:00	QCOM	19.77190971374512
2000-07-01 00:00:00-04:00	QCOM	23.479143142700195
2000-10-01 00:00:00-04:00	QCOM	27.083385467529297
2001-01-01 00:00:00-05:00	QCOM	18.65973472595215
2001-04-01 00:00:00-05:00	QCOM	19.271011352539062
2001-07-01 00:00:00-04:00	QCOM	15.665935516357422
2001-10-01 00:00:00-04:00	QCOM	16.641347885131836
2002-01-01 00:00:00-05:00	QCOM	12.403572082519531
2002-04-01 00:00:00-05:00	QCOM	9.05882740020752
2002-07-01 00:00:00-04:00	QCOM	9.10166835784912
2002-10-01 00:00:00-04:00	QCOM	11.991657257080078
2003-01-01 00:00:00-05:00	QCOM	11.863136291503906
2003-04-01 00:00:00-05:00	QCOM	11.860536575317385
2003-07-01 00:00:00-04:00	QCOM	13.773171424865724
2003-10-01 00:00:00-04:00	QCOM	17.857036590576172
2004-01-01 00:00:00-05:00	QCOM	21.983667373657227
2004-04-01 00:00:00-05:00	QCOM	24.23003387451172
2004-07-01 00:00:00-04:00	QCOM	25.96207618713379
2004-10-01 00:00:00-04:00	QCOM	28.248554229736328
2005-01-01 00:00:00-05:00	QCOM	24.443681716918945
2005-04-01 00:00:00-05:00	QCOM	22.072742462158203
2005-07-01 00:00:00-04:00	QCOM	29.99566650390625
2005-10-01 00:00:00-04:00	QCOM	28.940921783447266
2006-01-01 00:00:00-05:00	QCOM	34.067386627197266
2006-04-01 00:00:00-05:00	QCOM	27.024354934692383
2006-07-01 00:00:00-04:00	QCOM	24.58047866821289
2006-10-01 00:00:00-04:00	QCOM	25.63625144958496
2007-01-01 00:00:00-05:00	QCOM	29.032886505126957
2007-04-01 00:00:00-04:00	QCOM	29.618003845214844
2007-07-01 00:00:00-04:00	QCOM	28.938161849975582
2007-10-01 00:00:00-04:00	QCOM	27.045482635498047
2008-01-01 00:00:00-05:00	QCOM	28.280122756958008
2008-04-01 00:00:00-04:00	QCOM	30.70311546325684

Date	Ticker	Close
2008-07-01 00:00:00-04:00	QCOM	29.832050323486328
2008-10-01 00:00:00-04:00	QCOM	24.949708938598636
2009-01-01 00:00:00-05:00	QCOM	27.224321365356445
2009-04-01 00:00:00-04:00	QCOM	31.77266502380371
2009-07-01 00:00:00-04:00	QCOM	31.7426815032959
2009-10-01 00:00:00-04:00	QCOM	32.764522552490234
2010-01-01 00:00:00-05:00	QCOM	29.831398010253903
2010-04-01 00:00:00-04:00	QCOM	23.45099258422852
2010-07-01 00:00:00-04:00	QCOM	32.4001350402832
2010-10-01 00:00:00-04:00	QCOM	35.70866012573242
2011-01-01 00:00:00-05:00	QCOM	39.718994140625
2011-04-01 00:00:00-04:00	QCOM	41.27348327636719
2011-07-01 00:00:00-04:00	QCOM	35.47846603393555
2011-10-01 00:00:00-04:00	QCOM	40.086219787597656
2012-01-01 00:00:00-05:00	QCOM	50.0703125
2012-04-01 00:00:00-04:00	QCOM	41.10359191894531
2012-07-01 00:00:00-04:00	QCOM	46.3143424987793
2012-10-01 00:00:00-04:00	QCOM	46.05142211914063
2013-01-01 00:00:00-05:00	QCOM	50.03026580810547
2013-04-01 00:00:00-04:00	QCOM	45.82659530639648
2013-07-01 00:00:00-04:00	QCOM	50.77999496459961
2013-10-01 00:00:00-04:00	QCOM	56.30276870727539
2014-01-01 00:00:00-05:00	QCOM	60.08398818969727
2014-04-01 00:00:00-04:00	QCOM	60.62486267089844
2014-07-01 00:00:00-04:00	QCOM	57.53420639038086
2014-10-01 00:00:00-04:00	QCOM	57.51206207275391
2015-01-01 00:00:00-05:00	QCOM	53.96469879150391
2015-04-01 00:00:00-04:00	QCOM	49.02654647827149
2015-07-01 00:00:00-04:00	QCOM	42.35139846801758
2015-10-01 00:00:00-04:00	QCOM	39.73542785644531
2016-01-01 00:00:00-05:00	QCOM	41.05083465576172
2016-04-01 00:00:00-04:00	QCOM	43.4050407409668
2016-07-01 00:00:00-04:00	QCOM	56.03487396240234
2016-10-01 00:00:00-04:00	QCOM	53.78810501098633
2017-01-01 00:00:00-05:00	QCOM	47.673828125
2017-04-01 00:00:00-04:00	QCOM	46.34043502807617

Date	Ticker	Close
2017-07-01 00:00:00-04:00	QCOM	43.932376861572266
2017-10-01 00:00:00-04:00	QCOM	54.85540008544922
2018-01-01 00:00:00-05:00	QCOM	47.87845230102539
2018-04-01 00:00:00-04:00	QCOM	48.90814971923828
2018-07-01 00:00:00-04:00	QCOM	63.42947006225586
2018-10-01 00:00:00-04:00	QCOM	50.57115173339844
2019-01-01 00:00:00-05:00	QCOM	51.22795486450195
2019-04-01 00:00:00-04:00	QCOM	69.12544250488281
2019-07-01 00:00:00-04:00	QCOM	69.9498519897461
2019-10-01 00:00:00-04:00	QCOM	81.55055236816406
2020-01-01 00:00:00-05:00	QCOM	63.01340103149414
2020-04-01 00:00:00-04:00	QCOM	85.63446807861328
2020-07-01 00:00:00-04:00	QCOM	111.341552734375
2020-10-01 00:00:00-04:00	QCOM	144.90667724609375
2021-01-01 00:00:00-05:00	QCOM	126.66468048095705
2021-04-01 00:00:00-04:00	QCOM	137.19332885742188
2021-07-01 00:00:00-04:00	QCOM	124.43497467041016
2021-10-01 00:00:00-04:00	QCOM	177.2476348876953
2022-01-01 00:00:00-05:00	QCOM	148.6814727783203
2022-04-01 00:00:00-04:00	QCOM	124.79911041259766
2022-07-01 00:00:00-04:00	QCOM	110.9599838256836
2022-10-01 00:00:00-04:00	QCOM	108.58021545410156

APPENDIX III

STOCK PRICES FOR MANUFACTURERS (2000 TO 2022)

Date	AMD	ASML	AVGO	NVDA	QCOM	TSM
1/1/2000	29.5	26.21	11.05	1.62	49.2	11.24
01-04-2000	38.63	31.05	11.05	2.43	19.77	9.73
01-07-2000	24	22.74	11.05	3.13	23.48	5.16
01-10-2000	13.81	15.88	11.05	1.25	27.08	4.35
01-01-2001	26.54	15.26	11.05	2.48	18.66	4.92
01-04-2001	28.9	15.66	11.05	3.55	19.27	5.37
01-07-2001	8.15	7.89	11.05	2.1	15.67	3.35
01-10-2001	15.86	12	11.05	5.12	16.64	6.07
01-01-2002	14.71	17.85	11.05	3.39	12.4	7.33
01-04-2002	9.72	10.64	11.05	1.31	9.06	5.05
01-07-2002	5.34	4.36	11.05	0.65	9.1	2.47
01-10-2002	6.46	5.88	11.05	0.88	11.99	2.74
01-01-2003	6.18	4.62	11.05	0.98	11.86	2.66
01-04-2003	6.41	6.73	11.05	1.75	11.86	3.92
01-07-2003	11.11	9.23	11.05	1.22	13.77	4.55
01-10-2003	14.9	14.11	11.05	1.77	17.86	4.3
01-01-2004	16.23	12.9	11.05	2.02	21.98	4.38
01-04-2004	15.9	12.04	11.05	1.57	24.23	3.98
01-07-2004	13	9.06	11.05	1.11	25.96	3.46
01-10-2004	22.02	11.2	11.05	1.8	28.25	4.11
01-01-2005	16.12	11.8	11.05	1.82	24.44	4.1
01-04-2005	17.34	11.02	11.05	2.04	22.07	4.63

Date	AMD	ASML	AVGO	NVDA	QCOM	TSM
01-07-2005	25.2	11.62	11.05	2.62	30	4.33
01-10-2005	30.6	14.13	11.05	2.8	28.94	5.22
01-01-2006	33.16	14.33	11.05	4.38	34.07	5.3
01-04-2006	24.42	14.23	11.05	3.26	27.02	4.98
01-07-2006	24.85	16.38	11.05	4.53	24.58	5.44
01-10-2006	20.35	17.33	11.05	5.66	25.64	6.19
01-01-2007	13.06	17.42	11.05	4.4	29.03	6.09
01-04-2007	14.3	19.32	11.05	6.32	29.62	6.31
01-07-2007	13.2	23.12	11.05	8.31	28.94	5.98
01-10-2007	7.5	19.57	11.05	7.8	27.05	5.89
01-01-2008	5.89	16.81	11.05	4.54	28.28	6.07
01-04-2008	5.83	16.53	11.05	4.29	30.7	6.45
01-07-2008	5.25	12.1	11.05	2.46	29.83	5.54
01-10-2008	2.16	12.42	11.05	1.85	24.95	4.92
01-01-2009	3.05	12.03	11.05	2.26	27.22	5.58
01-04-2009	3.87	15.11	11.05	2.59	31.77	5.86
01-07-2009	5.66	20.64	11.05	3.45	31.74	6.86
01-08-2009	9.68	23.8	11.05	4.29	32.76	7.51
01-10-2009	9.68	23.8	12.81	4.29	32.76	7.51
01-11-2009	9.27	24.71	12.81	3.99	29.83	6.89
01-01-2010	9.27	24.71	15.11	3.99	29.83	6.89
01-02-2010	7.32	19.33	15.11	2.34	23.45	6.41
01-04-2010	7.32	19.33	16.03	2.34	23.45	6.41
01-05-2010	7.11	20.92	16.03	2.68	32.4	6.66
01-07-2010	7.11	20.92	18.18	2.68	32.4	6.66
01-08-2010	8.18	26.98	18.18	3.53	35.71	8.64
01-10-2010	8.18	26.98	21.15	3.53	35.71	8.64
01-11-2010	8.6	31.32	21.15	4.23	39.72	8.4
01-01-2011	8.6	31.32	24.72	4.23	39.72	8.4
01-02-2011	6.99	26.01	24.72	3.66	41.27	8.69
01-04-2011	6.99	26.01	24.91	3.66	41.27	8.69
01-05-2011	5.08	24.63	24.91	2.87	35.48	8.21
01-07-2011	5.08	24.63	25.08	2.87	35.48	8.21
01-08-2011	5.4	29.8	25.08	3.18	40.09	9.27
01-10-2011	5.4	29.8	25.28	3.18	40.09	9.27
01-11-2011	8.02	35.76	25.28	3.53	50.07	10.98

Date	AMD	ASML	AVGO	NVDA	QCOM	TSM
01-01-2012	8.02	35.76	25.79	3.53	50.07	10.98
01-02-2012	5.73	36.67	25.79	3.17	41.1	10.03
01-04-2012	5.73	36.67	27.7	3.17	41.1	10.03
01-05-2012	3.37	38.73	27.7	3.06	46.31	11.36
01-07-2012	3.37	38.73	24.9	3.06	46.31	11.36
01-08-2012	2.4	46.46	24.9	2.81	46.05	12.77
01-10-2012	2.4	46.46	27.09	2.81	46.05	12.77
01-11-2012	2.55	61.35	27.09	2.96	50.03	12.79
01-01-2013	2.55	61.35	24.32	2.96	50.03	12.79
01-02-2013	4.08	71.38	24.32	3.26	45.83	13.63
01-04-2013	4.08	71.38	28.06	3.26	45.83	13.63
01-05-2013	3.81	89.96	28.06	3.63	50.78	12.62
01-07-2013	3.81	89.96	34.96	3.63	50.78	12.62
01-08-2013	3.87	85.35	34.96	3.76	56.3	13.34
01-10-2013	3.87	85.35	42.3	3.76	56.3	13.34
01-11-2013	4.01	85.04	42.3	4.23	60.08	15.31
01-01-2014	4.01	85.04	49.39	4.23	60.08	15.31
01-02-2014	4.19	84.96	49.39	4.39	60.62	16.36
01-04-2014	4.19	84.96	54.19	4.39	60.62	16.36
01-05-2014	3.41	90.91	54.19	4.39	57.53	15.44
01-07-2014	3.41	90.91	67.65	4.39	57.53	15.44
01-08-2014	2.67	99.2	67.65	4.79	57.51	17.51
01-10-2014	2.67	99.2	80.99	4.79	57.51	17.51
01-11-2014	2.68	92.95	80.99	5.03	53.96	18.37
01-01-2015	2.68	92.95	92.34	5.03	53.96	18.37
01-02-2015	2.4	95.8	92.34	4.85	49.03	17.76
01-04-2015	2.4	95.8	99.16	4.85	49.03	17.76
01-05-2015	1.72	81.55	99.16	5.97	42.35	16.75
01-07-2015	1.72	81.55	97.84	5.97	42.35	16.75
01-08-2015	2.87	82.28	97.84	8.02	39.74	18.36
01-10-2015	2.87	82.28	106.58	8.02	39.74	18.36
01-11-2015	2.85	93.05	106.58	8.7	41.05	21.14
01-01-2016	2.85	93.05	116.53	8.7	41.05	21.14
01-02-2016	5.14	91.96	116.53	11.52	43.41	21.17
01-04-2016	5.14	91.96	129.94	11.52	43.41	21.17
01-05-2016	6.91	102.78	129.94	16.83	56.03	25.61

Date	AMD	ASML	AVGO	NVDA	QCOM	TSM
01-07-2016	6.91	102.78	137.03	16.83	56.03	25.61
01-08-2016	11.34	105.24	137.03	26.27	53.79	24.07
01-10-2016	11.34	105.24	161.03	26.27	53.79	24.07
01-11-2016	14.55	124.56	161.03	26.85	47.67	27.5
01-01-2017	14.55	124.56	179.25	26.85	47.67	27.5
01-02-2017	12.48	122.22	179.25	35.68	46.34	29.27
01-04-2017	12.48	122.22	201.14	35.68	46.34	29.27
01-05-2017	12.75	162.17	201.14	44.16	43.93	32.47
01-07-2017	12.75	162.17	216.12	44.16	43.93	32.47
01-08-2017	10.28	164.65	216.12	47.85	54.86	34.28
01-10-2017	10.28	164.65	203.95	47.85	54.86	34.28
01-11-2017	10.05	188.09	203.95	57.3	47.88	37.84
01-01-2018	10.05	188.09	189.89	57.3	47.88	37.84
01-02-2018	14.99	187.53	189.89	58.65	48.91	31.61
01-04-2018	14.99	187.53	186.25	58.65	48.91	31.61
01-05-2018	30.89	179.68	186.25	69.62	63.43	39.58
01-07-2018	30.89	179.68	190.21	69.62	63.43	39.58
01-08-2018	18.46	148.72	190.21	33.09	50.57	33.08
01-10-2018	18.46	148.72	230.02	33.09	50.57	33.08
01-11-2018	25.52	179.71	230.02	44.55	51.23	36.71
01-01-2019	25.52	179.71	275.9	44.55	51.23	36.71
01-02-2019	30.37	198.71	275.9	40.79	69.13	35.11
01-04-2019	30.37	198.71	253.53	40.79	69.13	35.11
01-05-2019	28.99	240.18	253.53	43.29	69.95	43.01
01-07-2019	28.99	240.18	258.49	43.29	69.95	43.01
01-08-2019	45.86	286.12	258.49	58.57	81.55	54.15
01-10-2019	45.86	286.12	271.83	58.57	81.55	54.15
01-11-2019	45.48	254.06	271.83	65.66	63.01	44.85
01-01-2020	45.48	254.06	244.4	65.66	63.01	44.85
01-02-2020	52.61	357.37	244.4	94.69	85.63	53.79
01-04-2020	52.61	357.37	289.86	94.69	85.63	53.79
01-05-2020	81.99	360.39	289.86	134.96	111.34	77.38
01-07-2020	81.99	360.39	323.24	134.96	111.34	77.38
01-08-2020	91.71	475.99	323.24	130.25	144.91	104.62
01-10-2020	91.71	475.99	420.29	130.25	144.91	104.62
01-11-2020	78.5	604.85	420.29	133.22	126.66	113.96

Date	AMD	ASML	AVGO	NVDA	QCOM	TSM
01-01-2021	78.5	604.85	429.24	133.22	126.66	113.96
01-02-2021	93.93	676.84	429.24	199.7	137.19	116.21
01-04-2021	93.93	676.84	460.28	199.7	137.19	116.21
01-05-2021	102.9	732.14	460.28	206.87	124.43	108.4
01-07-2021	102.9	732.14	508.11	206.87	124.43	108.4
01-08-2021	143.9	782.28	508.11	293.75	177.25	117.28
01-10-2021	143.9	782.28	564.02	293.75	177.25	117.28
01-11-2021	109.34	658.01	564.02	272.56	148.68	102.06
01-01-2022	109.34	658.01	537.12	272.56	148.68	102.06
01-02-2022	76.47	468.81	537.12	151.45	124.8	80.41
01-04-2022	76.47	468.81	522.3	151.45	124.8	80.41
01-05-2022	63.36	412.21	522.3	121.3	110.96	67.79
01-07-2022	63.36	412.21	462.35	121.3	110.96	67.79
01-08-2022	64.77	543.57	462.35	146.08	108.58	74.07
01-10-2022	64.77	543.57	554.5	146.08	108.58	74.07

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