How has the 2020 - 2021 Semiconductor Chip Shortage affected automobile production in the US?

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Abstract. The 2020 - 2021 semiconductor chip shortage is a crisis where the demand has outstripped supply as a result of the snowball effect of the COVID-19 pandemic. This paper examines the extent to which the shortage has affected the US automotive industry from 2008 to 2020, by observing through a microeconomic lens the shifts in both the supply chain for semiconductor imports and domestic automobile production in the US. Even though semiconductors may not have been the sole factor since cars use other inputs and materials, they are an important one in the automobile production process and could have contributed to the production decline amidst the pandemic. From 2000 automobile production has been in a steady decline due to a myriad of factors, such as a shift towards work from home, rising production costs with technology investments in quality and input price hikes. Production dipped sharply in 2020 as a result of the pandemic from 209 to 161 thousand vehicles. Despite this, the automobile share of semiconductor imports has steadily increased over the years from 8.8% in 2008 to 11.4% in 2020. This is primarily because semiconductors are used in the main computerized technology for cars, and as they become more advanced the demand for semiconductors have increase irrespective of production declines. There is therefore a negative correlation between them of -0.74. The shortage experienced in 2020 is not quite visible from the semiconductor demand, but rather as a possible factor for the production decline. Manufacturers were unable to cancel their orders, and other industries had increased their demand for semiconductors such as electronics and telecommunications. As more consumers shifted to remote work and the demand for connectivity increased, so did the demand for semiconductors within these industries relative to the automotive sector. This created a shortage where a lack of semiconductor inputs, contributed to a decrease in expected production. The main hypothesis is that due to the semiconductor shortage, automobile production would have declined much more in 2020 as opposed to other years.

Keywords: Semiconductors · Automotive Industries · Supply-Chain · Cost-Quality · Oligopoly.

JEL Classification: D00, D04, D20, D24, D50, F10

1 Introduction

The semiconductor chip shortage was slowly developing itself over time ever since the nascent stages of the pandemic in early 2020, as companies failed to cancel their orders, factories seized to produce, and workers were starting to be laid off. Prior to 2020, semiconductors were rising in demand from the automotive industry with an average increase of 8.17 billion units. But in 2020, even though the percentage share decreased marginally the number of semiconductors rose in comparison to 2019, bringing the average to 8.24 billion units. Which brings to question then, how was there even a shortage to begin with since the data shows that there was an increase in imports? The answer is that because there was an expected decline in automobile sales in 2020 relative to the previous years, automakers decided to cut their orders for much of the internal components required for the manufacturing process. One of which was semiconductors, which plays an integral role in the functioning of the vehicle touchscreen display, automatic computer settings and collision-avoidance systems. Many semiconductor producers that specialized in automotive chips (such as *Infenion, NXP and Renesas*) experienced flight and port restrictions, as well as personnel isolation, which suspended the production of chip enterprises and led to an overall reduction in capacity and shipment. A large number of semiconductor packaging and testing plants were also forced to reduce their production capacity, which could have contributed to the decline in imports [14]. As the demand for automobiles rose in the third quarter of 2020, car manufacturers were unable to meet consumer demand and suffered extensively from a loss of sales and market expectations as their semiconductor stock depleted. This showcases that even though the numbers detail that there was an increase in demand *due to prior orders*, in reality the demand was not being actualized into inventory for the manufacturers.

Given the relevance of the delays and restrictions created by the pandemic and its noted effect on both the semiconductor and automobile industry, this paper aims to examine the extent to which the 2020-2021 semiconductor shortage has affected US automobile production. A microeconomic analysis will be conducted to assess the oligopolistic nature of the automobile industry and how they maximize profits, after which, an input-gap analysis will be done to determine how the lack of semiconductor inventory could possibly affect production. Upon evaluating these effects, an econometric specification will be done to check what other factors could add meaning to the association between production and imports.

2 Literature Review

Prior to the recent exogenous shocks that resulted in the economic shortage for the automobile industry and sectoral shifts in the semiconductor industry, there has been a robust and steady growth for semiconductors but a steady decline for automobiles. From 2012 to 2020, the number of cars produced declined from

341.43 to 161.56 thousand cars, while the number of automotive semiconductors increased sharply from 6.497 billion to 8.779 billion units. The semiconductor industry specifically has been noted to experience periodic ups and downs in their overall production cycle, the upturns occur during high periods of demand which cause supply shortages while the downturns occur due to inventory buildup which causes falling prices. This cyclical movement is actually not as dependent on new orders being filed by downstream industries such as automakers and electronic producers, as it is on the *Philadelphia Semiconductor Index* and the overall inventories of the downstream industries [13]. It is therefore a stock-driven and index-oriented relationship for the most part. To understand from a firm's perspective, if a company realizes that it needs more semiconductors for upcoming production as part of its next process then these orders themselves would not impact the demand for the semiconductors in the global market as much as the current overall stock of semiconductor inventory. This is because the inventory represents global supply and the behavior of the index market, which is driven by consumer patterns. From data attained from the World Semiconductor Trade Statistics (WSTS), the share of the automotive industry of semiconductor demand was 11.7% in 2019 and 11.4% in 2020. Furthermore, the revenue from automotive semiconductor production was increasing from 2012 (an automotive share of 10%) to 2019 but then took a drastic dip, reducing by $3.2 billion due to the pandemic[8].

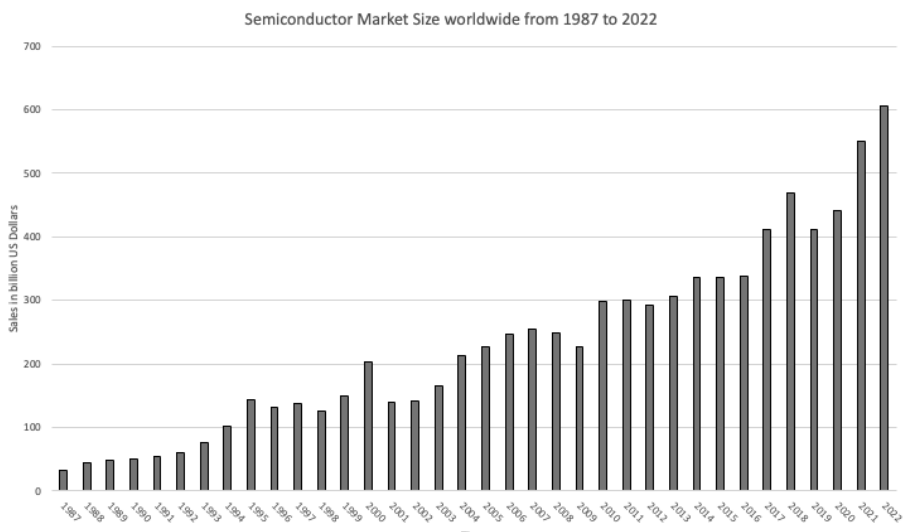

Fig. 1: Semiconductor Market Size Worldwide from 1987 to 2022

There are three main shocks here that have impacted the growth of the semiconductor industry, first is the shock in 2000 to 2001 which occurred as a result of the collapse of the dotcom bubble (a decline of $65 billion in 2001), the second occurred in the 2008 - 2010 period as a result of the global financial crisis (a decline of $22.29 billion in 2009), and the third in the 2019 - 2020 period as a result of the pandemic which decreased relative to the 2018 value by approximately $28.39 billion. The expected growth of semiconductors in 2021 and 2022 seem to be quite steep indicating an overall optimistic turnaround from the current shortage [7].

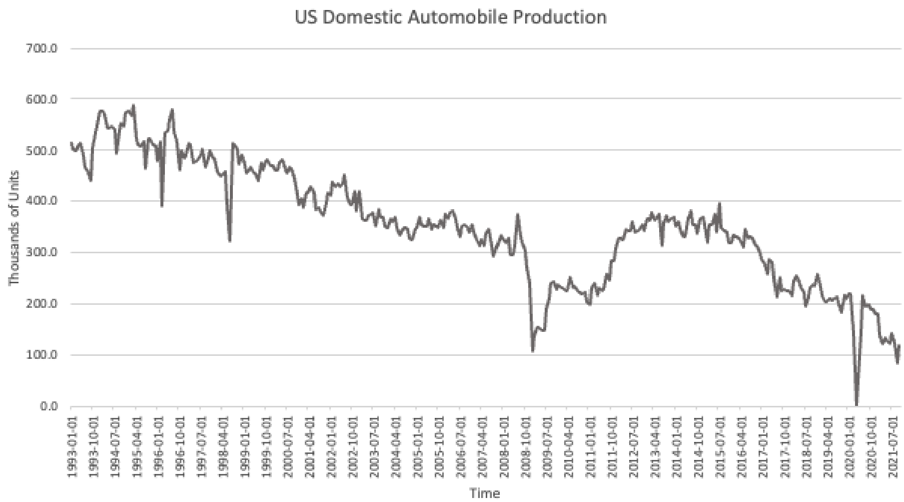

Fig. 2: US Domestic Automobile Production from 1993 - 2021

On the other hand, the US automobile production market initially evolved into an oligopolistic market which was mainly dominated by firms within the Detroit area such as *Ford, GMC and Fiat-Chrysler*. The market naturally grew to encompass other entrants such as *Tesla* which provided a more environmentally-friendly option with battery powered vehicles, thus shifting the overall dependence on oil. Despite prolonged robust growth in the automotive industry there was indeed a shakeout, with multiple producers exiting the industries due to a lack of resources and fierce competition from the '*big three*', which capitalized on their early entry and geographical concentration around Detroit [12]. The industry definitely experienced many issues over the years, the main one being the 2008 - 2010 recession and the subsequent bailout that occurred as a result of the car manufacturers filing for bankruptcy which reduced production from 375.4 thousand units in July 2008 to 107.5 thousand by January 2009 [6]. The government had to give nearly $80 million to GM and Chrysler to bail them out of a financial turmoil, and the *big three's* market share had shrunk from 78% in 1998 to 47% in 2008 [1]. The overall production increased till July 2015 where it grew by nearly 71% from its 2010 level. After which, total output began decreasing once again and sales remained relatively flat, which prompted factory closures and labor strife in the industry. Furthermore, the emergence of car-sharing companies such as Uber and Lyft and the increasing demand to work from home have made it more difficult for manufacturers to meet yearly expectations. The industry continued on this rather flat trend until the pandemic struck, causing production to plummet to a record low of 1.7 thousand units in April 2020. Currently as of September 2021, the market is hovering around 84.2

thousand units [6], far below its pre-COVID levels. Today the *big three* produce less than 60% of all automobiles and light trucks sold in the United States.

The automotive industry is expected to see more disruption within the next ten years than it has seen in the last fifty. Driven primarily by four key factors which are autonomous (self-driving), connectivity (computerized systems), electrifying (shifting towards more electrical power), and ridesharing (car-pooling applications and companies that are shaking traditional consumption). By 2030 according to the McKinsey model and research analytics, nearly 25% of revenues will be coming from these new disruptive business models [2]. This will naturally lead to an overall decline in production over time for traditional vehicles as consumers shift their preferences towards these alternatives. The future for the automobile market would be one where there is *coopetition* which involves co-operating with certain players and competing with others. A more open market is being foreseen where the *big three* are expected to face stiff competition from these disruptive factors. Especially from the onset of the pandemic, automobile manufacturers have to organize themselves more efficiently and react better once the shortage ceases.

3 Data Discussion

The main information on semiconductor imports to the US and automobile exports (representative of automobile production) from the US was sourced through the Census Bureau's trade data hub which was obtained for each US territory, encompassing all 50 states and the District of Columbia. The North American Industry Classification (NAICS) code *3344* signifies *Semiconductors & Other Components* while the code *3361* signifies *Motor Vehicle Manufacturing*. The main measure used to assess both the semiconductor imports and automobile exports was the general customs value in US$ which is the value of goods imported as appraised by the U.S. Customs and Border Protection from 2008 to 2020.

Other variables that have been included to standardize the econometric level effect between automobile production and semiconductor imports are, the minimum wage attained from the Bureau of Labor Statistics (BLS) [3], and population and household income attained from the Census Bureau [4]. The percentage share of semiconductor imports for the automotive industry was gathered from the World Semiconductor Trade Statistics (WSTS) [5]. Table 1 presents summary data for each variable from 2008 to 2020.

Over the years the average automotive production has steadily declined until 2020, where there was a sharp fall of nearly 23% as a result of the pandemic[1]. Contrarily, as automotive production decreased over time, the number of semiconductors imported for use in the automotive sector increased instead from 2012 to 2018, after which it fell by nearly 2 billion units. The reason for this *dichotomy* is because even though the number of automobiles produced reduced, the level

[1] Table 1 Explanations: Prod. signifies production, and S.I. means semiconductor imports.

Table 1: Summary Descriptions of Gathered Data

Variable	Observations	Mean	Std. Dev.	Min	Max
Value of auto exports (millions)	663	1175.467	2237.18	.191357	14396.87
Auto Share	663	.105	.0105253	.088	.12
Value of Total Semiconductor imports (millions)	663	1392.027	3980.115	1.725588	33849.73
Value of Auto Semiconductor imports (millions)	663	147.6443	428.8677	.1702629	4027.162
Population	663	6235644	7024651	546043	39500000
Household Income	663	57165.88	11350.4	32338	95572
Minimum Wage	663	6.10908	2.787373	0	14

of innovation and progression in automotive technology increased markedly over the years. Progress has been made towards more computerized systems, key-less entry, adaptive cruise control and EV/HEV models, to name a few, which have increased the overall demand for semiconductors within the industry. It is expected as cars evolve to include more artificial intelligence and environmentally-oriented components, the demand will continue to increase in the future. The problem with COVID is also quite apparent through the data in its impact on manufacturers, where they were unable to cancel their semiconductor orders and the number of automotive semiconductors increased slightly from 2019 to 2020 despite the pandemic. The market share of the auto industry however decreased marginally from 11.7% to 11.4% as other industries such as computer and electronics sectors increased their demand. This simply shows that irrespective of the pandemic, the demand for semiconductors remained relatively unchanged because of how integral and vital they are within the production process. Despite the share being relatively constant in 2020, it is worthwhile to note that the demand for semiconductors as shown through the import data is not what is experienced in reality. As mentioned previously, due to delays and port restrictions, the semiconductors have not been able to reach the manufacturers in time for them to meet production expectations.

From the summary descriptions presented in table 1, what is evident is that the mean auto share is 10.5% which is not that much and the standard deviation is also quite small, thereby indicating that over time there is very little change in the amount of semiconductors demanded by the auto industry. What is even more interesting is that the variation present within automobile exports is much more than semiconductor imports, which shows how volatile the auto industry is relative to semiconductors.

The *dichotomy* explained earlier can be easily understood through the visual relationship of figure 3. Where as the number of automobile units produced decreased over time from period 5 (2012) to 9 (2020), the number of automotive semiconductor units increased. The spread seems to be increasing in size as time progresses, which follows the prior understanding of the increasing demand for semiconductors as automotive technology evolves.

To assess this relationship further, the correlation between the two variables of interest in table 2 is 0.569, which is moderately positive in nature. This show-

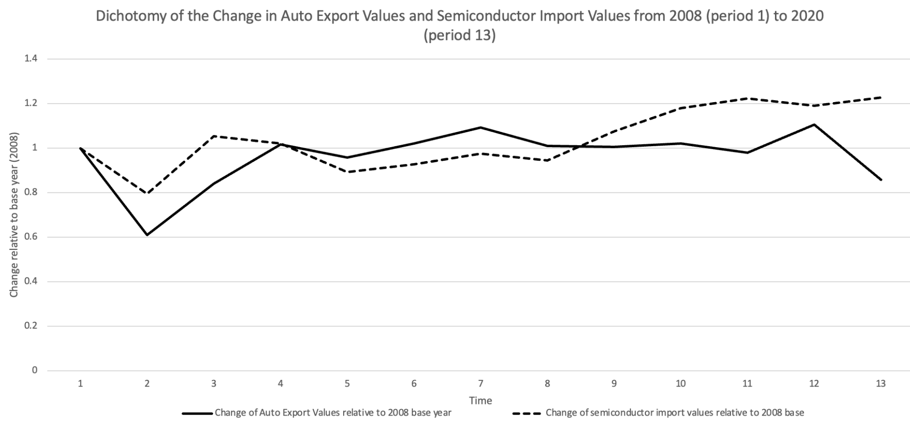

Fig. 3: Dichotomy of the change in Auto Export Values and Semiconductor Import Values from 2008 (period 1) to 2020 (period 13) with 2008 base year

Table 2: Cross-correlation table

Variables	log_auto_ex	log_semi_im	house_inc	pop	min_wage
log_auto_ex	1.000				
log_semi_im	0.569	1.000			
house_inc	-0.194	0.051	1.000		
pop	0.555	0.671	0.018	1.000	
min_wage	-0.052	-0.060	-0.034	-0.066	1.000

cases that despite the dichotomy witnessed in recent years, the overall trend and relationship is generally positive in nature. Where if there is an increase in the percentage of automotive exports there should also be a percentage increase in semiconductor imports. This makes sense in a general sense, because we would expect semiconductor demand and production to go hand in hand. The demand for inputs not just theoretically but also through the data explains this. More importantly, correlation is not causation hence why this in itself is not conclusive enough to determine whether there exists a meaningful relationship between the two variables, other variables would have to be included to explain the relationship better through a regression model.

4 Economic Theory

The main theoretical explanation for the increase in semiconductor imports for the automotive sector is due to evolving technology, rather than increased demand for automobiles. This explains the negative relationship between the two variables. On the other hand, with respect to automobile production, the consistent decline in quantity produced is due to increasing prices through quality improvements and reduced demand as consumers shift their taste and preferences, and move towards a more domestic lifestyle. This essentially signifies that even though the pandemic had a greater impact on the decrease in automotive production, it had a very marginal impact on the demand for automotive semiconductor imports. Which means that the decrease in production for the industry may not have primarily been a result of the shortage in imports, but other factors.

The US automobile market is oligopolistic in nature, where there exists competitive interdependence. Hence the decisions made by each firm affect the profits of their competitors[10]. The Cournot economic model can be used to represent the oligopolistic nature of the automobile market because US car manufacturers primarily operate in a quantity-setting fashion. This is consistent with the output quantity elasticity data that has been examined by *Berndt, Friedlaender and Chiang* in their 1990 paper where the authors analyzed how GM, Ford and Chrysler react to one another strategically with price changes in the market as opposed to a price-setting firm strategy, and through their study they were able to determine that the Cournot model explains the nature of the US automobile market[9]. The model defines a structure where firms choose a particular quantity to produce and price is determined by the market. Each firm will make the output choice that maximizes profits based on the expectation of how other firms choose their output. The mathematical underpinning to infer the cost structure of oligopolies in a n-firm industry can be understood as follows, let the cost function for each automobile manufacturer i producing vehicles qi be represented as $c_i = F_i + (a_i + b)q_i$. Where F_i is the individual fixed costs for each firm, a_i is the firm specific component of marginal cost and b is the component of marginal cost that is common to all firms in the industry[11]. The profit for manufacturer i:

$$\pi_i = q_i[f(Q) - a_i - b] - F_i \tag{1}$$

Since in cournot firms believe that they can change their output in equilibrium without other firms reacting. Therefore,

$$d\pi_i/dq_i = f(Q) - a_i - b + q_i f'(Q) \tag{2}$$

Therefore in equilibrium,

$$q_i = -[f(Q) - b - a_i]/f'(Q) \tag{3}$$

Since $f'(Q) < 0$, (3) shows that a_i and q_i are inversely related, so high-cost firms would produce relatively fewer units. This follows the general notion that increasing costs associated with technological advancement in quality would reduce the level of output per firm to meet profit levels. As time progresses, this is the general trend that we see where with advancements, the level of production within the industry decreases as more semiconductors and other internal components are demanded. However, given the current scenario of the pandemic even though the number of semiconductors demanded has increased, the number of units reaching US manufacturers has decreased as a result of shipping delays and port restrictions. This has created a vacuum within the industry and a lack of input. Semiconductors themselves are not substitutable with other car components, they are a necessity in the production process. Therefore, the shortage could have contributed to the overall decrease in production.

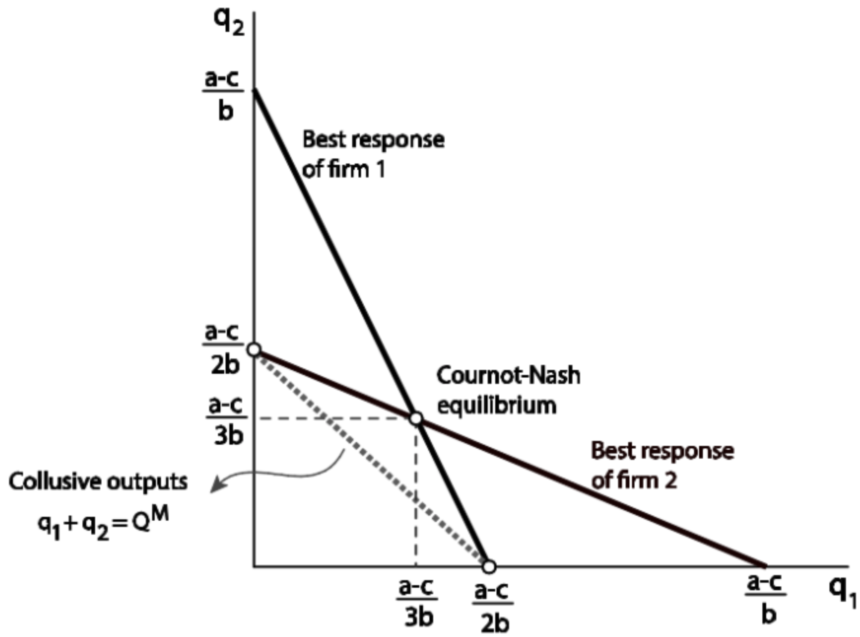

Fig. 4: Cournot-Nash Equilibrium

Figure 4 represents a Cournot model in an oligopolistic market scenario. To put it into perspective, in this graph the reaction curves of only two firms are showcased where they are operating in the market with little to no differentiation in product or demand and are facing different elasticities on the basis of their demand and cost structure. Both firms have a best response function that determines how they would strategically set their quantity in response to their competitor. The inverse demand function for each firm is given as $p = a - bQ$, and there are $n > 1$ firms in this particular industry and each firm produces with the marginal cost c. At the Cournot-Nash equilibrium point, both firms are setting their best response quantity relative to the other, where the best response for both firms is $a - c/3b$. In the context of the semiconductor shortage, given the lack of supply of inputs, the quantity of vehicles that would have been produced for both firms in this strategy-setting scenario would decrease causing both best response functions to shift to the left. This would lead to a lower Cournot-Nash equilibrium point where the quantity produced by both firms would decrease.

5 Econometric Analysis

To gather a more meaningful understanding of the association between automotive semiconductor imports and domestic automobile production, an econometric specification is vital. As seen from our prior correlation and evaluation, there is a moderately positive relationship between semiconductor imports and automobile production of 0.569 hence it would be fair to assume that β_1 should be positive, where the percentage increase in semiconductor imports should be associated with a percentage increase in automobile exports by β_1. It is also important to remember that the demand is not necessarily positively correlated with production but rather developments in technology and quality of automobiles.

$$log\_auto\_ex_{it} = \beta_0+\beta_1 log\_semi\_im_{it}+\beta_2 pop_{it}+\beta_3 min\_wage_{it}+\beta_4 house\_inc_{it}+\epsilon_{it} \quad (4)$$

The main independent variable, the value of semiconductor imports in this specification would be measured in log terms where the data is the value of semiconductor imports (in millions) imported for the US automotive sector. While the main dependent variable is also measured in log terms as the value of automotive exports (in millions) of newly manufactured cars from the US. Other variables that have been included to add meaning to the relationship and provide a more robust level effect are, the *pop* measured as a true parameter for the population in each state and DC from 2008 to 2020, *house_inc* which is the household income in each state and DC in the same time period and *min_wage* which is the minimum wage measured in the same way. Prior to running the panel-data regression it is prudent to check whether the results should be a fixed effects or a random effects regression. A *hausman test* was carried out to examine this. The test showcased a result of $Prob > Chi2 = 0.9246$ (5), which is not less than 0.05 and so we cannot reject the null hypothesis and would have to use a random effects panel-data regression to examine the associations.

From the panel data regression table what is interesting is that for regression model 1, where only the log of semiconductor imports is regressed on the log of automotive exports, the association is extremely small and marginal in nature. This as of now goes against the prior correlation analysis that was conducted. It also has a very low standard error of 1.33. As more independent variables are added to the regression model we see that the coefficient for *log_semi_im* increasing in value and becoming more statistically significant. By the fourth model which includes all the independent variables (without time-invariant effects), we see that our variable of interest is slightly positive in association at 0.182 with a higher standard error of 3.04 which is still quite low. This means that a percentage increase in the value of semiconductor imports to the US (in millions) will lead to a percentage change in the value of auto exports (in millions) of 0.182, which again is very small and marginal.

Other variables in model 4 such as minimum wage are not significant in association with auto exports but can indicate a possible indication of the direction in which its association may be if it was significant, but even then its associa-

Table 3: Panel-Data Regression Output Table

	(1)	(2)	(3)	(4)	(5) - with time-invariant effects
	log_auto_ex	log_auto_ex	log_auto_ex	log_auto_ex	log_auto_ex
log_semi_im	0.0784	0.0214	0.183^{**}	0.182^{**}	0.219^{***}
	(1.33)	(0.34)	(3.06)	(3.04)	(3.62)
pop		0.000000111^{**}	0.000000142^{***}	0.000000141^{***}	0.000000162^{***}
		(2.91)	(3.90)	(3.86)	(4.47)
house_inc			-0.0000384^{***}	-0.0000384^{***}	0.00000663
			(-10.25)	(-10.24)	(0.83)
min_wage				-0.00646	-0.0123
				(-0.59)	(-1.15)
_cons	4.715^{***}	4.218^{***}	5.664^{***}	5.707^{***}	3.674^{***}
	(13.52)	(11.10)	(14.63)	(14.44)	(6.50)
N	663	663	663	663	663

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

tion seems too small to have any real effect on the percentage change in auto exports. It was important to test whether the model needed time-invariant effects to be put in place in order to understand whether time was affecting the associations. The *testparm* command was run to examine this, which resulted in a $Prob > F = 0$, thereby indicating the necessity of time effects to be used. Time-invariant effects were put in place for regression model 5, which shows a slight increase in the coefficient for *log_semi_im* to 0.219 and also an increase in significance from $p < 0.01$ to $p < 0.001$. The interpretation of this association is that if there is a percentage increase in the value of semiconductor imports to the US (in millions) then there will be a 0.219 percentage change in automotive exports from the US (in millions), significant at the 0.001 significance level (higher than model 4).

Overall from what has been examined across all 5 models is that on average the association between the two variables of interest is one that is weakly positive in nature. Which essentially means that there is a very slight effect that semiconductors would have on automotive production in the US. Even with the shortage, the regression output suggests that there should be a negligible effect on the cars that are being produced, this clearly does not support the main hypothesis that the shortage contributed significantly to the production decline in 2020. However, what is important to note is that even though the association is significant, the other independent variables that were included are clearly not significant other than population, or effective enough to explain any association they or semiconductor imports may have on automotive exports. Perhaps it may be prudent to include or replace the current variables with other more representative variables such as the price of aluminum or tariffs placed on semiconductor imports or even corporate taxes placed on US auto manufacturers to explain the association a bit better. To further add to the regression analysis above, collinearity diagnostics are examined to ascertain whether there exists any multi-collinearity between the independent variables that may explain their lack of significance or mis-specified association.

From the collinearity diagnostics 4 what is evident is that none of the independent variables have a high variance inflation factor (VIF). They are all below 2 which is good and on average it is 1.41, so we need not be concerned about there being any potential multi-collinearity among the independent variables that could have misconstrued the regression output.

6 Conclusion

From what has been examined thus far, it is not exactly clear that the shortage itself has been the sole factor that has negatively impacted the quantity of vehicles being produced as there is a very slight association shown through model 5 of 0.219. In theory the shortage created an input gap within the automobile industry, where firms were forced to produce at a lower non-optimal point with fewer semiconductor components, but this is not exactly understood through the data or the regression model. Despite the shortage, there has been a downward trend in the production for automobiles and the sharp decline that was experienced in 2020 could have been a result of multiple factors, such as labor strife, the shift to domestic work or even the shortage itself, but the extent of the impact due to the shortage seems to be marginal. On an overall basis there exists a weakly positive relationship between automobile production and semiconductor imports, which is due to advancements in quality and the subsequent rising demand for semiconductors. As time progresses, it can be expected that the enhancement of quality for automobiles has led to more cars being produced due to rising demand as shown through the Cournot profit maximization equation. Furthermore, the Cournot-Nash equilibrium diagram visually showcases how auto manufacturers may react strategically with one another given the shortage.

In order to amend the low association and bring about a better representation of the data, other independent variables may be included such as corporate tax rates, import tariffs on semiconductors and even the price of other inputs such as aluminium. By including these variables that vary across either entities or time or both and which are strongly associated with the dependent variable can reduce the omitted variable bias that can be present in the regression model. Further econometric analysis can be done including these independent variables. Given more time, the data can be collected instead of on a yearly basis, on a monthly basis, to explain and quantify for more of the variation and time-invariant effects that could be potentially affecting the regression model. The number of years or months in each year can be extended beyond 2008 to 2000 in fact to gather more data points for each independent variable that is collected. Given that the pandemic and the shortage caused by it is a recent phenomenon, we cannot truly gather the impact that the shortage would have had since its still ongoing. In the future once the shortage and the pandemic are over, an econometric and regression analysis can be conducted to examine the true association the shortage would have had on US automobile production. The shocks for the shortage, the financial crisis and the dotcom bubble or Asian financial crisis can be standardized such that the trend or the associations are not impacted by these shocks. By doing so, we can then examine the effect each shock would have had on the general association that exists between the two variables of interest.

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A Hausman Test

Test: Ho: difference in coefficients not systematic

$$chi2(14) = (b - B)'[(V_b - V_B)^(- 1)](b - B) = 7.25 \tag{5}$$

Prob>chi2 = 0.9246
(V_b−V_B is not positive definite)

B Collinearity Diagnostics

Table 4: Collinearity Diagnostics Table

Variable	VIF	SQRT VIF	Tolerance	R-Squared
log_semi_im	1.82	1.35	0.5484	0.4516
pop	1.82	1.35	0.5492	0.4508
house_inc	1.00	1.00	0.9958	0.0042
min_wage	1.01	1.00	0.9942	0.0058
Mean VIF	1.41			