Can automakers cope with the increasing demand for hybrid gasoline-electric vehicles?

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Modeling Systems Dynamics
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NOTES AND INSIGHTS

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Abstract

This article uses system dynamics simulation to improve the understanding of the various factors that affect the sales and adoption of hybrid gasoline-electric automobiles. Consumers have more compelling reasons than ever before — high oil prices, environmental concerns, security concerns, etc — to purchase hybrid gasoline-electric vehicles. This article assess whether or not automakers will be able to cope with increasing demand from consumers.

Introduction

The continued use of petroleum products, such as gasoline, to fuel the world's economies is already impacting many aspects of life both in the United States and around the world. While these products are used in a variety of ways — producing electricity, heating buildings, manufacturing plastics, etc — much of the use of petroleum products can be attributed to transportation and, more specifically, automobiles and trucks.

Environmentalists have already found signs that the carbon-dioxide formed through the combustion of gasoline is warming the planet through a phenomenon called "global warming," which may have devastating environmental impacts.

More specifically, climatologists have projected that in the next 30 years the average global temperature will rise by almost 1° F or 0.6° C. Records also indicate that the average global temperature has risen by almost that same amount in the last century. This relatively rapid upward shift in the average global temperature may have devastating effects on the environment and on life as whole.

Africa, for instance, is already feeling the effects of global temperature changes. The UN Intergovernmental Panel on Climate Change ("IPCC") has predicted that it will become more difficult for farmers in Africa to farm, subsequently exacerbating the shortage of food that already pervades many parts of the continent. Africa's diverse ecosystem may also suffer as water disappears from certain areas.

Coral reefs around the world, most of which can only thrive within a very narrow range of temperatures, have also suffered. Already some groups estimate that the slight changes in ocean temperature in recent years has destroyed nearly 26 percent of the world's coral reefs. This too will have a major impact on biodiversity in the ocean, but also on food supplies and the seafood market, as seafood becomes less abundant.

A continued dependence on petroleum products like gasoline may also have implications for the security of the world. Nearly 80 percent of the world's oil sits below the Middle East, a region full of unstable regimes that some foreign policy experts feel are very backward thinking. The sustained high price of oil, through the sustained demand for oil to power automobiles, power plants, etc, is, according to New York Times columnist Thomas Friedman and other experts, keeping these regimes in place. This, of course, has huge implications for the safety of the world. These regimes fund religious extremism, a very potent threat to the world's security. And, because these regimes do nothing to promote innovation and homegrown industry, the economies in these regions suffer. As a result, many disillusioned citizens turn to Islamic fundamentalism.

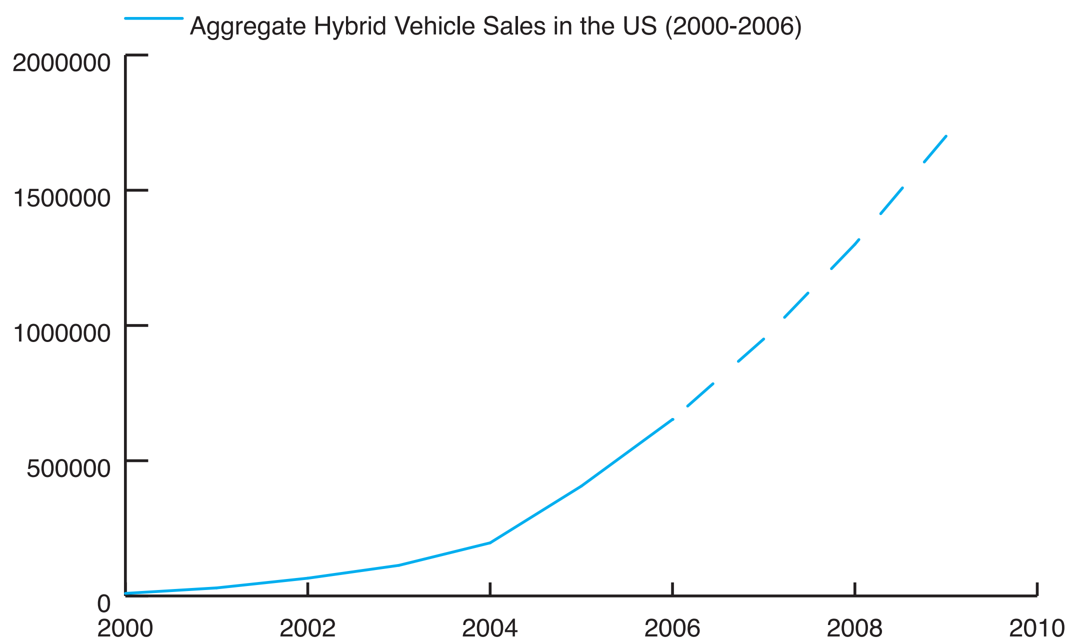

Fig. 1. Sales of hybrid gasoline electric vehicles in the US from 2000-2006, with projection to 2010. (Source: Electric Drive Transportation Association)

Abstract

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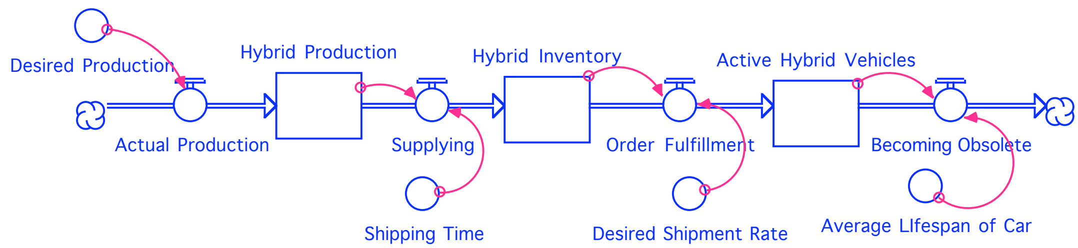


Fig. 2. The initial third-order material delay at the core of the model.

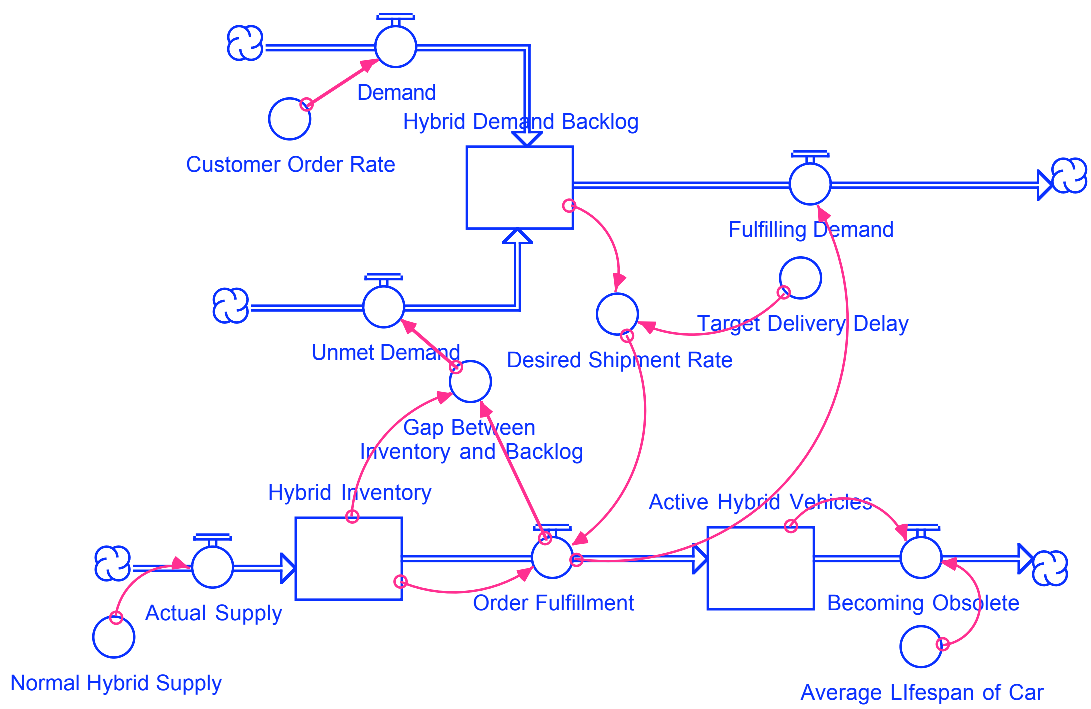
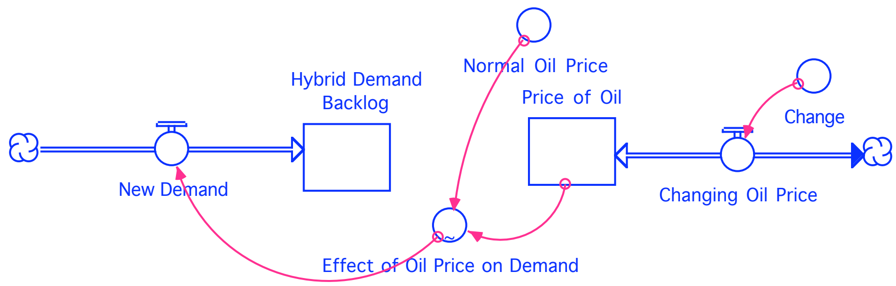


Fig. 3. The original material delay with the addition of a backlog structure.

Fig. 3A. The oil price test input and its relationship with the new demand.



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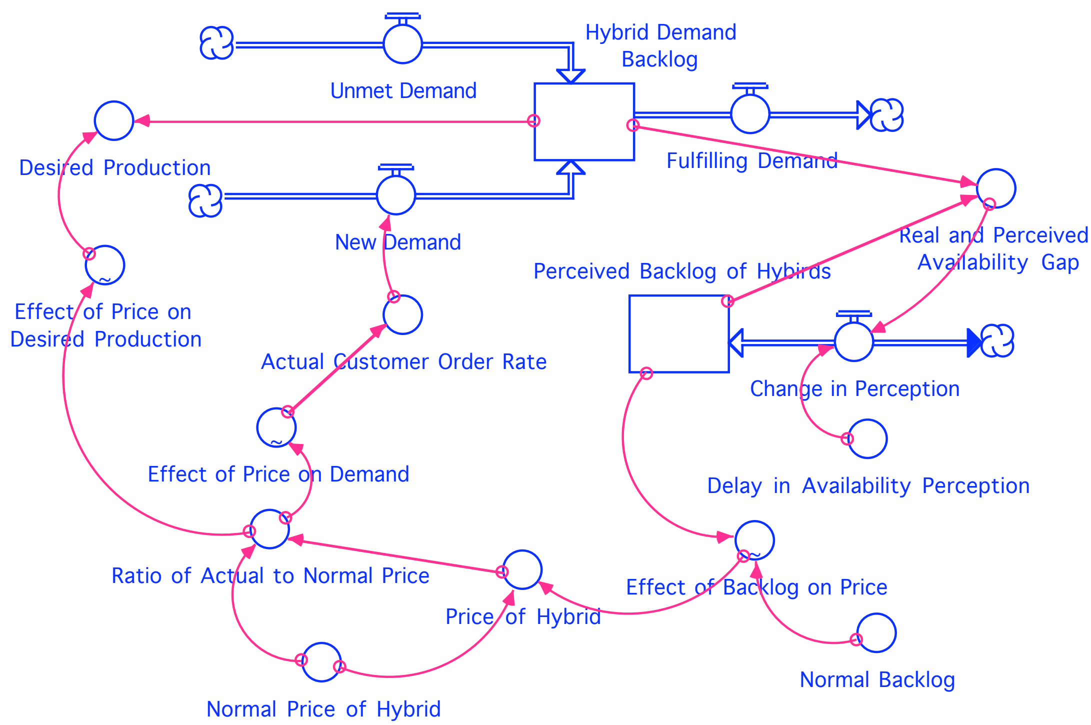
Thus, many believe that a reduction in gasoline use in transportation would be very beneficial. And, as such, many groups have proposed various measures and methods to make this a reality. In 1997 the Toyota Motor Corporation introduced the Prius to the Japanese market

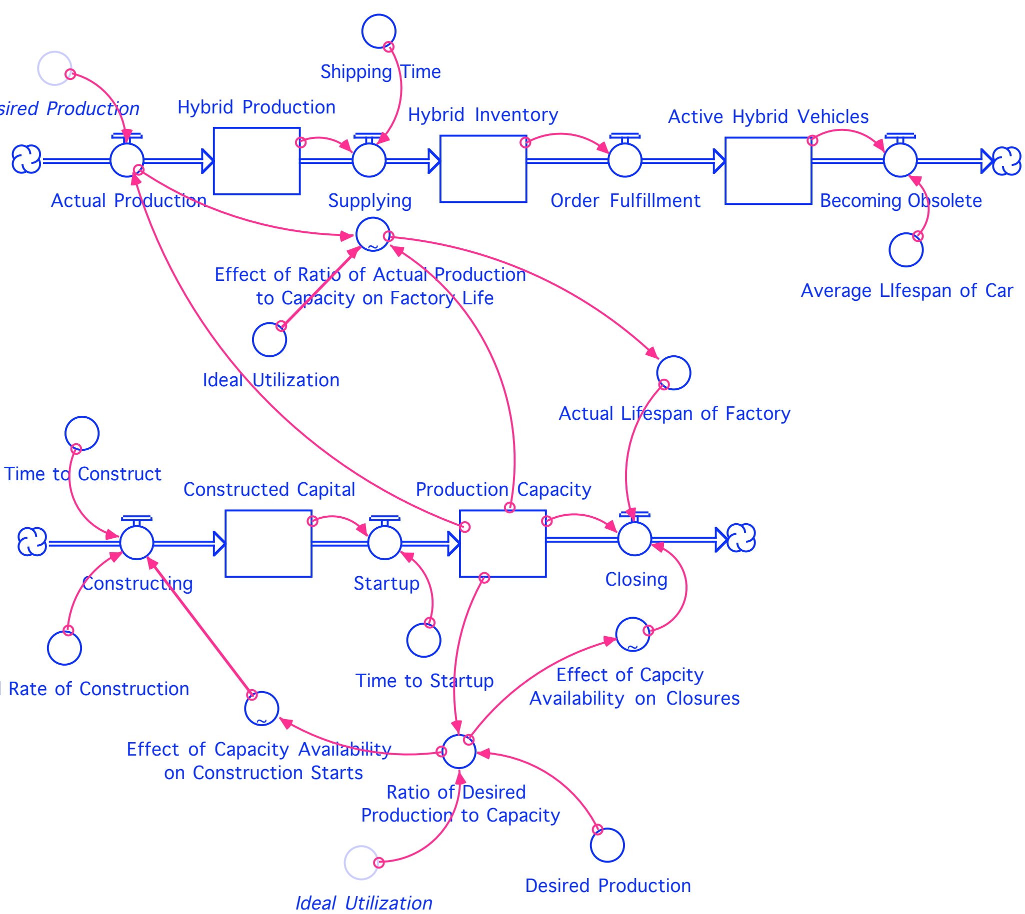
Fig. 3B. The price structure and its relation to the new demand and desired production.



and later, in 2001, to the worldwide market. The Prius differed from other vehicles in that it made use of a hybrid gasoline-electric drivetrain, which, through the use of an electric motor, more efficient gasoline engine and sophisticated software, managed to reduce the consumption of gasoline considerably. Further development of hybrid technology has improved fuel efficiency and reduced emissions further. And more carmakers have introduced vehicles using this drivetrain to the public.

All of these factors provide strong motivation for consumers to purchase hybrid gasoline-electric vehicles. To date, thousands of hybrid vehicles have been sold by various manufacturers, with an accelerating rate of adoption (see Figure 1) and projections put the sales on an increasing growth trajectory. But as demand for these vehicles has grown, manufacturers have experienced difficulties in keeping up with that demand, which limits their ability to penetrate the market. Hybrid vehicles also tend to be more expensive than their traditional gasoline-only counterparts, which may also impact their ability to become pervasive. Fluctuating oil prices too may have an impact on their adoption, as consumers may not want to pay the premium for hybrid vehicles if the prices of oil is low.

Fig. 3C. The production capacity component connected to the material delay at the center of the model



The Model

The model presented here centers around the relationship between producers and consumers in the sales of hybrid vehicles. Certain aspects of the system, such as the changing cost of gasoline-electric components or the effect of other, competitive products were ignored. These were either too insignificant to affect the outcome of the model or were too complex to model. All the equations and parameters used in this model are presented in Appendix B.

The model can be divided into three sections: the supply chain, the backlog and the decisions that affect the various components of the model.

The design process began with a simple third-order material delay (see Figure 2), the core component of the model. Several test values were added to the model's various components in accordance with the way that the model was expected to work. The goal in this step was to ensure that the model would remain in equilibrium when the actual supply was equal to the actual demand; or in other words, when the number of people buying the cars met the number being produced.

This structure, however, would not account for the myriad factors that influence supply and demand. But most notably, this structure lacked a feature to allow consumers to demand more than the suppliers supplied to the consumers; it had no backlog. This is an especially im-

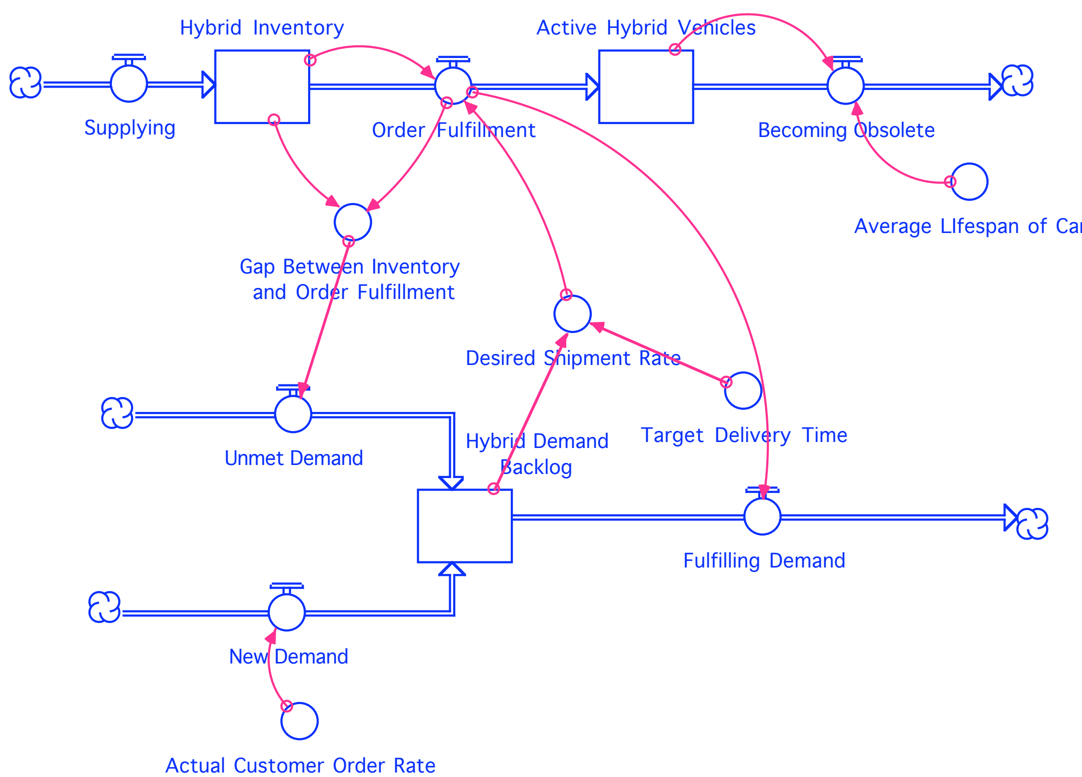


Fig. 4. A simplified cutaway of the backlog structure featured in the final model. It is possible to see the way that demand enters the backlog and is either fulfilled by the order fulfillment flow or returned to the backlog again by the unmet demand flow.

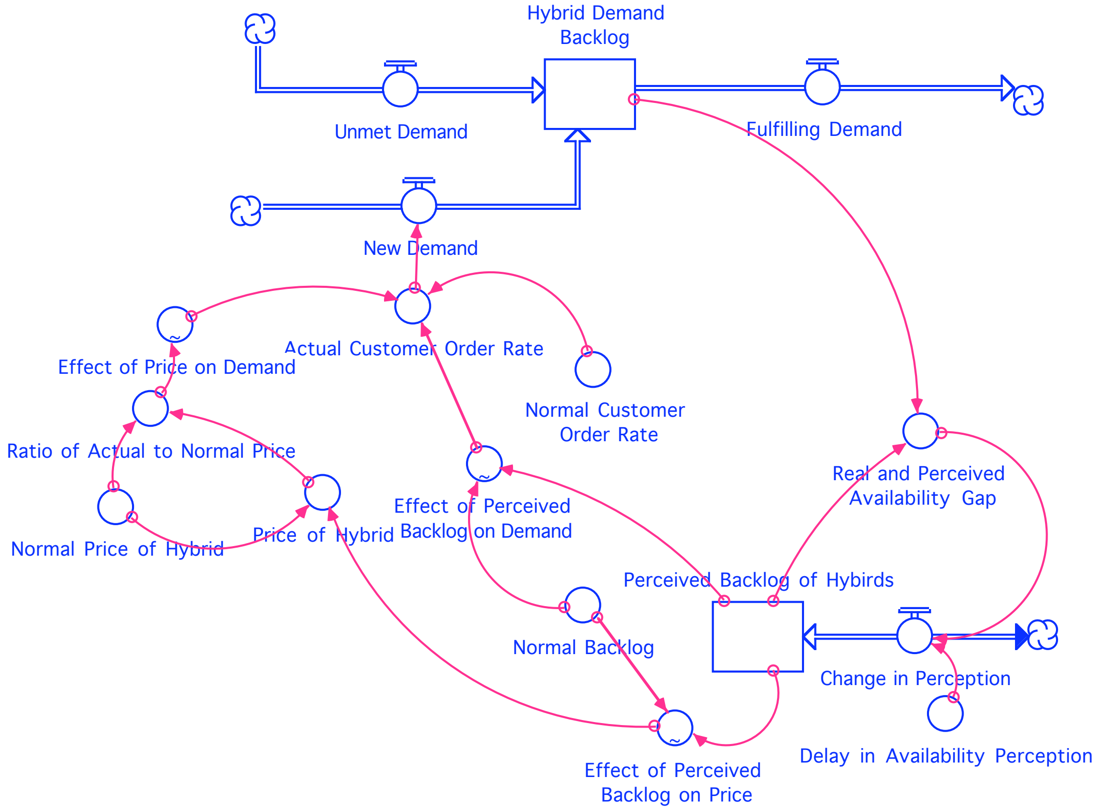


Fig. 5. A simplified cutaway of the backlog structure, with the two decisions that affect the demand, the price and perceived backlog. The left hand side of the model is the price structure.

portant component, as, for most of their history, hybrid cars have not been produced at a level capable of satisfying demand. So, the next step in the modeling process involved the addition of a backlog structure (see Figure 3).

But the addition of a backlog introduced a number of problems. In cases where the supply exceeded the demand, both the backlog and the inventory increased. This is not a realistic behavior, since, with inventory available to sell, the backlog should not increase. To remedy this, a feedback loop was introduced that reduces the production when it exceeds the demanded goods.

Of course, such a system is very unrealistic, most notably because it does not permit an increase in production to meet demand. So the loop was modified to more realistically model this behavior. A loop was created to ensure that the supply was reduced when inventory was in excess and vice versa.

Once the backlog was in place and, with test values, the model was put into equilibrium. Next, some other factors that affect the demand and supply were added. First, the backlog structure (see Figure 3) was added to the model. It uses a typical information delay to model the way that the backlog's size affects the demand, based on the current level and the perceived

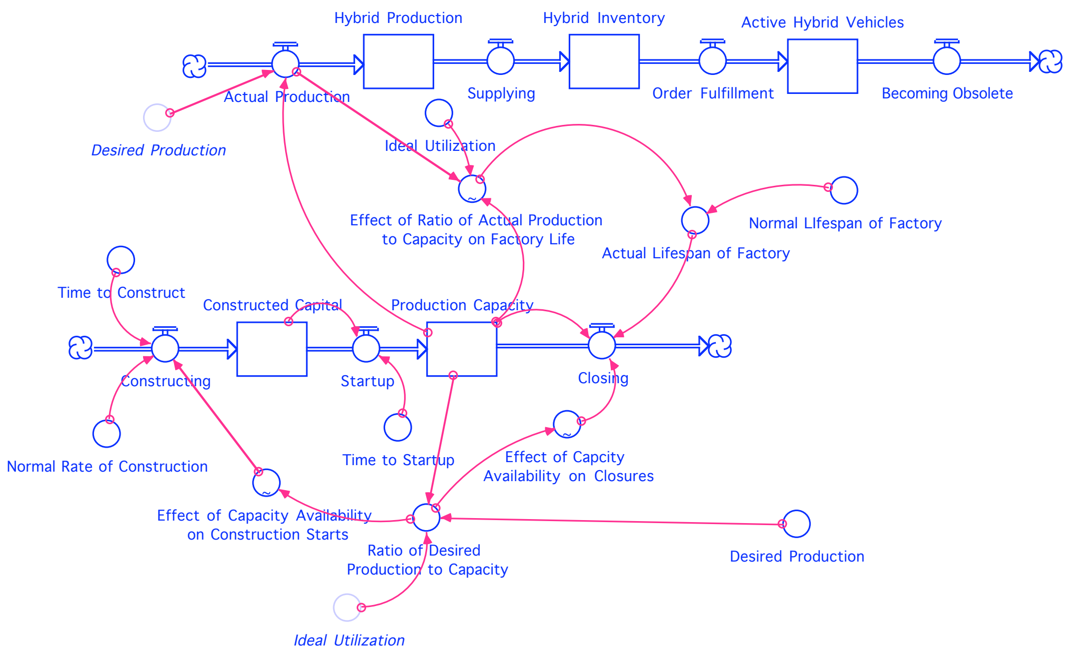


Fig. 6. A simplified cutaway of the production structure. It is possible to see the desired production with its two multipliers and the way that various factors alter the rates at which capacity is opened and closed.

level. Second, an oil price component was incorporated (see Figure 3A). Oil prices, however, are not easily modeled, so this component was designed more to look at two general situations: an increase or a decrease in oil price. The intensity, size and speed of the oil price's change can be modified, but the component cannot realistically model the price of oil. The oil price, in essence, became a test input.

Next, a price component was added to the model (see Figure 3B). It looks at several aspects of the model that could affect the normal price of a hybrid vehicle and then determines what the effect should be on demand and supply.

Finally, an additional material delay was added to model the changes in the various producers' abilities to manufacture the vehicles (see Figure 3C). This allows the model to accurately simulate the constraints that the manufacturers face when trying to either keep up with increased demand or rid themselves of excess manufacturing capacity from a drop in demand. With that component in place, several modifications were made to the names of different components to better reflect their purpose, resulting in the finished model (see Appendix A).

The Finished Model and How It Works

At the core of this model is the material delay containing the actual production, hybrid production, supplying, hybrid inventory, order fulfillment, active hybrid vehicles and becoming obsolete. In its first step it takes an actual supply — calculated in another section of the model — and adds it to the hybrid inventory. From there, the backlog structure (see Figure 4) takes in demand and drains the hybrid inventory. Vehicles leaving inventory are then registered by their buyers, and flow immediately into the active vehicles stock. The active vehicles stock, from a very macroscopic standpoint, represents the most important component of the model: it holds the actual number of hybrid vehicles on streets and highways. Of course, no vehicles last forever, so the active hybrid vehicles stock is depleted — albeit slowly — by the becoming obsolete outflow, which slowly diminishes that portion. On its own and as a component interacting with the rest of the model, the primary material delay worked successfully. When the demand equaled supply, the model was in equilibrium. Alternately, when changes were made to either the supply or the demand, the components responded in appropriate ways.

The backlog structure also plays an important role. Essentially, all demand must enter the backlog before it can be met, even when the demand does not exceed the supply. Granted, if the demand does fall at some level below the available supply, then the demand enters and exits the backlog immediately. The structure comprises: 1) a stock, the backlogged demand, if any; 2) two inflows, one for taking in new demand and one for collecting demand that the primary material delay was unable to meet; and 3) one outflow, which is a co-flow of the order fulfillment. New demand flows into the hybrid demand backlog stock through the new demand flow. Its value is determined by a set normal demand, which is affected by a number of other components, discussed later. Unmet demand flows into the hybrid demand backlog, only when the desired shipment rate it higher than the inventory.

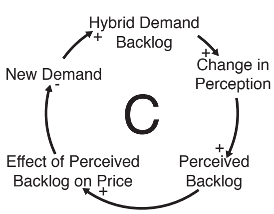
Two decision processes also affect the model's behavior: the price decision and the backlog perception decision. The backlog perception delay decision affects, based on the perceived availability of hybrid vehicles, the new demand for hybrid vehicles. It also uses an information delay to adjust the current perception to the actual availability of hybrid cars with a specified delay. The price decision affects the demand based on the price of a hybrid vehicle.

The oil decision affects the new demand based on the price of a barrel of oil. As will be detailed later, this does not produce any feedback within the model, as oil prices are impossible to accurately model. It does, however, affect the new demand based on a relative increase or decrease in the price of oil. Thus, oil price will act as a test input in the model.

Finally, the production material delay (see Figure 6) plays an important role in dictating how many hybrid vehicles can be produced at any given moment. Ideally, the firm would meet their desired production, the backlog, with a net upward or downward shift dictated by its two multipliers. This, of course, is not always possible. The desired production compared to the production capacity impacts both the factory closures and factory construction. This allows the firm to either close down excess capacity and reduce new construction, or keep existing factories open longer while augmenting their ability to produce with more new construction.

The Model Feedback and Loop Story

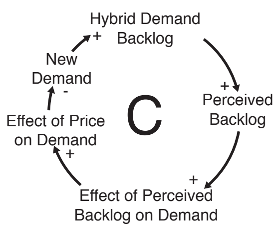
Demand-Backlog Loop



In this model, the amount of accumulated demand, the demand backlog, impacts the demand. As the demand increases, so too does the backlog, or the amount of time that customers must wait for the hybrid automobile they want. Customers, of course, usually like to take delivery of the products they purchase immediately, unlike other industries, such as the airline industry, where corporations will wait months or even years to take delivery of an airplane.

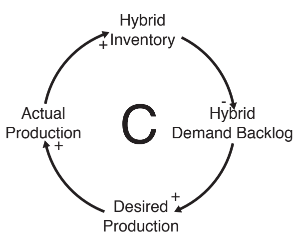
But customer perception may not always reflect the actual market conditions. Rather, they absorb information about conditions over time, through their friends, the news, or through word of mouth, which necessitates the addition of an information delay to effectively model that step in the feedback loop. The changed state of people's perceptions then impacts the new demand and that, of course, impacts the hybrid demand backlog. This structure, by virtue of its balancing nature, is counteracting.

Demand-Price Loop



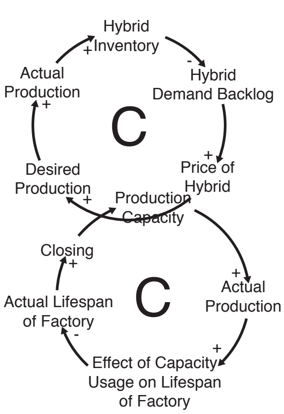
The price of a good also plays a significant role in determining the demand for hybrid gasoline-electric automobiles. Consumers will buy fewer if the price is higher. Here, as the demand and, subsequently, the backlog increases, the price also goes up, as the supply (detailed later) cannot adjust immediately to the backlog, meaning more consumers want the same number of goods. This increases prices and serves to reduce new demand. Obviously, if the opposite were to happen – if the demand decreased – the price would also decrease and that would increase demand.

Demand-Production Loop



Producers aim to produce and sell as much as possible, to maximize revenues. And, as the demand dictates how much supply will sell, it influences the supplier's choices. In this model, as the backlog increases, so too does the firm's desired production: if consumers demand more, producers will want to produce more. But producers cannot react immediately to market conditions. Instead, changes need to be perceived, personnel need to be moved, and factories need to be built, reconfigured, closed or opened. This introduces a delay before the supplied goods can increase to meet demand. Of course, eventually, the supply does increase, which helps to decrease the backlog, as more inventory is available to relieve it.

Price-Production Loop

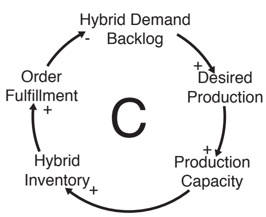


The producers of hybrid gasoline-electric automobiles stand to make the most money when the market price of their product is high. When the production of hybrid cars increases, so too does the inventory. With more product to meet the demand, the backlog and the perceived backlog both decrease. This decrease in perceived backlog also lowers the price of a hybrid vehicle. As producers stand to make less money by producing goods that sell at a lower price, this decrease in price reduces the desired production. As the desired production dictates the actual production, such a reduction also serves to reduce the actual production.

Production-Factory Life Loop

When stressed with increased or decreased demand, the production may fall above or below the ideal level at which the production capacity operates. Ideally, most factories operate at around eighty percent capacity so as to ensure less wear and tear on the equipment. If the capacity usage exceeds that ideal, then the life of the factory diminishes and the capacity is decreased: the capacity receives more wear and tear when it must produce more. Oppositely, if the capacity usage is below the ideal, then the life of the capacity will increase as it sees less wear and tear.

Demand-Capacity Loop



The demand, or backlog also affects the amount of capacity operational to produce hybrid vehicles. Obviously, if the amount of demand and, subsequently, the desired supply (because the most money stands to be made by meeting all of the demand), increases, the production capacity will need to also increase in order to meet that demand. Conversely, if the amount of demand and, subsequently, the desired supply, decreases, then the production capacity will want to shrink so as to reduce the amount of excess capacity.

Macroscopically

Actually running through all of these loops, perhaps the best place to start is the with a step increase in demand. Immediately, this would increase the backlog, which has a number of effects. In no particular order:

The new demand will fall, as the increase in demand makes its way through the Demand loop: more people will want the same number of cars, which increases wait time and reduces demand.

The price of a hybrid vehicle will also increase, as, again, more people want the same number hybrid vehicles. This impacts two pieces. First, the new demand will decrease, as some consumers will not want to pay the increased amount. Second, the production capacity and the supply will increase, as a more expensive good means better revenues for the manufacturers of the hybrid gasoline-electric automobiles.

The desired inventory, and, through the Inventory-Supply loop, the supply, also increases. Producers want to meet the new demand as it means more money for them.

The Model Boundaries

This system dynamics simulation of the propagation of hybrid vehicles into the market does leave out a number of very important components. Firstly, and most importantly, the model does not take into account the sales of substitute goods — other fuel efficient vehicles and conventionally powered vehicles — and their influence on the market. As of now, there are not many substitute goods and those that exist are not competitive, especially on the basis of price. Over time, however, as governments begin to subsidize these substitute goods or more efficient manufacturing processes emerge, this would be an extremely important consideration. But as important as this is to the model, the complexity of the entire auto market would make the model unwieldy.

The model also ignores certain segment of the luxury vehicle market, where brand loyalty tends to be greater. Currently, none of the primary European luxury car manufacturers — BMW, Mercedes-Benz, Porsche, Audi and Jaguar — manufacture hybrid gasoline-electric vehicles. A limited number of Asian luxury vehicles are produced with this technology, notably those from Toyota's Lexus brand. American manufacturers in general have been hesitant to enter the hybrid space. Thus none of their vehicles are hybrid either. This part of the market was ignored because it would increase the model's complexity and it has a relatively small effect on the factors in the model.

Certain liberties have also been taken with regard to oil prices. The model can look at the influence of increases, decreases, or even fluctuations in the price of oil on the sales of hybrid vehicles. It does not, however, contain any sort of feedback to affect the price of oil when the other factors in the hybrid market modeled here change. Oil prices and oil futures are impossible to model. It depends far too much on psychology and it involves far too many factors to model reasonably.

Quarters were used in this model as the unit of time measurement. Quarters are a standard way of managing supply and demand in the business world, so it makes sense to use them here to model the sales of this good. It starts at quarter zero, where it is assumed that none of these vehicles have been sold. This is a reasonable starting point as the market is relatively new. The model runs for sixty quarters, or fifteen years, which looks into the future long enough to determine the effect of these vehicles on the environment and on the economy. A fifteen-year period also helps to mitigate the fact that substitute goods were ignored, as most experts agree that these goods are more than fifteen years away from being competitive.

Model Testing

Broadly, as this model deals with a market, most testing involved analyzing equilibrium and any deviations from equilibrium. Specifically, the equilibrium of the hybrid demand backlog, order fulfillment, new demand and hybrid supply, were important. If the model was working properly, then, with equal supply and demand these four components produced flat curves on a behavior over time graph. More importantly, if the model were working properly, then any change in the supply or demand, making one larger than the other, would force the model to return to some level of equilibrium.

The initial testing involved the material delay at the core of the model. Initially, with equal supply and demand, this portion of the model produced correct curves. When, however, the supply exceeded demand or vice versa, it did not work properly: the inventory either increased to unreasonably high levels or became negative, which is impossible.

As mentioned above, several changes were made so that, in the end, the model behaved correctly. A backlog structure and a supply delay structure were added, which dealt with this problem. When those two structures were in place, the model was not only in equilibrium initially when the supply was equal to demand, but it also returned to a state of equilibrium when stressed with a decrease or increase in demand. (The supply, of course, is always a function of demand, so no stresses could come from the supply).

Once the completed model behaved correctly with respect to equilibrium, it was compared to historical sales of hybrid vehicles. This showed a major discrepancy between the general shape of the curves in historical sales charts and the graphs produced by this model. The historical sales showed an increase in sales at an increasing rate. This model, however, produced a curve that increased at a decreasing rate. The discrepancy stems from the elasticity of demand with respect to the perceived availability of the hybrid vehicles and the fact that demand is not constantly increasing for the duration of the model. In the historical model, there was little or no elasticity: the demand for hybrid vehicles did not decrease when the vehicles were not as available. But this model takes a more classical approach, assuming a fairly elastic relationship. The demand was not kept constantly increasing because this model is more concerned with the general behavior of the different components under stress and then recovering from stress.

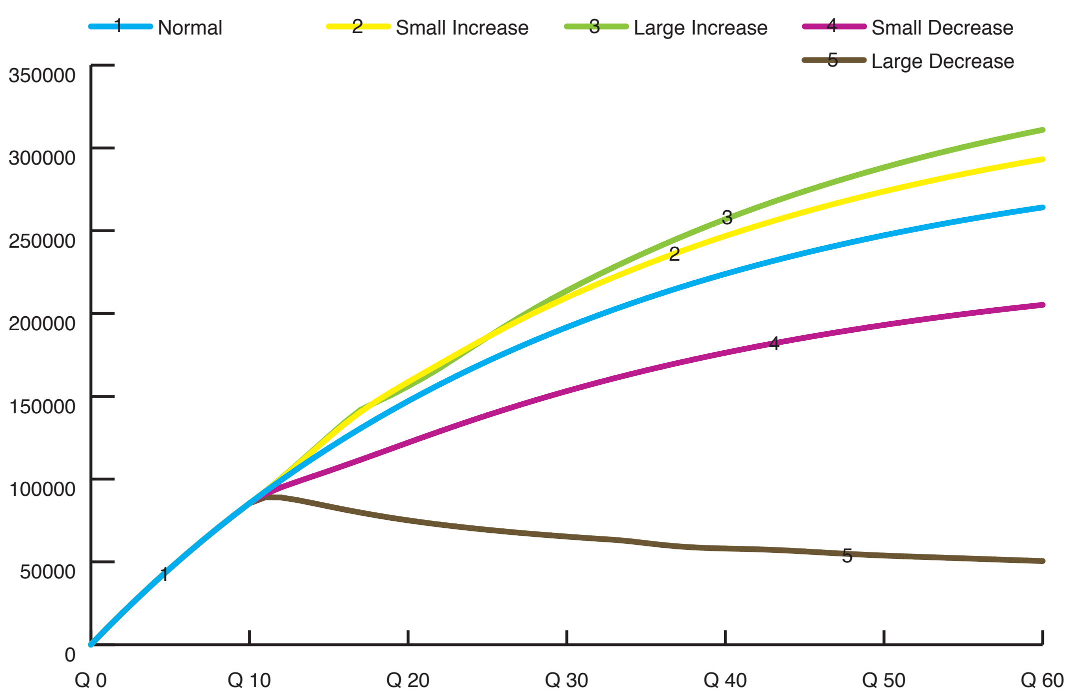


Fig. 7. A graph of the total number of active hybrid vehicles as created by the model. The curves represent an unchanged normal demand, a slightly increased and decreased normal demand after quarter 10, and a significantly increased and decreased normal demand after quarter 10.

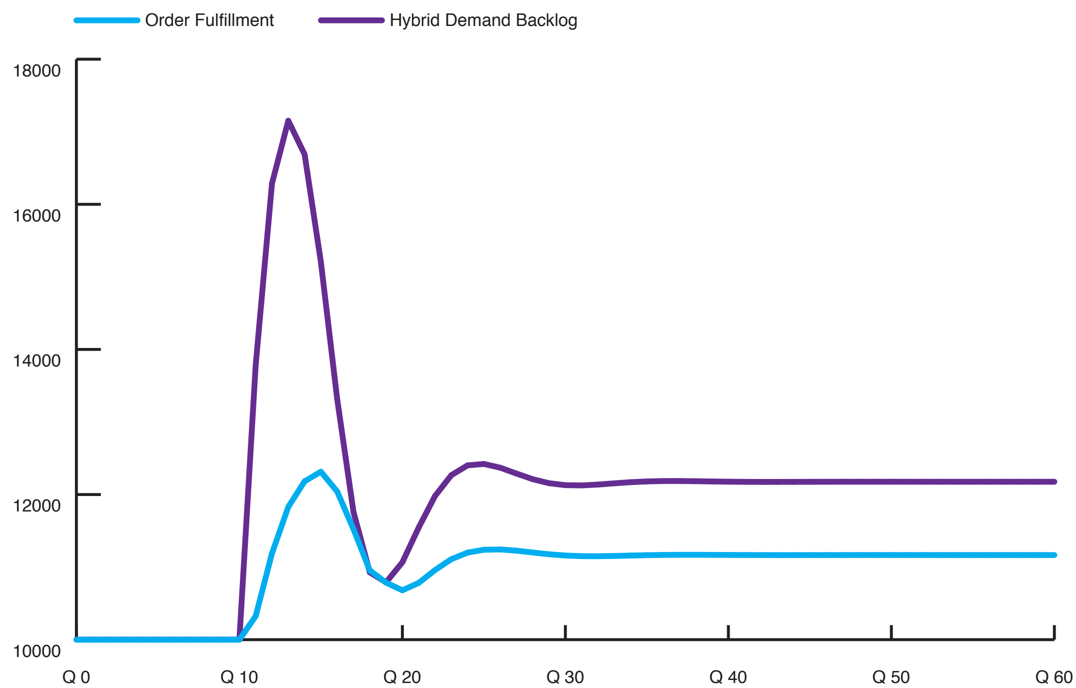


Fig. 8. A graph of the backlog and order fulfillment with a stress of 4000 extra units of normal new demand at quarter 10. It is possible to see the initial jump in backlog at quarter 10 and the eventual return to equilibrium at a higher level.

The Results of Modeling and Thinking

The most important curve in this model, the actual number of active hybrid vehicles, is, in most test cases increasing at a decreasing rate (see Figure 7). As previously mentioned, this deviates from the reference graph. But it does indicated that even with a constant demand that is not increasing an increasing number of hybrid vehicles will enter service. Even with a slight reduction in the amount of normal demand, the number of hybrid vehicles on the road continues to grow. The only cases that projected a small number of hybrid vehicles on the road were those that almost completely reduced the normal demand. In Figure 7, the only curve to show a decrease at any point was the curve representing the number of active hybrid vehicles after a large decrease in demand. In that specific test case, the demand was reduced from the normal 10,000 hybrids per quarter by 95 percent to just 500. Of course, as previously mentioned, this model does not deal with continuously increasing demand, the real-world behavior. So it is safe to assume that based on this system dynamics model that hybrid vehicles can make inroads into the automobile market and subsequently they can have an impact on climate change and oil demand.

And if these vehicles can make significant inroads into the market, the demand for oil and the carbon-dioxide emitted into the atmosphere would be significantly reduced. Most hybrid gasoline-electric vehicles, for instance, manage to drive twice as far on the same amount of fuel. The smaller, very fuel efficient hybrids have Advanced Technology Partial Zero-Emissions Vehicles status, according to the California emissions rating system, which is the highest

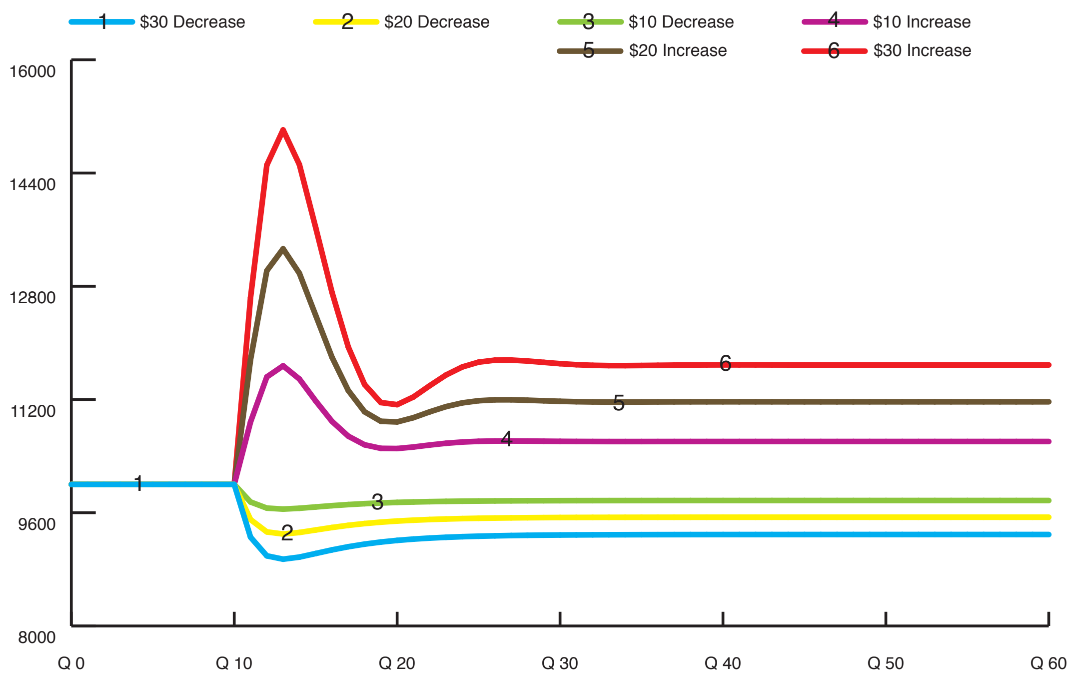


Fig. 9. A sensitivity graph of the hybrid demand backlog with different changes in the price of oil, as indicated on the legend.

rating for a gasoline-powered vehicle. Larger hybrid vehicles still manage to reduce emissions: the new Lexus LS hybrid, for instance, which is classified as a full-size sedan, manages to avoid the gas-guzzler tax.

But the other factors that the model shows may have a negative impact on the long-term adoption of hybrid vehicles. It is not clear whether current claims by auto makers that the wait times for hybrid vehicles are going to remain low are indeed true. This, of course, may affect the adoption of the vehicles: if people cannot take delivery of them, then they obviously cannot replace their conventionally powered vehicles with hybrid automobiles. When the model is run with a step of 4,000 extra units demanded to simulate a large jump in demand in quarter ten, as in the real world the backlog grows considerably. Then the huge new demand for the hybrid automobiles enters the system. As a result of that, just as in the real word, the huge backlog, and subsequently the actual wait time to take delivery, also drops back down to a level close to the initial equilibrium level. But after the model runs for several more quarters at that lower level, the other factors come into play and eventually bring the backlog up to levels nearly 20 percent higher than the initial equilibrium (see Figure 8). This translates into longer wait times for people to take delivery, which may impact adoption for the aforementioned reasons.

The relative price of oil also has interesting effects on the adoption of hybrid vehicles. Many experts have postulated that only with sustained high oil prices will consumers feel economically compelled to pay a premium for these vehicles. This is true to a certain extent. When different changes in the price of a barrel of oil were introduced into the model, it was possible to see how that affected demand in the form of the backlog. An increase in oil prices by $10, $20 or $30 all resulted in much higher demand from normal, indicating that it would help to spur the adoption of these vehicles (see Figure 9). And the effect became much more pronounced as the increase in price grew, as in the difference between curves "D" and "E" in Figure 9. But when downward changes in the price of oil were introduced, the demand for hybrid vehicles did not see as profound a decrease (see Figure 9). The $30 decrease in oil prices ultimately resulted in an 8 percent downward shift in demand from normal. Compare this to the almost 30 percent increase in demand when oil prices increased by $30.

The Key Learning from the Modeling Process

In modeling this problem, I learned a lot about the auto industry, supply chains and modeling in general. More specifically, I saw the cyclic nature of a backlog in a supply when there is a stress on demand. It was interesting to see that the current marketing campaign Toyota is using to promote the sales of its Prius hybrid — that there is no longer a long wait — may simply be a product of the cyclical nature of the backlog. I also learned that the supply chain, in bringing new capacity to manufacture online, has a number of different factors that influence it. I also realized just how complicated this one tiny segment of the auto industry is. When I began this model I though it would be fairly straight forward. But I encountered many unexpected behaviors that forced me to make the model more and more complicated to reflect the industry's true nature. And it was particularly interesting to see the way that combining the different components, which all have predictable behaviors on their own, can come together to reveal some unexpected results. The model also demonstrated how important delays, or the time it takes a company to react to changes, are to their operations. I always had some idea why companies spent millions of dollars to streamline their supply chain, but this model really illustrates how that can have an impact.

As far as the actual modeling was concerned, I realized that the production capacity was not an information delay (something that caused me a great deal of grief). I also understood how to add a backlog structure to a model, implementing a slightly less obvious delay structure and using a co-flow structure.

To the title of the paper, whether this technology will be able to impact climate change, this model has strengthened my belief that these cars can provide a fairly easy way for the world's economies to reduce our dependence on oil while we wait for zero-emissions vehicles, such as those using hydrogen or solar power, to become cheap enough and practical enough to entirely replace the internal combustion engine.

This model might have further applications in other fields as, in a general sense, this models any industry that has demand, a backlog of demand, a supply chain and a production system. Realistically, with some modification, this model could analyze the sales of products from airplanes to popular new consumer electronics devices.

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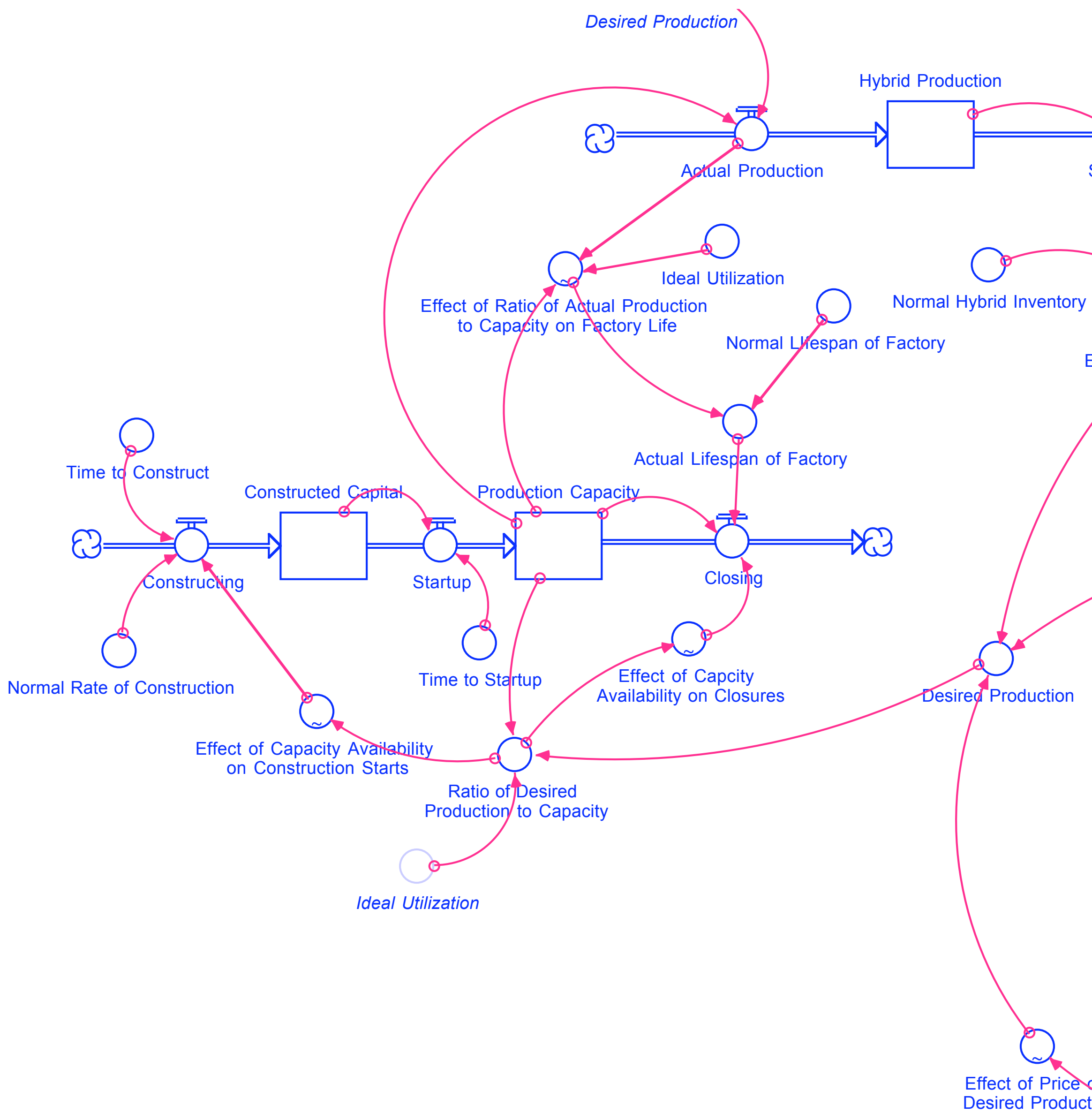

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