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What Game Theory tells us about Today's Automotive Mega Trends

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Abstract: Many countries, including Germany, are beginning to switch from traditional combustion engines to alternative, more environmentally friendly driving concepts. This change represents an existential threat to the German automobile industry, which ironically is a key player in realizing this new, green future that could threaten its own survival. Additionally, there is the collective dream of autonomous vehicles, which many believe to be the future of transportation, as well as the trend of automobile manufacturers becoming "mobility providers" instead. Although these three trends may appear to be completely unrelated, we will discover that the trajectories of these trends are inextricably linked through a game played between OEMs, consumers and the environmental movement. A key insight is that

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the Nash equilibrium found by Berz (2020) depends on the perceived likelihood of success of autonomous vehicles, and players can benefit from influencing each other's probability estimates.

1. Introduction

Three trends are currently changing the automotive industry: electromobility, autonomous driving, and new business models for mobility, in particular the Car-as-a-Service model. At first, it might seem as though these three transformations are independent of one another, but upon closer inspection and after casting the trends in a game theoretic light we observe a fascinating interaction between them.

Electrification, and with it the shift from the combustion engine to new driving concepts, is advancing steadily, not least due to the climate policy requirements of more climate protection and less dependence on fossil fuels. The fact that an electric motor is also significantly more efficient, has fewer components and requires less maintenance than a combustion engine has made it the main alternative for future mobility.

Increasing networking of the information and communication systems in the vehicle, as well as between the vehicles and its environment, form the basis for networked mobility. This should make the collective dream of fully automated driving (level 5) come true and, in addition to more flexibility also increase comfort and safety. Autonomous carpooling services might also reduce the environmental impact of traffic. The automotive industry, on the other hand, is certainly hoping for increased market potential through new use-cases and an associated increase in its customers' willingness to pay.

In particular, the new business models for mobility are the trend of car manufacturers themselves no longer selling cars, but becoming providers of mobility in the form of Car-as-a-Service. The urban mobility landscape has already undergone massive changes through offers such as car sharing. The fact that automotive OEMs are not alone in this market shows the opportunities this trend offers for future mobility. Probably the biggest advantage for car manufacturers is the possibility to calculate the costs of a vehicle over its entire life cycle. Life cycle costing allows them to calculate a better margin than other mobility providers who can only start from the purchase of a vehicle.

The interesting question for us now is how these trends are connected. In our game-theoretical analysis we want to get to the bottom of this question

and reveal these interdependencies. In order to do so we will have to make some pragmatic assumptions about the payoffs to the players in section 3.2. These assumptions are explained in detail and quantified, although the focus here is on the relative payoffs between choices, not on estimating precise utilities of the players. Focusing on the relative payoffs of players and keeping the other players choices fixed (ceteris paribus) is sufficient to gain insights into the strategic game at play and finding the corresponding Nash equilibrium.

1.1. E-Mobility

First, we want to take a look at the transformation towards electromobility. Electromobility is the use of vehicles that are powered by an electric motor and draw their energy either from the power grid or via a hydrogen fuel cell. Not only the drive technology will change, but also the entire value chain of the automotive industry, since an electric drive is much simpler in design and requires fewer components than an internal combustion engine. For the year 2030, the European research initiative Battery 2030+ has set itself the target of high-performance battery storage systems that are sustainable, safe and affordable at the same time.

1.2. Autonomous driving

Autonomous driving generally refers to self-driving vehicles or transportation systems that move purposefully without the intervention of a human driver. With the J3016 standard of the SAE International (Society of Automotive Engineers) defining six levels of driving automation, from SAE Level Zero (no automation) to SAE level 5 (full vehicle autonomy), only the two highest levels are relevant for the game-theoretical consideration in this paper. While level 5 autonomous vehicles are able to drive under all conditions, level 4 vehicles are limited to defined conditions such as urban areas or highways. In the last decade many promises were made that we will drive around in robo-taxis by 2020. But obviously the devil lies in the details and we will not see any real level 4 automation widely available before 2030. According to Bryan Reimer, a researcher of vehicle automation at MIT, "the timeline to driverless technology changing how I live and move is probably in the order of several decades, if not further away" (see Gessner 2020). Furthermore, he states that "there's an incredible amount of confusion in the general public around the context of self-driving" and "a

lot of that has to do with statements by Elon Musk and others talking about driverless capabilities." As we will see, one motivation for these overly optimistic predictions could an attempt to influence the Nash equilibrium of the game we are about to describe. Of course, the other is to persuade investors to loosen their purse strings further.

1.3. Car-as-a-Service

When we talk about car sharing, we focus on Car-as-a-Service business models and not Mobility-as-a-Service business models. This is mainly due to the fact that the car itself is the focus of this discussion and Mobility-as-a-Service integrates multiple forms of transport into a single mobility service such as cars, trains, bikes etc. Car-as-a-Service models include the traditional car sharing services like ShareNow (operated by Daimler and BMW) or SIXT share, car subscription services, ride hailing services like uber or SIXT ride and carpooling services where you share your ride with others. The real game changer will happen when these fleets become autonomous. Providers of such services can either be independent fleet management companies, bank affiliates or OEM captives (automotive banks) but for today we will only be focusing on the OEMs themselves.

2. Introduction of players

For the game-theoretic analysis, we would like to introduce three "players" into the game, to whom we will assign certain options of action and associated payoffs. Each player will have a set of two options.

The first player we would like to introduce is the environment itself, or the political will to protect it. The associated options are either sticking with internal combustion engines or shifting towards electric motors. The respective payoffs will be assessed by the degree of sustainability of these technologies and the degree to which they are used by the other players.

The second player is the consumer, who has the choice between autonomous vehicles or taking a seat behind the steering wheel. Autonomous vehicles, or for better illustration robo-taxis, have many advantages over their manually controlled counterparts from a consumer perspective. On the one hand you don't have to be fit to drive or have to have a valid driver's license. At the same time autonomous vehicles are safer and the driving time is not "lost", but can be used for productive tasks or simply to rest. We assume here that the customers' high regard for such

functionality translates into an increased willingness to pay and that this willingness to pay also overcompensates the high development expenses, if the technology becomes operational. Therefore, the customers payoffs for autonomous vehicles will be slightly higher as his appreciation for it exceeds his willingness to pay, unless the technology does not succeed, in which case customers will have a lower payoff since OEMs will have wasted other investment opportunities which the consumers would miss out on.

The key uncertainty in this model is the realization of driverless technology. As with any scientific endeavor, it is impossible to predict when, or if, driverless technology will be operational. There are many examples of tech-messiahs getting ahead of themselves and the automobile industry is heavily reliant on this technology becoming fully mature in time to pay off their large investments in electric cars. This uncertainty is represented by probability p of the random variable x, which can take the value 1 with probability p and 0 with probability $1 - p$. Additionally, we assume that $0 < p < 1$, because we can never be truly certain. The value 0 represents the state of the world where the technology is invented in time and the value 1 represents the state where it either takes too long or proves too difficult to implement.

If the technology doesn't evolve in time, then the automobile industry will have to switch back to providing manual driving, even if consumers want autonomous cars. To determine the equilibrium of the game the true probability p is irrelevant. What matters are the perceived probabilities of the automobile industry, the consumers and the environment, denoted by p_A, p_C, and p_E respectively. We will assume that these probabilities are public knowledge and therefore known by all three players.

The automotive OEMs are the third player in this game. Regardless of whether they are the ones who have to develop these autonomous vehicles, let's look at OEM options of action at an even higher strategic level. Namely, the question is whether OEMs will sell cars or mobility. Fueled by ongoing urbanization and the fact that fewer and fewer city dwellers want to own their own car, OEMs have to think ahead. Volkswagen (VW), for example, has already said goodbye to the marketing slogan "Das Auto" in 2015, signaling a change in their business strategy.

3. Quantifying the payoff matrices of the players

3.1. Environment

As far as the general climate footprint is concerned, electric cars are probably not significantly better than internal combustion engines, contrary to previous assumptions. In 2017, a widely cited study by the IVL Swedish Environmental Research Institute (Dahllöf and Romare 2017) showed a devastating CO2 balance for battery production, according to which 150 to 200 kilograms (kg) per kilowatt hour (kWh) of battery capacity would be emitted. In a published update of this study, the IVL now finds values between 61 and 106 kilograms of CO2 per kWh, i.e., on average less than half of the old ones. What remains to be seen is how this will develop further under the trend of ever larger battery capacities per vehicle. Among the reasons given for the corrected results are improved productivity and efficiency as well as a longer shelf life for e-car batteries. Instead of 150,000 kilometers, the study authors currently assume 250,000 kilometers for battery and car.

Another significant influence on more recent calculations is the consideration of the electricity mix, which plays a major role in production and operation. According to scientists at the Fraunhofer Institute for Solar Energy Systems ISE (Burger 2021), the German electricity mix was composed of just over 50% renewable energy and 49.5% of conventional energy sources for the first time in 2020, with the electricity mix shifting in favor of renewables for years now. According to a forecast by the German government the share of renewable energies in the German electricity mix could even rise to 80% by 2050.

For the environment therefore, electric cars are more favorable than cars with internal combustion engine. It is a strictly dominant strategy, which means that it is favorable regardless of the choices made by the other players. This can be seen in Figure 1, by comparing the payoffs of the environment for each combination of choices by the automobile industry and the consumer, and noticing that the payoff is always better for the environment when choosing electric cars, whatever value x ends up taking.

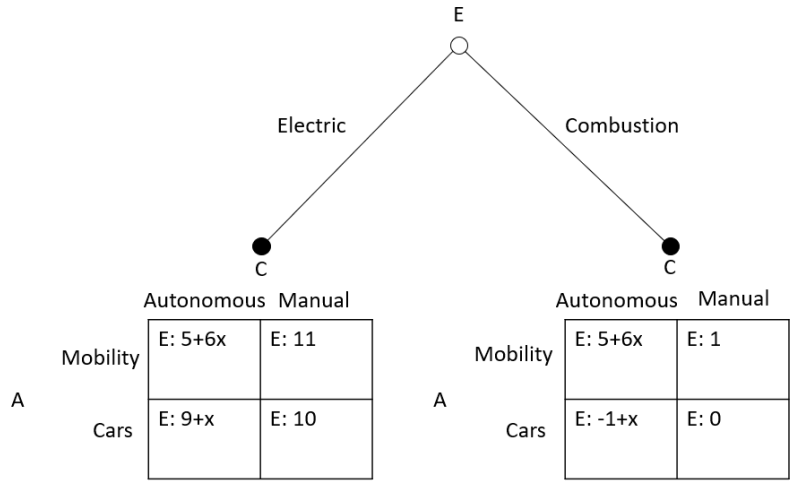

Figure 1: The payoffs of the game from the perspective of the environment (E), given choices by the automobile industry (A) and consumers (C).

Regarding autonomous driving and human driving, our hypothesis is that autonomous driving will increase the need for mobility as barriers to mobility become lower. Therefore, the environmental impact increases under these conditions. Note, in Figure 1, that the payoff to the environment E is always lower when consumers C choose autonomous driving over manual driving (ceteris paribus) and the technology is invented in time (x = 0).

This effect becomes particularly extreme when autonomous driving is combined with car-as-a-service models. This is due to the fact that the number of kilometers driven increases when vehicles are driven autonomously and, accordingly, in part without occupants. It can no longer be assumed that car-as-a-service models will reduce overall traffic, as was the original idea behind carpooling. It may be that the parking problem will be solved, because people will no longer have to park their vehicles in the vicinity of their destination. But then all vehicles will always be moving around, even when empty. A study by Moreno et al (2018) concluded that despite fewer vehicles being required to satisfy demand, the number of kilometers driven in cities would increase by 8%. If consumers end up choosing manual driving this effect is reversed and smaller in magnitude, since we assume that it without autonomous vehicles driving around empty the payoff to the environment of car-sharing is greater than individual cars.

Since even zero-emission vehicles impact the environment – be it only the particulate matter from tire abrasion or the noise generated purely by wind noise, let us assume that this applies to both internal combustion engines and electric motors, albeit to a lesser extent.

3.2. Consumer

A Capgemini Research Institute study (Winkler et al. 2019) shows that the percentage of consumers who want to get around in self-driving cars will double from 25 to 52 percent in the next five years. By 2029, as many as 62 percent prefer self-driving cars to a traditional vehicle. City dwellers and millennials are particularly open to autonomous driving due to an increase in comfort and safety.

With regard to costs a comparison is interesting, because both the price of diesel and the price of electricity are subject to considerable fluctuations. In June 2020, the price of diesel was 108.6 cents per liter on average, according to the ADAC. This results in a cost of 5.21 euros for a current VW Golf with a 150 hp two-liter TDI engine, which, according to the ADAC Ecotest, consumes 4.8 liters per 100 kilometers. In September 2021 however, the price of a liter of diesel was 140.0 cents, raising the cost of the same vehicle to 6.72 euros per 100 kilometers.

For comparison, according to the ADAC Ecotest, a VW eGolf consumes 17.3 kilowatt hours per 100 kilometers. The price of domestic electricity has been around 31.47 cents per kilowatt hour since the end of 2020. This means that charging at the domestic socket would cost around 6.00 euros per 100 kilometers with charging losses taken into account. This means that the costs for the electric vehicle per 100 kilometers would currently be lower than for diesel, but the calculation is only correct if the vehicle is actually charged at home with domestic electricity.

For our analysis, this means that we assume a slight advantage for electric cars compared to internal combustion engines for consumers. In terms of costs with the note that this is particularly effective when charging at the home socket and in terms of range, if we assume that the range of electric vehicles will actually move towards 1000 km by 2030, if industry forecasts are to be believed.

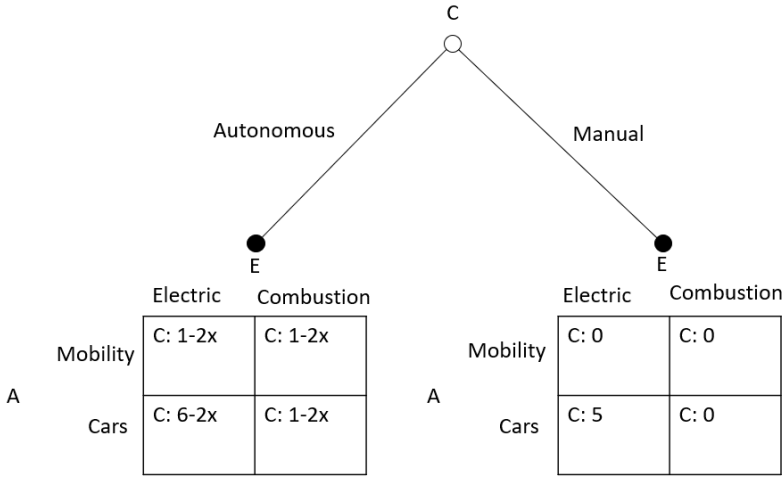

Figure 2: The payoffs of the game from the perspective of the consumers (C), given choices by the automobile industry (A) and environment (E).

We assume that autonomous driving is a strictly dominating strategy for the consumer if the technology is available ($x = 0$). As before, this can be seen in Figure 2 by comparing the payoffs of the consumer for each combination of choices by the automobile industry and the environment, and noticing that the payoff is always better for the consumer when choosing autonomous driving. The slight increase of 1 for choosing autonomous driving (keeping choices by A and E constant) is due to increased levels of comfort and security in autonomous vehicles, but is limited as the increased willingness to pay for these features will be exploited by the automobile industry.

If consumers choose autonomous driving, but the technology is not ready in time ($x = 1$), then the consumers will be worse off than if they had chosen manual straight away. The costs of producing autonomous vehicles are immense (Vogel 2020) and these costs will be passed on to the consumer if the gamble for renewable energy does not work out. Building an autonomous train in the region Pilbara in north-west Australia cost the company Rio Tinto 940 million US dollars, so we can only imagine how much self-driving car systems will cost to implement. The costs to consumers do not need to be strictly in monetary terms, but could also be in the form of reduced innovation from other projects the automobile industry could have invested in or less choice resulting from automobile

bankruptcies. These costs are denoted as $2x$ in Figure 2 above, where $2x$ was chosen so that the consumer is worse off choosing autonomous over manual vehicles if it turns out $x = 1$ and the costs from the bad investment are shared by both the consumer and the automobile industry, as we shall see in the following section.

Next, we assume a neutral stance of the consumer towards mobility solutions in a world with combustion engines, which means that the payoff for C in Figure 2 is the same regardless of A's decision (and keeping C's choice fixed). This may be surprising at first, considering that mobility solutions could increase CO2 emissions, but can be explained by the fact that the consumers preference for environmental protection was already accounted for by the environment player.

In a world with electric cars on the other hand, the consumer would heavily favor the automobile industry selling cars and not mobility services. As outlined above, electric cars imply a significant reduction in costs per km through reduced costs of upkeep and production costs. Whether the consumer can keep this benefit to themselves depends on the choice by the automobile industry, which will be able to keep most of the difference to themselves if they become mobility providers. The consumers are used to the current costs per kilometer of mobility in their mental accounting and will not complain if the prices stay the same, not realizing their potential for lower prices with the lower production and upkeep costs.

3.3. Automotive OEMs

Finally, we turn to the perspective of the automobile industry. The automobile industry is under considerable pressure to rapidly transform its products, invest heavily in new technologies and as a result alter value and supply chains that took years to build and optimize if electric cars are the new norm. This represents an existential threat to many companies in the industry and the switch to a mobility provider should be understood as a desperate survival attempt. The hope of many in the automobile industry is that they will be able to retain the profits from the cost reduction per km of mobility, as mentioned in the previous section about the consumers payoffs, to pay for the high initial investment costs.

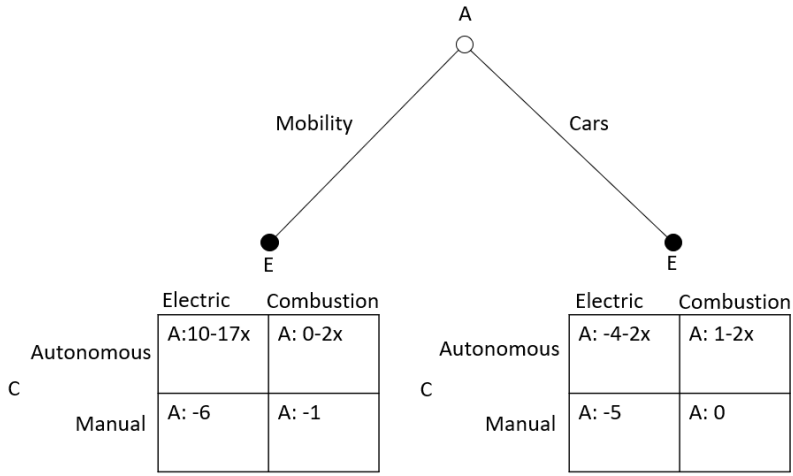

Figure 3: The payoffs of the game from the perspective of the automobile industry (A), given choices by the consumers (C) and environment (E).

If $x = 0$, then notice that the payoff to A in Figure 3 above is always higher if A sells cars instead of mobility, unless consumers choose autonomous driving and the environment chooses electric cars. The assumption is that consumers are unlikely to reap the benefits of electric cars in the form of lower costs per km of mobility, because the difference will be pocketed by the automobile industry. However, this will not work as long as mobility providers are restricted to carpooling. The key to recapturing the investment costs from switching to electric cars is that the automobile industry has to switch to selling mobility instead of cars and nothing less than the full automatization of traffic with robo-taxis is required in order to make it profitable for the automobile industry. Additionally, if E were to choose combustion engines, A cannot pocket cheaper costs per km of transport and therefore A will be worse off selling mobility and switching business model with no gains, hence why selling cars is favorable.

If $x = 1$, selling cars becomes a dominant strategy for the automobile industry because the technology will fail. If consumers choose autonomous cars, but the technology is not successful, then we see that the automobile industry is always slightly worse off than if the consumer had chosen manual cars from the get-go, due to the high sunk investment costs.

4. Analyzing the game

The resulting game with the payoffs for all players can be seen below in Figure 4, visualized from the perspective of the environment. To solve this game, we have to make assumptions about how the players deal with the uncertainty of x. For simplicity, every player knows the probabilities p_C and p_A and plays to maximize their expected value. By construction, the expected value of x is p_C and p_A, depending on the player, so we can replace x with p_C and p_A to solve the game.

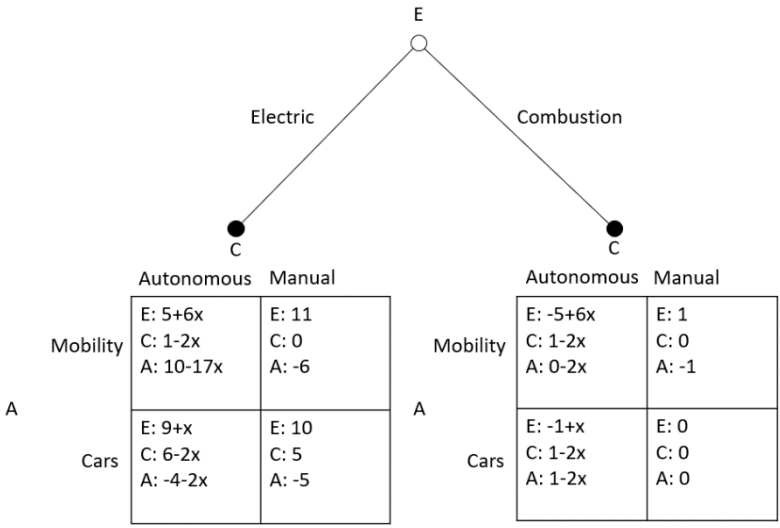

Figure 4: All payoffs of the game from the perspective of the environment. E: Environment, C: Customer, A: Automobile industry.

Recall from section 3.2, that the decision to use electric cars by the environment is a strictly dominant strategy for all values of p_E. By definition, the strictly dominant strategy is the best strategy to play regardless of the other players choices, so we know that the environment will choose electric cars and we can concentrate on the left-hand side of Figure 4. Solving the rest of the game depends on the values of p_C and p_A.

4.1. Case 1, $p_C \in (0,1/2)$*:*

Choosing autonomous driving is a dominant strategy of the consumer. Given that the automobile industry knows this, they have to choose between selling mobility and selling cars. For $p_A \in (0,14/15)$ the payoff to A is higher when choosing mobility, so in this case the Nash equilibrium is (sell mobility, autonomous driving, electric cars) with payoffs (A = 10-17x, C = 1-2x, E = 5+6x). This case is equivalent to the IFAMD market commentary Berz (2020). If $p_A \in (14/15,1)$, then A would choose to sell cars instead. With this high probability of failure, it is unfavorable for A to take the risk with the technology, despite the missed opportunity to make back the significant investment costs of electric cars.

Note that it would be better for the environment to end up in the situation where A sells cars with payoffs of 9+x instead of 5+6x, as long as $p_E < 4/5$, otherwise A choosing to sell mobility is better for the environment. This is because if A were to sell mobility and C were to choose autonomous vehicles, the chances of the technology failing would be high enough to end up with the highest outcome for E of +11. It would also be better for consumers if A sold cars, but both the consumers and the environment are forced into a sub-optimal equilibrium by the automobile industry that needs a full transformation towards autonomous robo-taxis and electric cars to make back the large investments for the upcoming transformation in the automobile industry and make their new mobility concepts profitable.

4.2. Case 2, $p_C \in (1/2,1)$*:*

In this case, choosing manual driving is the dominant strategy for the consumer and given that A knows this it has to sell cars, which gives us the NE (sell cars, manual driving, electric cars) with payoffs (A = -5, C = 5, E = 10). This equilibrium is closer to the optimal equilibrium for E, but is much worse for A who would have preferred to stay at the equilibrium (sell mobility, autonomous driving, electric cars) in case 1 as long as $p_A < 15/17$. The consumers force the new equilibrium onto the automobile industry by assuming probability p_C, even though A would have preferred to take the risk of autonomous cars, for fear of the costs they would face if the technology fails.

5. Conclusion

As we can see in the two cases above, the Nash equilibrium is determined by the subjective probabilities p_C and p_A. With a low probability of failure p_C, the automobile industry is able to force the other two players into the suboptimal equilibrium where it can make back the money it invested in making the switch to electric cars. A will do this conditional on its own estimation p_A being less than $14/15$, otherwise the risk is also too large for them and the optimal outcome for the consumer will be the equilibrium.

If p_C is larger than $1/2$, it becomes too much of a risk for the consumers, who would also face some of the costs of a failed investment in driverless cars. Consumers don't reap the massive benefits of autonomous driving that the automobile industry can, so they are quicker to switch to manual driving as the risk increases. By switching to manual driving, they leave the automobile industry no choice but to sell cars. As long as $p_A < 15/17$, A would have preferred staying with the outcome where they sell mobility and C chooses autonomous vehicles. But once $p_A > 15/17$, even A doesn't want to take the risk of selling mobility with autonomous driving, even though they are desperate to make back the high investment costs incurred by the electric cars.

Now let's take a step back and talk about p_A, p_E and p_C. These probabilities are not the true probability of success, but rather the perceived probabilities. Whether the value of p they are quoting is true or not is irrelevant for game theory, each player makes the best decision they can given their own probability and their knowledge of the other players probability. The interesting game may actually be played outside of this game, in the public discourse on technology, influenced by the three players, which can be used to manipulate the others probability estimate.

If $p_E > 5/6$, then the environments optimal probabilites would be if $p_C < 1/2$ and $p_A < 14/15$, since this implies that A will force C into the equilibrium (sell mobility, autonomous driving, electric cars), even though the autonomous driving will likely fail and therefore give E a payoff of 11. If the environment believes the chances of success are small then it would benefit from convincing C and A of the opposite, that the chances of success are actually high. If $p_E < 5/6$, then the environments optimal probability would be if $p_C > 1/2$, which would give it a payoff of 10. With a moderate to low probability of failure of the technology, the environment would benefit from convincing the consumers that the chances of success are

actually low. E therefore tends to benefit from shifting the consumers probability in the opposite direction of its own.

Finally, the automobile industry is the most interesting to look at, since A most likely has the most accurate estimate of the true probability p. Even though they may privately think that the probability of failure is quite high (p_A large, but still less than $14/15$), it is beneficial for them to convince the consumers that p is actually very low ($p_C < 1/2$). By convincing consumers that p is low they can manipulate the customers into choosing autonomous driving even though it is so low that it would not normally be worth it for consumers. If consumers knew that p is greater than $1/2$, they would choose manual cars and force the automobile industry into the other equilibrium.

The game outlined above may explain the overly optimistic projections by the automobile industry which has convinced us consumers that we will all be zooming around the city in driverless cars in no time. Unless the probability of failure is larger than $14/15$, A has orthogonal incentives to C and would like to convince them that the probability is actually less than $1/2$. Given that the true chance of success p is most likely low, as was outlined in Sections 1.2, a likely assumption would be that $1/2 < p_A < 14/15$, which implies that the automobile industry has conflicting incentives to the consumer and would like to convince them that the probability is actually $p_C < 1/2$. If successful, they will manipulate the game so that we end up in the equilibrium (sell mobility, autonomous driving, electric cars), which would not be optimal for the consumers, and possibly also for the environment depending on p_E. But in the end, it is likely that this scenario will save large parts of the German automobile industry on which many of us depend indirectly or directly, unless of course the true value of p is greater than $14/15$, in which case the automobile industry may be acting against its own best interests.

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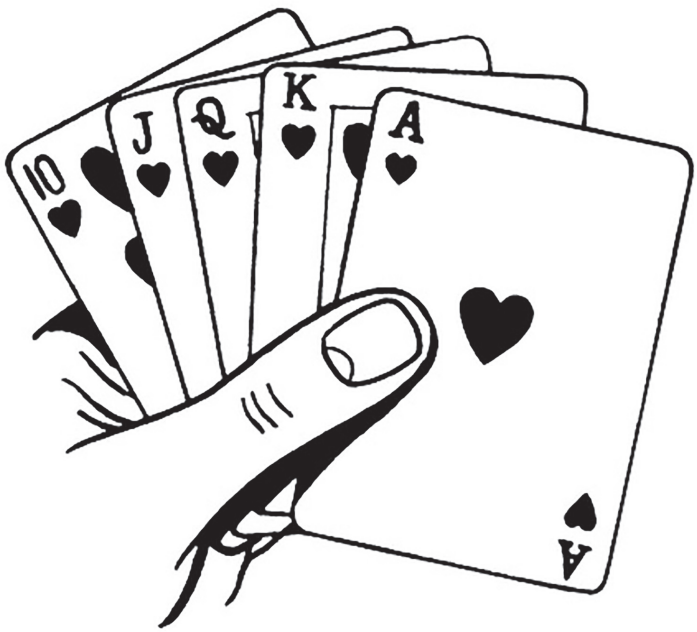

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