Disruption in the Automotive Footprint: Model Limitations, Model Extensions

– Why Tesla Was Doomed from Day One –

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The auto industry revolves around highly differentiated, complex, assembled, capital-intensive durable consumer products with long product cycles and ongoing service needs and with over a dozen major players supported by an even larger global supply chain. These features contrast with Christensen's (1997) archetypical example of disruption, the hard disk drive, which was an intermediate good in an industry with a small number of players and rapid product turnover. Due to its structure, the auto industry is unlikely to see disruption, despite claims that battery electric vehicles, new mobility business models, and autonomous driving will overturn the business of incumbents.

We are now witnessing Elon Musks slow-motion disruption of the global auto industry

Title of Steve LeVine post at Quartz, April 8, 2016

I. Introduction

A motor vehicle is a highly differentiated, complex assembled durable good with long product cycles, ongoing services needs, and a century-long history of incorporating new technologies. This is in contrast to the archetypical case of disruption put forward by Clayton Christensen of hard disk drives, which were an intermediate good with a rapid product cycle that were discarded rather than repaired, and which were purchased according to price and technical considerations with little product differentiation. Adding a new feature, or finding a way to "degrade" a feature while lowering cost proved sufficient to allow new entrants to displace incumbent disk drive firms. For a single firm to disrupt the automotive industry, it would need to be able to bring an array of products to market in a short span of time, and in a manner that could not be readily challenged by established firms. That is extremely challenging, as it takes 4 years for a *de novo* firm to develop a vehicle, put tooling in place and commence production. All stages consume

1. This paper is an outgrowth of a presentation to the Toronto-Torino conference series in Torino, Italy in November 2016. The RENIR conference scheduled for September 2018 is a followup on that initial set of conferences. Since 2016 I have presented versions of this work at the conferences of the Industry Studies Association and GERPISA and in a seminar at Washington and Lee University. Those opportunities have been invaluable. I thank Robert Chapman Wood of San Jose State University for pushing me to engage with the management literature on disruption. I truly appreciate my sometime co-author Peter Warrian's feedback and encouragement.

2. My apologies to Canadian and European conference participants for not using metric units, and for generally framing the paper in terms of the United States context.

large amounts of capital, up to $2 billion to design and test a new model, and $1.5 billion for plant and equipment. A firm needs good execution and luck that early models will be launched into a strong sales environment and do well enough to keep the business afloat and help it finance the launch of 4-5 additional models and 3 more assembly plants, all to gain at best a meager 1% market share.

Incumbent firms all offer multiple drivetrains. Adding an electric motor is not a fundamental challenge, though it does give a different weight distribution and so cannot just be "dropped in" as readily as a diesel drive. But neither the body, the interior nor the core steering, braking and safety features are affected. Furthermore, incumbent assemblers have $1 billion or more R&D budgets, including "advanced engineering" teams developing knowhow and suppliers in advance of commercialization. Within the limitations of the normal 4-6 year product cycle, carmakers are poised to respond quickly.

I begin by reviewing the management literature on "disruption." I then look at historic examples of disruption in the automotive industry, followed by a systematic analysis of product differentiation and other features of the industry that work against rapid change. I then analyze three purported "disruptors" of the industry, battery electric vehicles, new mobility business models, and autonomous vehicles. For each I discuss the social, cost, business model and technical challenges they face. Then there's diffusion: I argue that even if these barriers are overcome, the nature of the motor vehicle industry means rollout will require over two decades and so will not be "disruptive" in any meaningful sense. Finally, I turn to Tesla as an example of why disruption is hard. After 15 years in operation, the company only has three models in production, two of which "long in the ears," has only a limited distribution and service infrastructure, and has never demonstrated an ability to make a sustained profit. It thus seems fated to join an array of other would-be disruptors such as Fisker, Faraday and Aptera.

II. Disruption

Christensen (1997) and colleagues developed the concept of "disruption" around the hard disk drive market, which saw a rapid succession of "leading" firms. Revisiting their research at the 20 year point,[3] they defined it as:

> "Disruption" describes a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses. (Christensen *et al.* 2015, 4)

In particular, Christensen diagnosed the phenomenon as stemming from an "attack from below" in which products inferior in one or another dimension eat into the incumbent leader's business. In economics

3. In their 2015 paper they cite Uber as a disruptor, under the mistaken assumption that it would be financially successful. In that they proved wide of the mark.

jargon, this is similar to the concept of "fringe firms" in a monopoly market. The "innovator's dilemma" in their initial presentation is because in the short run it's rational for a leading firm to ignore small, outside firms. That's because fighting them is more costly than the small bite they take out of profits. Now at some point, *if* the fringe keeps expanding, *then* the leader's monopoly will disappear. Christensen and various coauthors elaborated on this concept, stressing that it is a strategy for entering a market that can threaten incumbents, and that alongside their original "attack from below" was "attack from new (ancillary) markets." Entering the main market head-on or "attack from above" aren't therefore disruptive because they will engender an immediate response from incumbents. They imply that it is therefore unlikely to be successful, and in the 2015 followup argued that even if the new entrants establish a toehold, they will not find it possible to expand quickly.

Christensen's archetypical example had several characteristics. First, it was an intermediate good sold to computer and mp3 player manufacturers, and so was invisible to final consumers. Second, there were at any point in time only a few players in the segment, so entrants faced incumbents earning high margins. Third, these were non-durable goods that in general could not be repaired and which had no resale market. Fourth, the product was modular, a box that could be screwed into place and plugged in with a standard connector. Historically, in the era of mainframe and desktop computers, the focus of product development was on improving storage density and decreasing latency (and of course price). For mp3 players and laptops, reductions in physical size were important even at the cost of "degraded" capacity and slower speed, giving new entrants a potential market. There was no need for a purchaser to stick with a particular vendor due to design interdependencies. Fifth, the product cycle was short, potentially under a year, while customers were also constantly redesigning their laptops and music players. A fringe firm could potentially grow very quickly, because customers were constantly making new sourcing decisions.

Criticisms of the concept abound. Utterback and Acee (2005) examine a set of industries to check the robustness of Christensen's "attack from below" typology. Their examples of discontinuous technical change including vinyl records, the slide rule, and motor vehicle carburetors, all of which effectively vanished. Using yes/no characterizations of cost, primary technical features and ancillary technical features, they find examples of all 8 possible permutations. These include products that were initially more expensive, counter to the "attack from below" thesis. Their counterexamples included digital cameras, which were initially more expensive, and performed more poorly. Similarly, gasoline engine fuel injectors were more expensive than carburetors, but their equal in delivering a consistent fuel/air mixture, while lowering emissions. Likewise calculators were initially far more expensive than a slide rule, and could not handle logarithmic and trigonometric functions, only basic arithmetic. They concluded that the "attack from below" model was at best one pattern.

Sood and Tellis (2011) take a different tack, developing histories of 36 technologies in 7 industries, in part to offset the survivorship bias of Christensen's histories of "winners". They find that in about half of their cases incumbents were the initial commercializers of the new technologies, and incumbents tended to do better at commercialization than new entrants. Furthermore, old technologies are not static; new technologies could fall behind, even when they eventually displaced the old. Finally, incumbents did not necessarily lose in the case where there was an "attack from below" by entrants with new technologies. But most innovations were higher in cost; cases of "attack from below were a distinct minority. In sum, they argued that there can be no presumption of disruption of incumbents in an industry due to the advent of a new technology.

A common problem is the lack of a clear definition of "disruption." What time frame is required? Christensen and his collaborators finesse that issue by defining it as a strategy, a process, not an outcome. Indeed, they emphasize that such strategies will frequently fail, and may take time–their hold up Nucor as a "disruptor" even though it took 40 years for them to change the dynamics of the industry (Christensen et al. 2015, 11).[4] While in their restatement they emphasize "disruption" is a strategy not an outcome, in the wider literature (and their earlier work), "disruption" is variously used to refer to the displacement of both dominant technologies and dominant firms. An example is Schmidt and Druehl (2008), who examine the set of 75 "disruptive" innovations provided by Christensen and Raynor (2003). They conclude that many were "encroachment" from above, at odds with the Christensen picture of pervasive disruption from below. Likewise, in a special issue of the *Journal of Product and Innovation Management* that generated a subsequent rejoinder by Christensen (2006), Danneels (2004, 249) attempted to pin the concept down as: "A disruptive technology is a technology that changes the bases of competition by changing the performance metrics along which firms compete." This is at odds with the later reformulation that emphasizes strategy and process rather than firm or technology.

So new technologies enter industries with varied patterns, and are as often as not commercialized by incumbents. But over what time frame? Slow-moving does not make for disruption. In addition, is the focus a technology, or a company? From the perspective of managers or investors – or management science – the company needs to be the core of the analysis, not the technology. Now ambiguity of time frame is not totally inappropriate; industries operate on different clockspeed (cf. Fine 1998). Portfolio managers are evaluated every 90 days, and even value investors only to try to project profits out 4 or 5 years. But unlike the hard disk drive industry, automotive assemblers work with long product cycles, where planning begins with the launch of the previous model for a product that won't come to market for 4 years and will cease production only after 8 or more years. In 2017 firms were developing vehicles that

4. The slowness of that process suggests it was not central to the bankruptcies in the US of Big Steel firms.

would not launch until 2021, and had penciled in the timing of successor models in the 2025 time frame; advanced engineering was already working on what might go into those (author interviews with suppliers, December 2017 and February 2018). I return to these issues of time frame and focus in the conclusion.

III. Historic Change in the Automotive Industry

Can we find examples of disruption in the auto industry? I argue that there are two reasonable examples where it occurred from the technical end. I also give examples of major changes, "attack from below" and "attack from above", that failed to be disruptive. While over the longer haul new technologies and new business models have shifted the nature of competition in the industry, they occurred too slowly to be disruptive in any useful sense of that term.

The first example is the rise of the internal combustion engine, which offered a better use case and value proposition to users and rapidly displaced the battery electric vehicle between 1903 and 1905. This however was in the nascent period of the industry, before product details had solidified, during which at peak 300 firms were in operation. Furthermore, steam cars were also pushed out of the marketplace, though firms such as the Stanley Motor Carriage Company survived until 1924 (Loeb 2004).

An example that was not disruptive was the assembly line, introduced by Ford from 1913, just in time to sell into the boom in the US economy that came with the outbreak of World War I. While this certainly helped expand the scale of the industry, Ford's focus on moving downmarket allowed firms that emphasized product differentiation in the mid- and upper-end of the market to continue in business. Indeed, Chevrolet did not begin production until 1913, when Ford was already increasing the throughput of his factory, while Chrysler was not founded until 1925. Ford was not the only firm to succeed in volume production. While exit in the US market increased, the postwar slowdown was as important as the assembly line.

More disruptive was the rise of the all-steel body, which was pioneered by the Budd Company in 1913 (Nieuwenhuis and Wells 2007). However, it was only with improvements in stamping and joining in the 1930s that wood frames (such as those made by the Fisher Body Corporation) gave way to mass-produced fully metal bodies. The dies and presses needed to work with steel raised the capital investment required for making a vehicle, as did the development of more automated engine casting and machining. The net result was that small companies could only afford to make 2-3 models with infrequent changes, in contrast to the full product range and annual model change pioneered by General Motors. The result, in the US and other markets, was the disappearance of fringe firms and the growth of oligopolies.

In particular, "attack from below" with small cars was only fleetingly successful, and did not prove a road to success for smaller firms such as Nash, Rambler or Studebaker. In the post-World War II era there were 3 periods in which subcompacts seemed to offer a route to growth. One was circa 1958, when the American Motors Rambler and a wave of European imports, such as the VW Beetle, captured a chunk of the market. However, the Detroit Three responded with downsized vehicles such as the Ford Falcon, while the level of European imports fell. A second small car boom took place a decade later, circa 1968, when the VW Beetle sold over 500,000 cars in a single year. Again, that proved fleeting. AMC, Ford and GM launched rival small cars in (respectively) the Gremlin, Pinto and Vega, while the Rabbit, launched as a successor to the Beetle, was poorly received in the US. VW soon closed the assembly plant that it built in Pennsylvania.

A decade later, in 1979, the second oil crisis ushered in a 3rd wave of subcompacts, this time dominated by imports from Japan, including cars the Detroit Three imported from affiliates (Isuzu for GM, Mazda for Ford and Mitsubishi Motors for Chrysler). This was coupled with a steep recession that saw overall automotive sales plummet, and thrust the Detroit Three[5] into red ink (with Chrysler only surviving with help from a US government loan). That wave of subcompacts peaked at 33% of the market. However, petroleum prices peaked in 1981, and by 1986 had fallen by half, and during the duration of the 1990s the real gasoline price remained below the prior historical low of 1972. Subcompacts dropped to 7% of the market. Thus while demand in the US has periodically shifted toward smaller vehicles, that has always been temporary, and firms soon returned to making large cars.

While small cars did not prove disruptive, thanks to government policy they did pave the way to enduring new entry. Past history suggested that the rapid drop-off of demand for subcompacts would have seen Japanese firms withdraw from the US market, as had happened twice before with European cars. Policy intervened. The voluntary export restraint (VER) of May 1981 required Japanese firms to organize an export cartel to limit exports to the US to 1.68 million units. That created an incentive to construct "screwdriver" plants that assembled imported parts to avoid the VER. While Honda was already planning to set up local production, Nissan and Toyota were clearly driven by policy to set up their US assembly operations. This intersected with the side effect of quantitative restrictions: if sales are limited, then firms move upmarket to increase profits. Under the VER, Japanese firms could end competition among themselves and raised prices 25%. This gave them the money to develop mid-sized cars that sold better in the US than in Japan. When oil prices eventually fell and the market for compact cars collapsed, Honda,

5. Today the "Big Three" would be GM, Toyota and Ford. I therefore use the term "Detroit Three" to refer to GM, Ford and Chrysler, though with Fiat's acquisition of Chrysler that term too is anachronistic.

Toyota and Nissan were firmly entrenched in the US market.[6] While it took another 10 years, the Detroit Three oligopoly collapsed. In other words, only policy prevented a repeat of the temporary import surges of 1958 and 1968.[7] Entry from below took 30 years to work, from initial exports in the late 1960s through the construction of factories in the 1980s and the expansion of market share in the 1990s. Ironically, it was US government policy that drove this transition as much as it was corporate strategy. Furthermore, it did not displace incumbents, it only lowered their profitability.[8]

The same dynamic underlies the entry of new firms in China, which at first glance would seem to fit disruption via "attack from below" but where the real driver was again government policy. Initially local markets there were insulated from competition, even from producers in other regions of China. After 2000, the explosion of demand kept prices and profits high, reinforced by tariffs of 80%-100% prior to WTO provisions that came into force in 2006, and 25% thereafter. The overall market was dominated by the output of joint ventures with global automakers, with VW and GM the leaders, producing versions of models made in Europe, and (given limited supply capacity) higher-priced sedans. Local firms could survive under this price umbrella, helped by buy-local policies for government purchasers and local taxi companies, even though they focused on economy cars with limited features, staid (or blatently "borrowed") designs, and low prices. State-owned firms had an additional advantage, the profits from joint ventures. All the major players (such as Dongfeng, SAIC, Great Wall and Geely) began operations before 2000. In addition, firms such as Great Wall happened to make SUVs, prior to the post-2010 market shift towards such vehicles. However, while several of these firms may survive, the decline in profit margins stems from the rapid introduction of new vehicles by joint ventures. These JVs have also moved downmarket, now that they have enough assembly plants to meet demand for higher-priced models, and have launched a range of SUVs. To date new entrants have not been disruptive, and several have consistently lost money.[9] Nor have they been able to mimic the VW Beetle or Honda Civic with models that allowed entry into global markets. Despite entry from below, the Chinese operations of VW, GM and other global firms have continued to expand.

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6. Six small-car entrants did exit from local production, including Hyundai, VW, Suzuki, Mazda, Mitsubishi Motors and Isuzu, while Chrysler ended up with the plant Renault built in Ontario. VW and Hyundai subsequently opened new plants in the US, and Mazda in Mexico.

7. I have not looked at the opposite end, the impact of imports of European luxury cars and later Japanese high-end marques on Chrysler, Lincoln, Cadillac and Oldsmobile, the luxury car brands of the Detroit Three.

8. The 2009 bankruptcy of GM and Chrysler had as much to do with the differential cost of retiree healthcare and pension obligations as with the erosion of market share. New entrants had no retiree obligations, because initially they had no retirees, and because they used defined-contribution retirement plans. The Detroit Three recognized this problem and negotiated a VEBA (Voluntary Employee Benefit Association) in 2007 to cap these "legacy" costs. But the phase-in was set for 2010, too late to help (Smitka 2011).

9. Early entrants such as GM and VW have also done better than later JV entrants such as Ford, PSA and FCA.

Another restructuring of the industry reflects the rise of light trucks and truck-light crossovers and sports utility vehicles. Vans were present in the US from the early 1960s, but most were used as work trucks, not hippy vans. That changed with the Chrysler minivan in 1984, and the resurgence of Jeep. Prior to the minivan light trucks comprised 20% of the overall market. From 1984 through 2004 that share rose step by step to 56%. The level fell back to 50% during 2006-2013, but over the last 5 years again rose steadily, reaching 68% in June 2018. This however is due to shifts in consumer preferences, and has affected incumbents on the basis of their orientation to sedans, with a differential impact on the profitability of individual firms. Other markets—Japan, China, much of Europe—are likewise seeing consumers move towards vehicles in which occupants are more upright. This helped resuscitate seemingly marginal firms such as FCA in the US and Great Wall in China. Again, the origin lay in policy, not corporate strategy: US CAFE fuel economy standards were tighter for sedans than light trucks. Trucks also benefited from the "temporary" 1963 Chicken War tariff targeted as a selective reprisal at the VW van, which at the time was the only imported light truck in the US market. It proved permanent: in 2018 light trucks continue to be protected from imports from outside of NAFTA (Smitka 1999). In source and in impact the rise of light trucks has not been disruptive, though it has reshaped product strategy across the global industry and generated both winners and losers.

Finally, automotive components have been subject to technological displacement. Regulation – emissions standards – led to the replacement of carburetors by fuel injectors over roughly a decade (Utterback and Tellis 2005, 13-14). Antecedents dated to 1957, but it was the first microcomputer engine control modules that made injectors practical. GM first used them in 1979, and had completed its switch away from carburetors by 1990. This was a totally new technology, but it was adopted because of regulation, as the initial versions were more costly and no more reliable. Several incumbents made the transition, including Bendix and Bosch, but others were driven from the market.

Another example might be manual transmissions, which have given way to automatic transmissions. For the most part, however, manual transmission firms remain the leaders, as the core for both remains carefully engineered gear sets. Similarly, incumbents dominate both the old and the new technologies in areas such as belt-driven and electric water pumps and hydraulic and electric steering systems. Otherwise much of the change in automotive components represents the addition of new features, from radios and now infotainment systems to more sophisticated lighting, seats, safety systems and emission controls and new materials aimed at lightweighting for fuel efficiency. Some of these created space for new entrants, but few have displaced incumbents (through repeated waves of M&A activity makes tracing the details challenging).

The biggest disruptor has come from customers, the final vehicle assemblers, with their ongoing globalization. This started in the 1980s with the initial forays into high-volume foreign assembly by Nissan, Honda and Toyota, and continuing with the development of global platforms by existing multinationals such as VW, Ford and General Motors. At present the same platform is now produced around the world, and requires that they can procure identical components in each region. Suppliers are thus expected to be able to manufacture the same alternator or brake assembly in China, Brazil, Europe, Mexico, Japan and Southeast Asia. This stimulated repeated waves of realignment, as suppliers established a global production and engineering infrastructure through a combination of direct foreign investment, and acquisitions/spinoffs. However different today's supply chains appear, this was not an outcome driven by strategy at individual suppliers or any discrete innovation. Instead it was an outcome driven by the globalization of the entire industry, amplified by the expansion of China and other developing country markets that have made them larger than the combined markets of NAFTA and the EU. This process fits under none of the uses of "disruption."

In sum, it is difficult to find examples of disruption in the auto industry during the past 50 years under any definition of the term. This is not to say that the North American industry today looks as it did in 1950. Vehicle technology has changed a lot, particularly since 1980, under the impact of fuel efficiency, emissions and safety regulation. Government policy that aimed to protect the Detroit Three led to new entry in NAFTA, while the evolution of the EU led to cross-border entry into the British, French, Italian, Scandinavian and German markets that had once been reserved for national champions. This era also saw the rise of consumer conveniences. By the late 1930s about 20% of US cars came equipped with radio, but in 1950 they remained an expensive option, and in 1963 were still in only 60% of new cars. Developments continued, with better noise filters and transistors, the addition of the FM band, 8-track tapes, cassettes, CDs, and now Bluetooth connections. Air conditioning and automatic transmissions had been commercialized before WWII but in 1950 were still novelties. Better paint, sunroofs, remote keys, unleaded gasoline, radial tires and cruise control are all of recent vintage, and provide a sense of the breadth of change independent of areas affected by the regulation of safety, emissions and fuel efficiency.

There may be examples of disruption if we extend the analysis to Japan and Europe. For example, in Japan two scooter manufacturers (Honda and Suzuki) were eventually able to enter the industry by launching inexpensive vehicles, while several 3-wheel producers developed production expertise and distribution networks that facilitated their shift to making 4-wheel vehicles (Mazda, Mitsubishi and Subaru). However, these shifts occurred when Japan was still relatively poor with a small market populated with two dozen or more players. The story is akin to the shakeout among multiple producers using varied business models, as posited in "population ecology" models of entry and exit. This is similar to what happened in the US prior to the Great Depression (Klepper 2002, Klepper and Simons 1997), and reflects experimentation in a new market rather than deliberate disruption.

In sum, in the automotive industry change is normal, disruption is not. Motor vehicles are high-tech products, ranging from their use of novel steel alloys and composites with up to 2 miles of wiring connecting multiple computers with sensors and user interfaces. The automotive industry represents a huge market, with a supply chain constantly showcasing new technology to their integrator-assembler customers. But even at the level of the individual component, incumbents are the main innovators. For any given innovation, who is first to market shifts, but for almost every component there are multiple suppliers active in R&D, and able to launch competitive products within 3-4 years. Competitors typically catch up within one model cycle, at times with the help of their customers.[10] Even at the level of discrete components, disruption is the exception, not the norm.[11]

IV. Industry Characteristics and Systematic Barriers to Disruption

As claimed in the introduction, the structure of the auto industry makes disruption unlikely. This section addresses these factors *seriatim.*

A. Product Differentiation

Motor vehicles are highly differentiated, from those aimed at goods transport to ones providing utilitarian passenger transportation. Alongside variation to serve different uses, passenger cars in particular reflect deliberate attempts to improve margins (that is, to price discriminate) and create cross-model branding. Alfred Sloan made this strategy explicit at General Motors in the 1920s, capitalizing upon the collection of disparate brands put together by Billy Durant, the firm's founder, to offer cars in a hierarchy of price brackets and in each bracket, a selection of styles. Thus GM offered a vehicles ranging from entry level Pontiacs to top-of-the-line Cadillacs, whose refined styling and high price made owning one a mark of status (Farber, 2002). Choices over color, trim level, accessories, engine size, and front versus all-wheel drive further differentiate the final product. Advertising reinforced this, portraying vehicles as family-friendly, or sporty, or rugged to match different consumer self-images. When successful, firms could not only charge higher prices but could generate repeat sales. Such brand loyalty makes it harder for new

10. No car company wants to buy from a monopoly, and may even require a firm to cross-license an innovation before adoption to guarantee they have a second source.

11. This statement reflects 24 years of observation of supplier innovations as a judge for the Automotive News PACE award. One part of the evaluation is based on a competitive analysis backed by reference calls to customers, who are evaluating the innovation against the products of other suppliers. In very few cases is the conclusion that a firm has a lead that competitors won't overcome within 2-3 years.

entrants to gain market share. In general, product differentiation lessens the appeal of any single model to purchasers as a whole.[12]

Gaining substantial market share in the auto industry thus requires fielding a range of models, from entry-level cars to family-oriented minivans and crossovers to expensive luxury SUVs and sports cars. While modern engineering methods enable multiple "top hats" and drivetrains to be added to a single platform, each such model takes 2 years to engineer and production entails $100 million or more for the tools and dies to turn out unique (exterior) sheet metal.[13] Suppliers need to make parallel investments for seat and instrument panel production, glass, suspension and other components perceived by the final consumer. Developing a new platform or drivetrain is even more expensive, but because they can be used for multiple models, they benefit from economies of scale. Given the global operations of assemblers, they have a wider product portfolio than that available in any single market, eg, compact sedans may be sold in Mexico but not in the United States. That gives an established firm a greater ability to respond to new trends in any particular market more quickly than a new entrant that has only a scant handful of models and an engineering team able to work on only one new model at a time.

A new entrant must pick one segment for its initial product offering in a particular geographic market. Even if it does well, and can expand into smaller national markets via exports, that may still leave it with under 1% of its "home" market and even less of the 100-million-unit global light vehicle market. With finite engineering resources, a new entrant will find it difficult to launch a new model more than once every 2 years,[14] and that pace will be slower if the size is sufficiently different to require a different platform and drivetrain. Of course, as the next section indicates, the fashion component of the industry, accentuated by ongoing innovation of product features, requires that models be periodically redesigned. For mass-market vehicles that is typically on a 4-year cycle, which further constrains the ability of a new entrant to develop a full product lineup, as early in its life as a firm a *de novo* car company must being

12. I had foresworn buying new vehicles, but the collapse of new car sales from 2007 led to a shortage of used cars. Indeed, on one car lot a used SUV was actually priced higher than the pristine new model year equivalent. So 2 of my last four vehicles were bought new, and one is a stick shift. In contrast, my pickup was already 25 years old when I bought it, and I've not repaired the body where it's rusted through. Utilitarian–but it also means I fit right in if I'm out in the local community, away from the university crowd.

13. For an established firm, product planning commences with the start of production of the previous model, 4 years before it is launched and 8 years before it in turn goes out of production. As noted below, detailed development takes less time. Firms try to maintain flexibility in styling and other key characteristics until as close to launch as possible.

14. From start to finish a new model can be developed in 36 months. As noted above, initial model planning and styling may start 18 months before prototype CAD files are frozen. It then takes approximately 18 months to the start of production (SOP). By then planners and stylists will already be working on another model, and design engineers can also begin shifting to new projects as the pre-production approval process progresses and pre-production CAD files are frozen, 6 months ahead of SOP. Except as prototype "mules" encounter minimal problems, production CAD files are frozen 2 months ahead of SOP.

devoting engineering resources to updating existing models rather than expanding its product portfolio. This is a consequence of the durable good aspect of a motor vehicle, as detailed later.

Engineering an electric motor may be less costly, as evidenced by the large number of startups (particularly in China), but an EV still requires sophisticated power controls and drive motors designed for the packaging and performance of a particular model. In general, costs have been falling with the improvement of computer-based engineering tools, but those gains are greatest internal to experienced manufacturers, who can expand databases of designs and test parameters and protocols. Simply buying the latest and best CATIA system from Dassault is not sufficient. Offsetting that, suppliers can provide almost all of the discrete components of a vehicle and offer guidance on integration. That requires that a new entrant build an engineering staff with the capability of tapping external knowledge, and that suppliers view the venture as sufficiently promising to devote engineering resources to a project.

B. Differentiation and Economies of Scale

A second implication of product differentiation is that for at least two decades, sales per model have been falling. In the 1960s, annual sales of 200,000 vehicles for a single model were normal, while a good seller surpassed 500,000 units in a year – Ford sold over 1 million Mustangs in the 2 years after its April 1964 launch. The record was set in 1965, when Chevy sold 1,046,514 Impalas.[15] With such volumes, car companies devoted an assembly plant to a single model, and for high-selling models built branch plants in different regions to lower the costs of delivery to dealerships.[16] For example, General Motors had a plant in the San Francisco Bay area (the Freemont plant now owned by Tesla) as well as the Southgate plant in Los Angeles, and plants in New Jersey and Framingham, Massachusetts. As differentiation increased and per-model volumes fell, all such outlying plants were closed (Rubenstein 1992). Similar changes took place in Europe (Klier and Rubenstein 2015). By the end of the 1990s production in the US and Europe was instead concentrated in an "auto alley" or "auto corridor" that placed plants near the geographic center of sales.

The "standard" assembly plant for a mid-market vehicle turns out about 1 car per minute, 500 per shift, 1,000 per day and 240,000 in a standard work year. As noted, the tension is that sales per model are much lower today. In the US in 2017, only 2 models were selling at an annual rate above 300,000 units, both pickup trucks. Another 9 models sold 200-300,000 units, only 3 of which were sedans. In contrast, 54 models had sales between 50,000-100,000. To enable that, companies standardized what had once been disparate plant-level processes, and designed new vehicles around those processes. Firms now routinely

15. https://en.wikipedia.org/wiki/List_of_automobile_sales_by_model

16. Another factor behind multiple plants was that normal operating capacity was lower than now. I have however no data to back that assertion.

assemble multiple models on the same line, allowing them to achieve economies of scale in production despite lower per-model volumes (Brincks et al. 2018). However, this is much easier when models are derived from the same platform, and thus are similar in length and engine and transmission placement.

Achieving high plant-level production volumes is thus difficult for a small company. Turning out models from disparate platforms in the same plant is challenging; mixing large and small vehicles is not conducive to smooth flows through body-in-white welding, the paintshop, and final assembly. It only works if the plant was oversized from the start, including extra assembly line stations to handle tasks needed for one model but not another. Because of the low per-model volumes that result from product differentiation, a new entrant needs a model lineup to generate sustainable sales and insulate itself from shifts in consumer tastes and the competition from the new models of competitors. But that works against production efficiency, until such time as a new company has enough models derived from a particular platform to keep an assembly plant running at capacity.

C. Durable Goods and Distribution

The biggest challenge Henry Ford faced in 1920, as the initial post-WWI surge in demand peaked, was that he was competing with himself in the form of used Model T's. Lowering prices to keep new car sales high resulted in the availability of more used cars at an even lower price. The downward spiral ended only in 1926, when losses were so great that Ford shut down the entire company for almost a year, until the launch of the Model A in 1927. Automotive firms learned the hard way that they must regularly refresh their product portfolios to lessen the competition with their own used vehicles.

Durable goods purchasers must also be supported by a service infrastructure. Even though the intrinsic quality of vehicles in the US has risen, such that the average car remains in service for 12 years, mechanical parts do wear out. Owners must also repair damage from poor roads and collisions. Consumers are sensitive to the availability of such service, and so to sell new vehicles, a manufacturer must put in place a sufficiently dense network of repair facilities. They must also provide parts inventories to support the fleet of vehicles on the road for 12-15 years.[17]

Passenger vehicles are the most expensive purchase a household makes after a house. That is only possible because financial markets are adept at financing durable goods. The loans and leases to which 80% of consumers resort are made more affordable through the trading in of an existing vehicle. That requires an auto firm to set up a system to arrange financing and to appraise and remarket trade-ins, either via used-car auctions or an in-house retail operation. In addition, financing and insurance draw upon the

17. Over 90 years after the last one was produced, it is still possible to a Model T, from Champion spark plugs to the wood frame that underlies the body of every Model T, the latter from a specialized 7-person firm in North Carolina.

presence of service networks and resale markets, as they enable collision insurance providers to project repair costs, and firms packaging leases to price the residual (end-of-lease) value and to buy insurance against actual values turning out lower than anticipated. A new entrant intending to sell in any volume needs to be able to provide this package of services themselves, or to work with independent firms to support the market for their vehicles.

These are not an issue for "boutique" cars priced $100,000 and above, as they are often weekend drives for well-heeled purchasers who can pay cash or arrange financing themselves, who are not as concerned about resale value, and who are not inconvenienced if it takes time to get repairs. However, for any entrant to be a threat to the VWs, Toyotas and Fords of the world, they must be able to sell in volume, which in the US market means a price point below $35,000. Furthermore, in the core of the market purchasers both comparison-shop and (because they don't have an extra vehicle) purchase out of inventory; they may travel 200 miles to obtain a better price, but they are sensitive to the distance to and reputation of service centers.

One potential route to meeting these needs is to vertically integrate into distribution and service. That has never proved a stable solution for several reasons. First and foremost, vertical integration consumes capital and amplifies risk. In contrast, an independent dealership network draws upon the strengths of the franchise model, which is particularly important for rapid expansion because it benefits from the self-selection of experienced managers and rests upon their financial resources to provide real estate, sales and service facilities and cover the needs for inventory of new and used vehicles and repair parts. In the US, coverage of the major metropolitan markets requires 200-plus dealers. These average $6 million each for physical facilities and infrastructure.[18] Even if financed by bank loans and real estate leases, the attendant liabilities are on the balance sheet of the dealer, not the car company. Dealers also finance inventory, which averages over 2 months' sales. Across the US as a whole, that is roughly 8 million vehicles worth $360 billion. With franchising that, too, is removed from the balance sheet of car companies – a large metropolitan dealer can easily have $20 million tied up between new and used inventory. A minimalist national network thus can easily require an investment of $3-$4 billion.[19] Along with economizing on capital, a franchise system improves cashflow, as it is typical for the car company to be paid when a car is made, not when it is sold. Most car companies own very little real estate while with just-in-time production their inventories consist of a day's worth of work-in-progress, and no finished vehicles.

18. These figures reflect an email discussion with David Ruggles, a dealership consultant who has both managed and owned stores, and Greg Irwin of BWG Consulting.

19. A rough rule-of-thumb is that firms aim for 60 days of inventory, or 1/6th of annual sales. If Tesla achieves $18 billion in revenue in 2018, then moving away from pent-up demand to "normal" sales suggests it might need to hold $3 billion in inventory of different combinations of trim, color and drive options, so that a consumer unwilling to wait weeks for their car can drive away the same day in something close to their dream vehicle.

Company stores also face incentive incompatibility. The factory's goal is to move the metal, as they focus on keeping capacity utilization high while smoothing production across time. The "store" is concerned about profitability, inclusive of the value received from trade-ins, services, finance and insurance (particularly extended warranties), and not just new vehicle sales. They also face the reality of high variability in sales over time, particularly at the level of individual models, and would prefer to vary their orders from the factory accordingly. The store is also happy to trade off lower volume against a higher sales price, and will gladly steer a customer from a low-margin new car into a high-margin used car. In contrast, the factory is happy with low dealer mark-ups that translate into higher new-car, and view used car sales as stealing from new car sales.

Historically aligning these conflicting incentives in the context of downstream integration into sales has never worked. From a managerial perspective, the high temporal and geographic variability of sales makes it impossible to distinguish whether a store manager is gaming the system or facing a shock they cannot control. The factory wants to pay store managers a salary; in a franchised system, it is quite common in good times for a franchise owner to out-earn their "factory rep" by an order of magnitude – and to lose money in bad. In short, an internal, bureaucratized management structure does not mesh well with the vagaries of retail, and fares poorly in aligning the different links in the value chain from factory to customer to after-service (Dicke 1992).

In sum, that motor vehicles are a durable good raises the hurdle for entry into the auto industry, which is exacerbated by product differentiation. By the 4th year of operations a new entrant needs to devote scarce resources to updating existing cars when for growth and stability they need to expand the range of vehicles they make. Developing a car requires 4 years, particularly for a new company, and a new company must also develop a drivetrain, whereas existing companies can spread the costs of an engine family and platform across many models, and keep them in production for 2 or more model cycles. Similarly, production facilities are lumpy investments that cost roughly $1.5 billion and require 3 years to plan, build and launch. While low-volume producers can trim some of these costs, in a global industry that makes and sells 100 million vehicles a year, a firm sells 1 million units a year is a small player. Yet production at that scale entails 4 factories ($6 billion total) with 6 models ($750 million each) on 2 platforms ($1-2 billion each) and 2 drivetrains ($2 billion each for an ICE). An electric car may be able to lessen drivetrain costs, but to make even a small dent in global markets a BEV venture must still invest at least $15 billion in production facilities and development costs. The cyclicality of the industry makes controlling debt vital. So franchising distribution is critical, as vertical integration into retail and service pushes the total capital cost to $20 billion, while increasing the risk of a mismatch between production and sales.[20] These financing needs balloon if an entrant chooses the wrong segment for one of its early vehicles, or launches into a down market. An inexperienced engineering team is also prone to make mistakes, over-engineering some features which raises production costs,[21] while in other places not being conservative enough leading to high warranty costs.

D. Competitive Structure

If you want to disrupt an industry, target one dominated by a monopolist with fat margins – that is, avoid the automotive industry. In the 1960s, the US passenger vehicle market was supplied by 3½ firms (American Motors was a fringe player prior to its acquisition by Chrysler in 1987). Until the 1973 oil crisis, the Detroit Three had a 20% return on investment and a 40% return on equity. It should be little surprise that eventually new entry eroded the industry's margin, though it took roughly 65 years between the rise of the Detroit Three in the 1920s to the end of their oligopoly in the early 1990s. Similarly, the formation of the European Common Market led to the collapse of the various national monopolies, with the process starting in the late 1960s but not complete until 2010.[22]

In 2018 production in NAFTA includes the Detroit Three, four German firms (counting Audi as separate from VW), five Japanese firms (Mazda's Mexican plant is now open), and two Korean firms (counting Kia and Hyundai as separate firms), while the Chinese-owned Volvo is commencing production and Tesla remains in operation. Imports add to the competition among these 16 "local" firms. Europe is similar, while China has even more producers. Car companies average only modest margins over the business cycle, pulling in huge amounts of cash when capacity is fully utilized, while hemorrhaging money during downturns; at peak volume producers top out with roughly a 10% profit margin.[23]

The luxury end of the market is more appealing, with much higher gross margins. However, that is not for lack of effort by would-be entrants. Only Toyota's Lexus succeeded in becoming a rival to BMW and Mercedes, each selling over 24,000 vehicles in June 2018. In contrast, Infiniti and Acura have not caught on. Failure is easy: Cadillac, Lincoln, Chrysler and Oldsmobile all lost their dominant position or exited

20. This tension is what led to the *de facto* bankruptcy of Toyota in 1950. The Toyoda family lost their controlling stake in the firm, and creditors forced the firm to split in independent firms, Toyota Motor and Toyota Sales, to give creditors greater insight into whether inventory levels were being kept under control.

21. A recent teardown of a Tesla Model 3 by UBS noted its use of "military-grade technology." In the automotive context, that should not be taken as praise! CNBC, "Tesla Model 3 is 'military-grade tech years ahead of peers' but still expected to lose money." August 16, 2018.

22. The EU provided a "block exemption" to the industry that segregated national markets at the retail level until 2003, preventing consumers in one country from buying a car in another. Price differentials persisted until the remove all restrictions in 2010. See Smitka and Warrian (2017), Chapter 3.

23. Tesla uses idiosyncratic accounting that results in a margin that looks better than those of other firms even though it loses rather than makes money.

the luxury market, as was the case of the defunct luxury marques of Mazda and Mitsubishi, which never made it beyond the Japanese domestic market. Volvo is in the midst of a (possible) turnaround, while at one point Porsche had exited the US market, and Audi and Land Rover are relative newcomers.

These marques carry a second advantage, in that they are better able to serve as launch pads for new technologies. Purchasers of high-end vehicles want to differentiate themselves from their neighbors, and are more willing to buy options that are not widely available. In addition, the roll-out process in the auto industry means that new features are typically high in cost, as production and engineering have yet to be depreciated and technical uncertainties mean they tend to be over-engineered. Production capacity also starts out small, a good match for the low sales volumes of such vehicles. That makes them the natural niche to launch features such as adaptive cruise control, lane-keeping functions, self-parking capabilities, heads-up displays, turbochargers, and many other components.[24]

In fact the individual sensors and component functions that are needed for self-driving vehicles – radar and cameras, electrically controlled braking – have first been introduced on high-end vehicles, and in Europe rather than the US or Japan.[25] Only if a company finds consumers receptive are such technologies migrated to higher-volume vehicles. That also requires that suppliers can in fact lower the cost and complexity of components, which does not always prove possible, as in the case of heads-up displays or batteries. There can also be a mismatch between the pace at which firms at different stages of the supply chain are willing to invest in capacity; production is only as good as its weakest link.

Would-be new entrants in the US – Tesla, Fisker, and Faraday – have aimed at the high end of the market, or began as subcompact imports; among such firms only Tesla has not gone through bankruptcy.[26] Furthermore, producing luxury cars does not lessen the pressure to achieve scale economies; BMW and Mercedes are profitable because global volumes far surpass sales in any single market. While both the Mercedes C-class and the BMW 3-series represents attempts to move downmarket, it has proven easier for volume car manufacturers to support luxury marques than for luxury firms to become volume players.

24. Two counterexample are start/stop systems, which were easiest to launch on the small engines of compact cars, and electronic power steering, where the 12V power available to early systems meant they were unable to handle the weight of anything larger than a compact car. The move to 48V electrical systems permits the expansion of both into larger vehicles and to providing additional functionality, such as power boost and not just engine start.

25. An exception is eSteer, where the initial systems had too little power to steer anything but a small vehicle.

26. Aptera wanted to enter the lower end of the market, but never went beyond showing concept cars. Faraday has been recapitalized after its initial failure to build a plant in Nevada, and is making a second attempt, while Fisker was bought out of bankruptcy is trying to restart operations. Mahindra faced the 25% "Chicken War" tariff. Several Chinese firms have explored the market but they (or would-be dealers) concluded they would be unable to meet safety regulations and the expectations for basic consumer features that are available on used cars in the US without pricing themselves out of the market. Instead it is only the joint ventures of global firms that have been able to export to developed country markets. Chinese firms do export in low volume to developing markets such as Peru.

Success in the luxury segment is not disruptive to the industry, because of its limited impact on the lower-priced segments that are the core of the market.

E. Global production and distribution footprint

Car companies have a hard time achieving economies of scale through operations in a single national market. In contrast, if you sell everywhere, you don't have to sell a lot anywhere. Global operations also help insulate a firm from swings in sales in any single market, and from the volatility of exchange rates. Logistics costs, trade barriers and local idiosyncracies place limits on globalization; nevertheless, firms with any volume ultimately assemble where they sell. Even luxury firms such as BMW, Audi and Mercedes assemble vehicles in NAFTA, the EU and China.

To disrupt the industry, a new entrant needs to become a global firm in short order. That's a tall order, because selling in volume requires setting up local distribution, including warehouses stocked so that a service center can get parts it needs within 1-2 business days. Markets aren't homogeneous, either. Right- versus left-hand drive, European versus American headlight standards, tastes in cupholders, upholstery, color, and use of rear seating all require modifications; meeting safety and emissions standards may require local testing, even if an experienced firm designs platforms to meet the full range of national mandates. Such quirks require government relations offices in each country as well as a local engineering presence able to influence parent company decisions. Exporting is not as straightforward as it might seem – the only Chinese vehicles exported to the US are made by GM, Honda and Volvo.

Local production is much harder. Work standards, construction and job safety standards, and the availability of specialized equipment installation and maintenance capabilities mean that running a "transplant" requires years of preparation.[27] Commonly available materials differ from supplier to supplier (and not just country to country), so a plant needs local purchasing capability with testing and engineering support. This becomes particularly important if a plant aims to buy materials and components locally, and not just assemble and paint imported "kits". Tesla demonstrates that selective expansion is possible for low-volume products such as the Model S. Sellin in volume is much harder, but without such ability no carmaker (or supplier) can be disruptive.

E. The Global Supply Chain As Enabler

Not everything is a barrier. In 1900 Henry Ford and hundreds of fellow tinkerers in the US and Europe could buy virtually everything they needed from suppliers, and with at most a helper or two could assemble a prototype in their garage. Ford's rapid expansion and need for uniformity to support his

27. Members of the GERPISA auto research network visited the Audi plant outside Puebla, Mexico in June 2016, while it was still under construction. They had begun their apprenticeship program over a year before, so that they would have a group of workers with a basic understanding of robot operations and machinery maintenance.

assembly line led to him to integrate into producing engines and transmissions, rolling steel for the body and glass for windshields. While GM and VW never got into smelting ore, their scale allowed them to take that process even further in terms of making their own parts. Large auto companies found it difficult to manage the variety of parts manufacturing, and given the politics of senior management, it proved difficult to stop buying parts even if outside firms had lower costs. Vertical integration also raised capital needs; the poor credit rating of Toyota in the late 1940s and 1950s is one reason that they and other Japanese firms turned to outside parts producers and spun off internal ones such as Denso (Smitka 1991). A broader supply base also offered a deeper pool of engineering approaches and technologies, important as competition rose and regulatory pressures increased.

The downside to vertical integration was apparent by the 1990s (Womack *et al.* 1991). GM spun off their parts-making operations as Delphi in 1999, while Ford created Visteon in 2000. During the same period Japanese, European and American suppliers expanded outside their home markets; by 1990 about 300 Japanese and 300 European suppliers had established a presence in North America. Interacting with the rise of global car platforms, during the past 25 years several waves of consolidation and reconfiguration has produced a set of roughly 100 global suppliers. Innovation helps them meet customer needs and thereby preserve margins. Carmakers still make their own engines, but transmissions, chassis components, front-end modules (including braking and steering systems), instrument panels, seats and most other components are bought from independent suppliers who do much of the engineering.

The strength of today's automotive supply chain makes it easier to enter the industry. A would-be car company still needs to be able to design a vehicle that is easy to manufacture, and to integrate components into functional systems. For example, noise, vibration and harshness/handling (NVH) come from the interaction of different components and so are hard for a single supplier to address. In any case, it far easier for a novice to produce a credible car than was the case 25 years ago. Firms such as Geely began by turning out crude assemblages of parts made by local suppliers with key components from other vehicles used unchanged. In the case of Geely, they shifted from local to global suppliers, facilitated by moving their engineering center to a location near Shanghai region. They were soon turning out sophisticated cars, leveraging the engineering resources major global suppliers have built up inside China (Song and Abe 2012, Balcet *et al.* 2012). Tesla was likewise able to draw upon suppliers for the basics of making a vehicle, and to help them bring to fruition innovations such as the "ventless" heating/cooling system in the Model 3.

Maximizing outsourcing reduces the capital requirements of entering the industry, lessening the need for investment in plant and tooling and lowering up-front engineering costs. It is possible to contract body-in-white welding, painting and assembly from Magna Steyr (which will open a plant in China in 2020); buy transmissions from ZF, heating/cooling systems from Denso and Sanhua, seats from Lear, wire harnesses from Yazaki, and on and on. Furthermore, if the promise of future orders is sufficiently enticing, suppliers share their engineering expertise, up to developing a "black box" component that can be dropped into place without the customer having to attend to details. This is paralleled on the downstream side, where franchising dealers lets new entrants set up a distribution network quickly, using other people's money and management skills. The latter has been the norm for vehicle producers since the 1920s, but the move away from vertical integration in parts production has come to fruition only in the last 15-20 years.

V. Technological, Societal and Business Cases Barriers: BEVs, AVs, and New Mobility[28]

> ***The storage battery is one of those peculiar things which appeals to the imagination and no more perfect thing could be desired by stock swindlers than that very self-same thing***.
>
> Thomas Edison, 1883, as cited by John Peteresen, Seeking Alpha

New technologies are not paper entities reflected in a patent. For commercialization they must be embedded in the social context of a particular product, they need to be cost-competitive with rival technologies, they must be backed by a business case that offers likely profits, and they must not face any game-stoppers in safety and the ability to scale up production due to process limitations or supply chain and distribution issues. Not all emerging technologies turn into butterflies, much less unicorns; most never hatch. Charismatic leaders and copious funding to cover up-front losses cannot make up for technologies that simply aren't viable, nor can access to capital make up for business plans that have no path to profitability.

A. Autonomous Vehicles

Social Context

Consumers own vehicles for more than their utilitarian transportation function. They are a status symbol, a reflection of lifestyle, and in contents if not exterior, are personalized. Owning an autonomous vehicle might initially be a high-end status symbol, as initially few will be available and they will be high in cost, reflecting the underlying need for multiple sensors and processors. The normal expectation of the proponents of autonomy, however, is that these will be shared vehicles. That will not be compatible with the social signaling function of owning a vehicle. It will also work against the option value of an owned vehicle for spur-of-the-moment use and for keeping car seats, favorite toys, umbrellas, coffee mugs, and work paraphernalia inside the car. Would an shared AV really be useful to a soccer dad, making multiple

28. There is as yet no standardized acronym. CASE – connected, autonomous, shared, electric – is only one of several variations, with and without "connected" as part of the list.

stops of unknown duration? The key is whether consumers will want greater autonomy in their personal vehicles, and the extent to which new business models prove viable (discussed below).

A second social issue is insurance. The greater the control exerted by the vehicle, the greater the liability will be for the car manufacturer.[29] At present liability rests primarily on the vehicle operator. For an AV, deep-pocketed manufacturers present a perfect target for lawyers, and even driving 10x better than a human would leave too much liability for any auto company to bear. While that may be less of a barrier in countries where there is a cap on liability for individual accidents, that is not the case with the US. State-by-state legislation may enable the development of regional fleet applications. Selling AVs to individuals will be problematic unless there is national-level legislation.

Cost

The ultimate cost of the incremental hardware for autonomous vehicles may be $2000 or less. Radar already sits on a single circuit board, on which the antenna can also be printed. That suggests a unit cost of under $100. While no solid-state lidar is yet on the road, moving-mirror systems such as that on the Audi A8 are already well under $1,000, and will also likely end up in the $100 range. Automotive-grade cameras are more costly than those in cell phones – they have to be able to survive 15 years of vibration, dirt, heat and cold – but they are also under $100. Robust autonomy will require the integration of a panoply of sensors, including perhaps 5 radars, 4 lidars, and 6 cameras. This hardware will thus eventually cost around $1,500, but will incur additional costs for packaging into a vehicle. If connectivity is included – cars with radio transponders are already on the road – the total will still be under $2,000.[30] Cars already have multiple CPUs, so providing the processing power for AVs may add only a small increment to system cost. In addition, braking and steering must be electronically controlled, and vehicles will need GPS, but these are already on many vehicles. In addition, in the short run insurance costs will rise because the cost of repairing a vehicle with multiple sensors – sensors will sit on the corners of a car, and AVs will not be immune to hitting deer or being hit by another vehicle.

The real unknown is thus the software cost. Since this will be a sunk cost, the marginal cost of adding it to a vehicle will be zero. Developers will seek to price their system to recover development costs; how they will do so is unclear. Indeed, it may be hard for software suppliers to charge for their product in the long

29. Even if the source of a defect lies with a supplier, the initial liability falls on the carmaker. The more costly the issue, the harder it is for a car company to pass that liability on to others. Takata was the source of faulty inflators, but with their bankruptcy, Honda, BMW and others are left "holding the bag".

30. The resolution, frame rate and poor dynamic ratio of cameras means that by themselves they are unable to support autonomy functions. Lidar and radar, for example, provide direct measurements of distance and relative velocity, and operate in different parts of the electromagnetic spectrum so complement each other in low and bright lighting and bad weather.

run, thanks to competition among OEM internal development projects and outside developers who will try to bundle it with hardware. If past software marketing models are any guide, the initial price to car companies will be kept low to encourage diffusion, and because developers will try to buy market share for their software. Car companies are very careful, however, to divide up systems to make sure that there are multiple suppliers for each component. Unlike with operating systems or search engines, autonomy will not be a market where the winner takes all. Of course this implies that players in the AV software segment may never earn enough to justify their upfront investment.

My analysis is thus that the cost of autonomy will rest with the hardware component. Early vehicles will perforce be over-engineered and will use low-volume, high-cost sensor systems. That however is little different from other new automotive technologies, and will not be a fundamental barrier to eventual diffusion. However, to the extent that such technologies raise the average price of a vehicle, it will limit diffusion to the upper half of the market. In addition, as such systems improve, older vehicles will be less valuable. It may also be impossible to guarantee the robustness of such systems for more than 10 years, much less the 15 years expected today of safety-critical components in current vehicles. That would raise the effective cost of vehicle ownership.[31]

Business Case

The dream of a truly safe vehicle is decades old, predating the availability of sensor systems.[32] Headlights, safety glass, and power brakes were early steps in that direction, followed by the mandate for passive restraint systems, met by adding multiple airbags.[33] Active systems began with anti-skid braking (ABS), followed by electronic stability control (ESC). These are now being extended with a range of active driver assist system (ADAS) applications, including adaptive cruise control, automatic emergency braking, lane-keeping functions and now self-parking and (restricted) self-driving functions, such as Audi's TrafficJam and Cadillac's Cruise. One issue is thus whether consumers will be willing to pay a premium for these functions, and whether they will perceive additional value in the next improvement. If someone is willing to pay $1,000 for automated driving in low-speed traffic (TrafficJam) or normal situations on limited access highways (Cruise), will they be willing to pay an additional $1,000 for a system that can handle normal daytime driving in fair weather on most local roads? for auto valet systems in parking garages?

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31. In the US, the average passenger vehicle is 12 years old, and trucks remain in operation even longer. For example, my first pickup truck lived to age 30. Its replacement is currently 24 years old.

32. I sat through such a presentation in a visit to Delphi as a PACE judge for the initial vehicle radar system over 20 years ago.

33. In most of the world driver and passengers are all expected to use seat belts by insurers and courts in deciding payouts in accidents. That was not true of the US, which led to car companies implementing airbags. They are now universal in all developed country markets.

There are clear use cases such long-haul trucking, regular shuttle services, and operations inside parks and container ports. As long as AVs continue to face challenges with night-time operations and inclement weather, they will not be a full substitute for manned taxis or personal vehicles, while parcel services and many types of freight require a person on the vehicle to unload and stock store shelves or carry packages up steps and obtain a signature. The same is true of transportation for the elderly, who need assistance getting from their door to the vehicle, or for carrying groceries into their kitchen. To reiterate, a business case already exists for limited applications. A 5% share translates into 5 million units a year, enough to support commercialization.

Proponents overpromise on social benefits. AVs won't decrease congestion, because that's a function of rider density, and being able to space and reposition cars automatically won't increase density because of empty backhauls. Job- and school-related travel are highly correlated, meaning that a large fleet size is needed relative to average capacity needs. Autonomy does not alleviate that constraint. Furthermore, ride sharing is something consumers resist, when income allows; initial studies show that the cheaper taxi services of Uber and Lyft pull riders from high-density buses and subways, but do not decrease vehicle ownership. To lessen congestion, policy should discourage car use and subsidize public transport.[34]

Note that the situation is different from the perspective of the "hard" side of the industry's supply chain. Continental, Valeo, Delphi/Aptive, Magna and others are already supplying cameras for backup, 3D view, lane-keeping and lane-departure functions, and radar for adaptive cruise control. Electronic Stability Control (ESC) means brakes are already electronically actuated, while eSteer is now physically robust enough to be found on the Ford F-150. Lidar and IR cameras for improved night-time functionality are not yet in common use, but are now on the road. Suppliers are investing in R&D for future systems, but in general price their components are priced to earn a profit. Even if full autonomy is never realized, they stand to gain.

Technological Hurdles

Outside of carefully geofenced locations, where signage and roads are 3D mapped in great detail and construction and accidents are fed into the system, autonomous vehicles are not yet technically viable. In the US alone motor vehicles provide 3 trillion passenger-miles per year, and operate in weather good and bad, in daylight and at night, and on marked roads and rough gravel tracks. While AVs can already handle normal situations, there are many "edge" conditions where they fail – as do human drivers.[35] Spotting a policeman directing traffic around a fallen tree, and interpreting their hand signals is one example.

34. Public transport that isn't losing money is charging too much from a social perspective.

35. In Uber's fatal AV accident in Arizona in March 2018, the vehicle's sensors "saw" the pedestrian, but did not classify her as an object to which the software needed to react.

Another is distinguishing between an empty box and something that might be solid. These are not everyday occurrences for any given driver, but they are encountered somewhere in the US multiple times every hour.

The simplest approach to the policeman issue is to hand control back to the driver. For the issue of objects that defy ready classification, over time machine learning should make an AV equal to an experienced, alert driver, but the result will be a probabilistic classification – AVs will both swerve unnecessarily and hit debris that causes damage, as do human drivers. The challenge is to reduce such accidents to a level that is socially acceptable in terms of popular reaction and financial liability.

AVs themselves do not employ artificial intelligence. Instead there are built upon "machine learning" to identify objects, determine their location and velocity, and then to decide what to do. That learning process begins with many man-years of workers sitting in front of computer screens, circling stop signs, bicyclists, traffic lights and lane markers, to tune algorithms. In the background, computers are working with the combined input from GPS and maps – there *should* be a stop sign visible – with the output of multiple sensors (infrared lidar, short- and long-distance radar, multiple cameras and even ultrasound for parking and blindspot detection). Objects have to be identified – 3 edges, one not horizontal/vertical, and several red pixels in the camera feed from that angle ought to be the stop sign, while lidar and the comparison between image scans provide distance. That ability improves as the human trainers flag false positives and false negatives. Those then need to be used to create driving rules – stay within the lane markers, extrapolate their location if they are temporarily not visible, and decide what to do if other cars aren't staying in the lane you know is there because you have radar and lidar working with 3D maps that include every telephone pole, sign and guard rail. That leads to the role of social constructs, noted above. Even if autonomous vehicles are on 10x safer than those with a human behind the wheel, AV-initiated accidents will occur – with 3 trillion passenger miles, identifying stop signs with 99.9999% accuracy means that on average stop signs will be missed once every 5 minutes, and mistakes of some sort made somewhere many times every minute.[36] There will also be edge cases for which AV systems have yet to be trained, either because they have not shown up in field testing, or were missed because the car behaved appropriately for unrelated reasons.

That leads to issues of the human-machine interface (HMI). Inclement weather or problematic road conditions (construction, accidents), or hardware problems will lead to system disengagement, and require that the driver take over, if only for reasons of liability. As systems move beyond basic ADAS

36. To make a conservative estimate, 3 trillion passenger-miles translates into 1 trillion vehicle miles. With at least one stop sign encountered every 10 miles driven, AVs encounter 100 billion signs a year, and an error rate of 0.0001% means 100,000 wrong interpretations per year while there are 525,600 minutes in a year.

functions focused on driver warnings to self-driving, however partial, handoff to the driver becomes increasingly problematic. The premise of self-driving, however, is that it will let the driver can nod off, or attend to email.[37] In the former case hand-off will fail, and the car needs to stop, hopefully after maneuvering to the side of the road. Otherwise it needs to re-engage the driver, but it can take 10 seconds to look up, evaluate why the AV system is shutting off, and taking action. In the interim, a vehicle moving at 70 mph will have traveled 1000 feet. So AV systems must be proactive, refusing to take over if the driver is not "engaged," and working to re-engage an inattentive driver.

The initial approach to that issue was to mandate that a driver have "hands on wheel" (HOW) and to add sensors to confirm that. That also shifts liability because if the driver is in control, then the driver is (mainly) at fault in an accident. The first HOW sensors checked for physical resistance, but were easily fooled.[38] AV developers then turned to capacitive sensors, which are far more sensitive, in that they can distinguish a hand holding the steering wheel from fingers just resting on the wheel. HOW still does not address whether the driver is "engaged" and capable of taking control. For that purpose, head and eye tracking are needed, to confirm whether the driver is alert (eyelid behavior changes when someone is drowsy or drunk) and whether they are periodically looking at the road. This requires infrared LEDs to provide illumination such that cameras can track eyes through polarized sunglasses. So far some companies (such as GM and BMW) are moving forward with incremental AV functionality backed by these HMI systems. In contrast, Ford believes the HMI problem cannot be adequately resolved, and they will not launch autonomous vehicles until they can achieve robust SAE Level IV functionality and dispense with steering wheels and brake pedals (Ford 2018).[39]

***B. Battery Electric Vehicles* (BEVs)**

Social Context

Drivers are largely indifferent to how their vehicles are powered, selecting drivetrains in response to operating costs and government policy (gasoline cars in the US, diesel ones in France). BEVs differ in offering impressive low-speed torque (where diesels also have an advantage over ICEs). The key difference is that ICEs impose no need to plan in advance, as in almost all populated areas of the US a 24-hour gas station exists within the range remaining when the low fuel light goes on. That is not true for

37. Uber's fatal autonomous vehicle accident in Tempe, AZ on March 18, 2018 occurred despite the presence of a driver who had zoned out and did not see a woman clearly visible in the road.

38. Videos quickly appeared on YouTube of drivers sitting in the back seat, having hung water bottles from the steering wheel to provide the requisite force to the sensor

39. A possibly apocryphal tale is that experimental Ford AVs crashed repeatedly on test tracks. Even though the whole purpose was to make the AVs fail where other cars would not be affected, the engineers whose sole job was to monitor failures kept nodding off. See the real-world example of the fatal Uber AV accident noted above.

electric vehicles, as battery energy density and cost make providing a long range challenging, while recharging is slow and in many regions charging stations are scarce. That gives birth to "range anxiety."

Range anxiety is a social constraint to which the transportation market could adapt. In the US and other countries most families use their vehicles for commuting and local travel; average daily use is no more than 20 miles, so a range of 60 miles with access only to overnight charging is adequate. Owners can be supplement their BEV with an ICE rental vehicle for vacations and other long trips. Small commuter cars, however, are exactly what consumers do not want to purchase: they want larger vehicles that can be used in a wide variety of ways and so offer greater utility, and evince range anxiety that is not commensurate with their daily car usage.[40] After all, cars are in part a status symbol, in part a luxury consumption item, and not just a means of transport. Even with existing battery technology, most cars on the road could soon be small BEVs, complemented by rental ICE cars for longer trips. But then most cars on the road could already be efficient and reasonably priced subcompact diesels that get 60 mpg. Those are not what people buy. It is not clear how or even whether social structures can be changed to facilitate greater BEV uptake.

Residential patterns add to the challenge. In dense urban settings, where the reduction in point-source emissions by using electric rather than internal combustion motors would be most beneficial, households generally do not have a dedicated parking spot or otherwise have a physical setting that allows overnight charging. Even in Detroit, entire sections of the city that consist of single-family houses only have non-exclusive street parking. Such individuals would have to resort to shared charging stations and pay daytime electric rates. Nevertheless, shifting social expectations towards a realistic daily vehicle range would greatly enhance the market acceptability of BEVs.

The current push for BEVs reflects environmental considerations. BEVs have no emissions and so are ideal in urban areas with severe air pollution. Electric drive motors are also highly efficient, and while there are losses in batteries, power control and the motor itself, it can turn 90% of available battery energy into turning the wheels, versus at best 40% for a combustion engine.[41] In regions where electricity is generated through "dirty" coal-fire power plants, such as Poland or India, or much of China, total CO2 emissions are worse than those of the CO2 emitted, well-to-wheel, by a modern combustion engine. The same is true in the US, where on the East Coast coal remains more important than natural gas or

40. BEVs are thus a much better fit for Europe, where daily commutes are shorter and there are enough public charging stations to make trips from Paris to the beach or to ones favorite vineyard feasible. For a nice account of user experience see Dent (2018).

41. BEVs still have rolling resistance from tires, losses in differentials, axles and braking, and need to use battery charge for heating in winter. This is reflected in EPA ratings: BEVs are not twice as good as high-efficiency ICEs.

renewables (ANL 2016).[42] The environmental case for BEVs in Canada or Norway, with high shares of natural gas and hydroelectric, is very different.

The production of lithium/nickel/cobalt batteries is energy intensive and mining is environmentally noxious. At present the metals in BEV batteries cannot be recycled, while ICE drivetrains can be almost entirely recycled. But electrification is not the only alternative. In Brazil (and potentially in South Asia and much of Africa), sugarcane-based biofuels provide an alternative that is already commercialized, technically advanced, low in cost, and (unlike corn ethanol or oilseed-based biodiesel) can be grown with minimal fertilizer and on land that has little value for food crops. Brazilian agronomists work with 2,000 different sugarcane cultivars, and the country's R&D infrastructure is turning out innovations that continue to lower process costs and improve sugar/ethanol conversion efficiency. Ethanol is compatible with existing ICEs, and can be used with gasoline in any proportion to reflect seasonal and local variations in availability. Land-to-wheel efficiency is already greater than that of BEVs, and Brazil's CO2 emissions are already below the 2025 EU target of 99 gm/km.

In Brazil BEVs are not a desirable from an environmental perspective because ethanol ICEs are superior. If cellulosic fuel production pans out, or algal biodiesel production, in certain countries or regions BEVs may likewise be inferior choices. As noted, in coal-dependent regions gasoline or diesel are the best alternative. Hydrogen fuel cells are likewise highly efficient and their only point-source emission is water. So far the high cost of hydrogen infrastructure and the low energy density of compressed hydrogen (that is, large in-vehicle fuel tanks) make it unattractive for passenger vehicles, but it may prove viable for buses and other fixed-base transport as an electric vehicle alternative to batteries. CNG (compressed natural gas) can also be used in existing ICEs, has low emissions, and can draw upon the network of pipelines that already exist in many regions. Powering vehicles with methane is certainly preferable to burning it off at the wellhead, To the extent that governments prioritize environmental considerations, multiple drivetrain/fuel systems will coexist.

Cost

The key constraint on the market for BEVs is battery cost. Even for consumers whose workplace provides free charging, the savings in fuel costs does not cover the extra expense of batteries. One component of cost, detailed under technological hurdles, is the metal content of battery cathodes. Another is that energy density is low, so that for any given range a BEV is significantly heavier than a comparable ICE vehicle, a disadvantage amplified by range anxiety. Part of the higher cost is a reflection of the need for extra battery capacity to offset the weight of the battery, with additional increments to construct a chassis/suspension capable of carrying that weight. Current electrolytes are flammable and batteries are oxygen-

42. The US does not have a national grid, so the environmental benefits vary from region to region.

rich, so shorting out leads to a fire. Additional weight must be added to create a robust pack to protect the batteries, and to add active cooling and heating because the chemistries operate best when warm but are unsafe when hot. Less flammable electrolytes may enter production *circa* 2022, but at present there are no battery technologies whose charge/discharge capabilities, energy density and longevity represent a qualitative improvement over the existing nickel-cobalt-aluminum (NCA) and nickel-cobalt-manganese (NCM) batteries (Blomgren 2017, Morgan Stanley 2017). Products such as cell phones are a high-value market for higher density batteries. If and when new chemistries become available, we should thus see big improvements in cell phones before they appear in BEVs. So far that has not happened, so any change relevant to BEVs is at least 5 years away.

Electric drive motors and power controls are no longer the limiting factor. Rapid switching and precise control of high currents using IGBTs allow highly efficient drive motor designs that were developed in the 19^{th} century but could not actually be made. Improvements in cooling and efficiency now allow the IGBT power chips to be packaged integral to the motor unit. Coil design, coil winding, and magnetic materials are better as well, which allows more compact drive motors. Higher production volumes combined with normal industrial engineering methods will facilitate obtaining economies of scale and improving process throughput. Batteries are the issue.

Business Case

The mass market business case hinges on less expensive, higher energy-density batteries backed by the provision, in one way or another, of charging infrastructure to relieve range anxiety. Commercial viability also presumes a robust materials supply chain, discussed in the next section. An additional challenge is that ICE engines continue to improve in fuel efficiency, which enables downsizing of engines systems with feed-in benefits from lighter chassis, brakes and suspensions. In addition, the electrification of vehicle systems (removing the parasitic load of always-on belts and hydraulics, and also saving weight. Light hybrid systems provide additional efficiency enhancements. Examples are start/stop systems that lessen engine idling, and alternator/motors that provide acceleration boost and enable engine downsizing and regenerative braking. Hybrid electric vehicles may need only a 1 kWh battery; plug-in hybrid electrics require 10 kWh; a Tesla Model 3 uses 75 kWh, the Jaguar iPace 90 kWh.

Light electrification is facilitated by 48V systems, which have already begun to replace 12V systems in Europe. Not only can light hybridization use far smaller batteries than those needed for a BEV, their battery charge/discharge patterns are compatible with the use of LiFePO4 chemistries that are lower in cost, do not need active cooling/heating, and use non-flammable electrolytes. They do not need to be assembled into special packs and do not need to be moved under the floor of a vehicle due to weight considerations, nor do they require a heavier-duty suspension. Such systems require no external charging, and hence avoid the infrastructure needs of BEVs. Even in markets where BEVs are desirable from an environmental perspective, they must chase a moving target to provide a value proposition to household vehicle purchasers.

The commercial barriers remain high. In China the central government offered subsidies of roughly US$8,000 per EV, backed by additional local cash subsidies and favorable licensing treatment. The latter is a major consideration in cities such as Beijing, where vehicle licenses allocated by lottery have 20 applicants per winning draw. Pardi (2017) found that in 2016, Beijing had add-on subsidies of up to €15,000 (for a BEV with range over 250 km) and exempted purchasers from the 10% provincial portion of China's VAT, and included a free license plate (worth €2,500) for the first 50,000 EVs registered. Only 58,196 BEVs were sold, for a market share of just under 8%. In other words, what purchasers valued was getting a license plate, not a BEV, despite the large cash and tax subsidies for going electric. Consistent with that, in the 13 provinces with the lowest subsidies, BEVs accounted for only 0.1% of vehicle sales. Cost and convenience are barriers that so far BEVs overcome only with unsustainably large government subsidies. In Norway, which has the highest penetration of BEVs, exempts purchasers from the 25% VAT and registration fees, as well as all subsequent annual vehicle taxes, all road tolls and give BEVs free parking. Again, expensive subsidies are not sustainable; Norway began to phase then out in January 2018.

Many niche markets already use BEVs, from forklifts operating inside buildings to short-range delivery vehicles and buses that operate from a central terminal, such as delivery trucks for the German Post Office. These not only can be charged overnight (or in a factory, during rest breaks and shift changes), but also can use less energy dense (hence heavier) batteries that are less expensive. Since delivery vehicles may be stopped or moving only at low speeds much of the time, BEVs offer attractive operating benefits as ICEs are least efficient at low speeds.

Technological Hurdles

Pure battery electric vehicles suffer from two major defects: high cost and low energy density, in a world where "traditional" ICE engine vehicles have great range and continue to improve in efficiency. As of February 2018, the powders for the cathode of a Tesla 3 battery pack by themselves cost $50 per kWh, or $4,000 for an 80 kWh Model 3 battery (rated at 75 kWh). To that must be added the electrolyte, anode, conductors, and case, assembly costs of cells, the materials and assembly of the battery pack that protects the batteries in vehicle, and incorporates wiring, cooling and control functions that add another $100 per kWh, for a total cost of $12,000, not including the drive motor and power controls. Low energy density means that the battery pack weighs 1,054 pounds, whereas a full gas tank delivers more energy than a Tesla battery pack at a cost of 6 pounds per gallon, or under 200 pounds inclusive of the tank.

While companies continue to make incremental improvements, none of the chemistries currently in production will lead to a qualitative improvement to energy density or cost. Breakthroughs are announced almost daily, tracked for example in articles in Science Daily. Upon close reading, these include announcements of computer simulations of new materials that have not actually been made. The more careful articles generally note that early commercialization is at least 5 years away. Production then has to reach the point where it satisfies high-value applications such as medical equipment and cell phones, and supply enough cells to make multiple 80 kWh packs for a fleet of test vehicles. Only then can auto companies evaluate real-world performance and safety, and gain clarity on costs and whether production can be scaled.[43] The original chemistry for today's lithium-ion batteries was demonstrated by John Goodenough in 1980; Sony first commercialized it only in 1991 (Sanderson 2018). While the pace today is likely to be faster, rollout is an 8-10 year process, and ramping up capacity sufficient to make millions of BEVs would take years more.

Furthermore current chemistries rely upon cobalt, which is subject to supply chain issues. The largest reserves are in the Democratic Republic of the Congo, with political risks. Much also comes from illegal mines and is extracted with child labor, so cannot readily be used in countries with business ethics guidelines. Cobalt is also a co-product of copper and nickel. New mines for those metals take 20 years to develop, and because cobalt comprises only a very small percentage of output will only move forward if copper and nickel prices are high. Given current chemistries, announced plans for the 83 additional BEV models to be launched by 2021 will require more cobalt than is mined on a global basis, and supply cannot respond quickly. Prices have fallen from $92,000 per MT in spring 2018 to $64,250 on August 6, 2018, but BEVs are already the biggest market for cobalt, so that decline does not seem consistent with BEV plans (Petersen 2018a, 2018b; Jaffe 2017; Sanderson 2018).

As noted above, charging infrastructure remains an issue. Standard household current is sufficient for overnight charging, and most houses built in the US in the last 60 years have 220V wiring to the house with 100 amp service. Some locations may not have local transformer capacity to handle widespread EV charging, though that constraint is primarily a daytime issue. Indeed, by smoothing load, night-time charging can improve the generating efficiency of electric utilities so that electricity costs may not rise despite higher overall demand (Denholm *et al.* 2015, Zhang and Markel 2016, Yuksel et al. 2016).

Rapid charging is another story. The capital costs for a Tesla supercharger in 2016 were up to US$270,000, and required commercial electric power service.[44] In addition, with the present small BEV

43. For example, 3D printing allows higher energy density, but can't be scaled up. See Science Daily, "3D printing the next generation of batteries," July 30, 2018.

44. https://ark-invest.com/research/supercharger-cost-comparison from July 11, 2016

fleet, utilization rates are low so charging stations must be subsidized. Government support in the US is minimal, though VW's legal settlement for emissions cheating is helping build out a more robust set of open-standard stations. In much of the EU, governments have paid for the creation of a network along national highways. But given current social constructs, it is battery technology, not charging, that is the bottleneck to BEV diffusion.

B. New Mobility Models: Uber, Zipcar and others

> ***No one can explain how Uber could earn billions for its investors in an industry that historically has had razor-thin margins producing a commodity product.***
>
> ***Horan (2017), 2***

Social Context

Vehicle sharing was pervasive in the early history of motor vehicles, and remains common in developing countries. Taxis comprise a large slice of the vehicle fleet; extended families share a car. Even into the 1970s, US college students typically did not have a car.[45] Public transportation was the norm. Into the early 1950s, workers in Detroit used the city's streetcar system to commute – trams went right up to the factory gates.[46] The history of motor vehicle industry is that of a transition from shared to private transportation. The personal vehicle is an extension of one's home, with the "drive's" interior reflecting individual aesthetics, cupholders and audio systems and spare clothes, tools, toiletries and child seats stashed to meet family needs. *A priori* the idea that the US will see a return to the "sharing economy" of our great-grandparents seems ludicrous. For the same reason, Morgan Stanley (2016) argues that new mobility firms may find traction in low-income markets such as India that have limited personal vehicle ownership.

Major urban centers require public transport; there simply is not enough surface area devoted to roads to permit people to move about if they rely solely on lightly shared Uber vehicles or hourly ZipCar rentals. Scania Brazil estimates that if their largest urban transit bus was replaced by private cars, a city would need an additional 9,000 square meters of roads and parking spaces.[47] Data substantiate the low efficiency of ride-hailing. Graber (2018) has data points for 2014 and 2017, both suggesting under 60% utilization

45. Older readers can reflect on their own experience. In my case, in the early 1970s my brothers and I traded household chores to pay one another for use of the sole family vehicle. In a similar vein, I became the co-president of my college's outing club in part because it guaranteed me a seat for hiking and cross-country skiing trips.

46. That is one reason that manufacturers moved out of Detroit. As factory architecture moved away from the compact multifloor structures of the steam era, which were serviced by a railroad spurs, and changed to one-floor buildings with large parking lots adjacent to highways for ready truck access, there simply were no adequate sites inside the city. The construction of GM's infamous "Poletown" (Detroit-Hamtramack) assembly plant required the exercise of eminent domain to buy up and demolish an entire neighborhood to create the requisite space.

47. Scania presentation on June 14, 2018, GERPISA conference, Sao Paulo. This was for their largest bus, but the underlying numbers on area per passenger car were similar to those used in a panel discussion of urban planners.

both for Uber and for regular yellow medallion cabs. While central Manhattan "hailed" rides increased from 378,000 in 2013 to over 450,000 in 2017, the average speed of a ride fell 25% from 6.5 mph in 2010 to 4.7 mph in 2016. Moving around Manila in the Philippines is impossible at times, between buses (high-density), jeepneys (up to 20 passengers in crowded into an extended jeep), Grab cars (perhaps two passengers on average) and the pervasive "trikes" (modified motorcycles) that seat at most 2 passengers. Ride hailing leads to congestion, and in Manhattan, to the monopolization of already scarce parking spots by Uber drivers waiting for their phone to ding.

Will consumers move away from car ownership, shifting the nature of the entire new vehicle market? No, using a taxi or the slightly less expensive Uber or Lyft on a daily basis is well beyond the budget of most people in the labor force; depending on the city, it makes financial sense to own your own vehicle if you drive from 4,000 to 8,000 miles per year. Can automakers monetize the vehicle fleet to generate a continuing stream of post-factory revenue? No, in an earlier case of "peak auto", firms in Japan, Europe and the US all invested in car rental agencies. That did not go well, with Ford, GM and VW divesting completely. These operations faced the same pressure as company stores for car retailing: the interest of car rental firms is in buying in-demand vehicles that maintain their residual values and so lower the effective cost of adding such vehicles to their rental fleet. In contrast, car companies are tempted to use rental fleets as a way to dump models that aren't selling well. Ride-hailing services operated by car companies will encounter the same pressure, to push short-term sales at the cost of future resale values.[48]

Cost / Business Case

Uber and Lyft both lose money – in 2017 Uber had a loss of $4.5 billion on $7.4 billion in net revenue (King and Newcomer 2018). Looking through the patina of high-tech buzz, these companies are selling taxi franchises to individual drivers, with the convenience of cell phone apps and automatic payment and receipts to distinguish them from hailing a cab on the street or calling a dispatch center for a pickup. Portraying themselves as software companies playing in a winner-takes-all market, they have sought rapid growth by capturing market share from incumbents. In this they benefit from the pervasive imposition by local governments of a medallion system (to use the New York City terminology) that limited entry into the "yellow cab" market, resulting in the normal monopoly ills of high prices and poor service (inevitable, due to limitations on the total number of cabs). In practice, Uber and Lyft operate on both sides of the cost equation: they set fares below those of traditional cabs to "buy" market share, while paying drivers more than the market rate so as to rapidly increase fleet size (Hall and Kreuger 2018). Since the market for traditional taxis faces few entry barriers and does not generate above-normal profits (absent any

48. One possible difference is that ride-hailing services may keep cars in services for 4+ years, whereas rental cars end the used car market in 6 months, and leased vehicles in 2-3 years. The longer the term, the longer it takes for the feedback effects from forcing sales to show up in the market for new cars.

monopoly premium from local regulation), this implies that Uber and similar companies are structurally unprofitable.

Uber and its peer thus do not at present have a sustainable business model. At some point, therefore, they must either raise prices or cut driver compensation. Media reports suggest that over the past two years driver pay has been cut, but an online check of sample fares in several locations this year suggest that fares remain 30% or more below those of yellow cabs (Grabar 2018 and author observations). Providing a competitive return on the capital invested – $13 billion for Uber alone – will require establishing local monopolies and setting fares above those historically charged by traditional taxis. Hall and Kreuger (2018) found that drivers do not earn an hourly income much above those of cabbies, and because Uber demands that drivers provide a car less than 4 years old, capital costs are actually higher.

Unfortunately for Uber, entry into ride-hailing remains easy. Lyft is the best testimony for that; despite a late start, they hold 30% of the market in many places. Similarly, Uber has withdrawn from several markets, including China, because new entry increased losses beyond even what Uber management could stomach. Uber exited the Philippines, where Grab is the leader, followed by U-Hop. The competitive landscape there includes 5 other firms: MiCab, HirNa, Owto, Hype, and Go Lag (Jiao 2018). Furthermore, in no market has Uber been able to drive out incumbent "yellow cabs" and their local equivalents. Indeed, in Sao Paulo incumbents have aligned with "99" which allows drivers to both pick up fares on the street or be hailed via a cell-phone app. As should be obvious from the many entrants, Uber's intellectual property rights are not a barrier to entry; it is quite feasible for a group of a dozen programmers to get together to write a "hailing" app.[49] Entry will keep profits at or below zero.

Short-term neighborhood car rental businesses such as ZipCar and Autolib' fare no better. They have high labor costs, because providers need to inspect and potentially clean cars after each use – those who use the cars treat them as a commons for which they have no personal responsibility.[50] In addition, to provide flexibility Autolib' allowed cars to be returned to any open parking spot, so there was the additional need to reposition cars to locations with a depleted inventory. Because such services depend upon customers who arrive on foot, they need to be in dense residential locations, and thus have high real estate, insurance and labor costs. Subsidies (parking spots provided by the Paris city government) and generous up-front funding proved insufficient for Autolib', which shut its doors July 31, 2018. The lack of mention of ZipCar in the financial reports of Avis Budget Group implies that they too lose money.

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49. I understand from discussions at the Industry Studies Association that one San Francisco office building houses 6 different ride-hailing startups, and that at least one US city set up its own program on behalf of local cabbies.

50. Personal observation in Paris in 2015 and 2017, including photos of unkempt cars, complemented by discussions with GERPISA Executive Director Tomasso Pardi, who resides in Paris and followed the firm's downward spiral.

Given the number of ventures in different markets and with different strategies, it is possible that several will find a business model that allows them to survive.[51] In the meantime, investors are in effect subsidizing both drivers and riders. Kim *et al.* (2018) show that this increase in the number of cars in the taxi segment helps neighborhoods away from the urban core (such as midtown Manhattan) in which traditional taxis concentrated, as both regular cabs and Uber drivers move to previous underserved areas. Of course lower prices mean that over ridership is up, another clear benefit to users. However, the other margin of adjustment is that the expansion of taxi services pulls individuals away from public transport. That threatens the viability of such systems, which in the US are already under political pressure to make a profit (Grabar 2018). In any case, Uber and similar firms have not eaten into the market for new cars. If anything, they're good for the existing auto industry: drivers buy their Uber cars from a dealership, just like everyone else, but must trade up for a newer vehicle more quickly than the average purchaser.

Technological Hurdles

As the discussion of business models indicates, the fundamental problem of New Mobility models is that they face no technological hurdles. The underlying software is sufficiently generic that intellectual property rights provide no effective protection to entrants. Even though high initial turnover suggests undue optimism on the part of new drivers, the equilibrium appears be one in which Uber and its peers must provide compensation adequate to match other job opportunities net of operating expenses and capital costs. Eventually autonomous vehicles might be able to eliminate driver costs, offset by higher vehicle costs and labor for the cleaning and maintenance that drivers normally provide at no incremental cost. The time frame under which that might be both technically possible, financially viable and feasible from a legal and liability perspective is unclear. Uber's recent moves away from developing autonomous vehicles suggests that may be a decade or more away (Isaac *et al.* 2018).

VI. Diffusion

The North American market includes about 70 assembly plants; Europe has about 80. Direct costs for a new plant are $1 billion, not including model-specific tooling or real estate and associated infrastructure, which local governments frequently provide to recruit a plant to their jurisdiction. Furthermore, existing plants are not easily transferable to another firm, as paint processes, the location of "hard" points throughout body-in-white welding, and the sequencing of assembly tasks are reflected in the layout and

51. Car dealerships and carmakers are experimenting with swapping services, in which (for a high fee) a luxury car users can choose a different vehicle once a month (for a mere $2,000 a month). Such services in effect lie in between car rentals, where few people borrow a car for more than a few weeks, and traditional leasing, where the volume lies at 2-year and 3-year maturities.

equipment of a given plant. Robots, for example, have very little resale value because they tend to be modified for a particular customer, and moving to another location requires removal from concrete foundations and disassembly.[52] For a new entrant into the vehicle market to capture 10% market share in North America alone would thus require building 7 new assembly plants while developing the vehicles they would produce and purchasing design-specific tooling and dies. With a 3-year lead-time for building a new assembly plant, and another year to ramp up production with a new model and a new labor force this is a daunting task. At the initial stage a new entrant will not have the staff to develop more than one new model at a time, or build more than one plant. That's true even for an experienced firm in a new market. Realistically, expansion takes two decades.

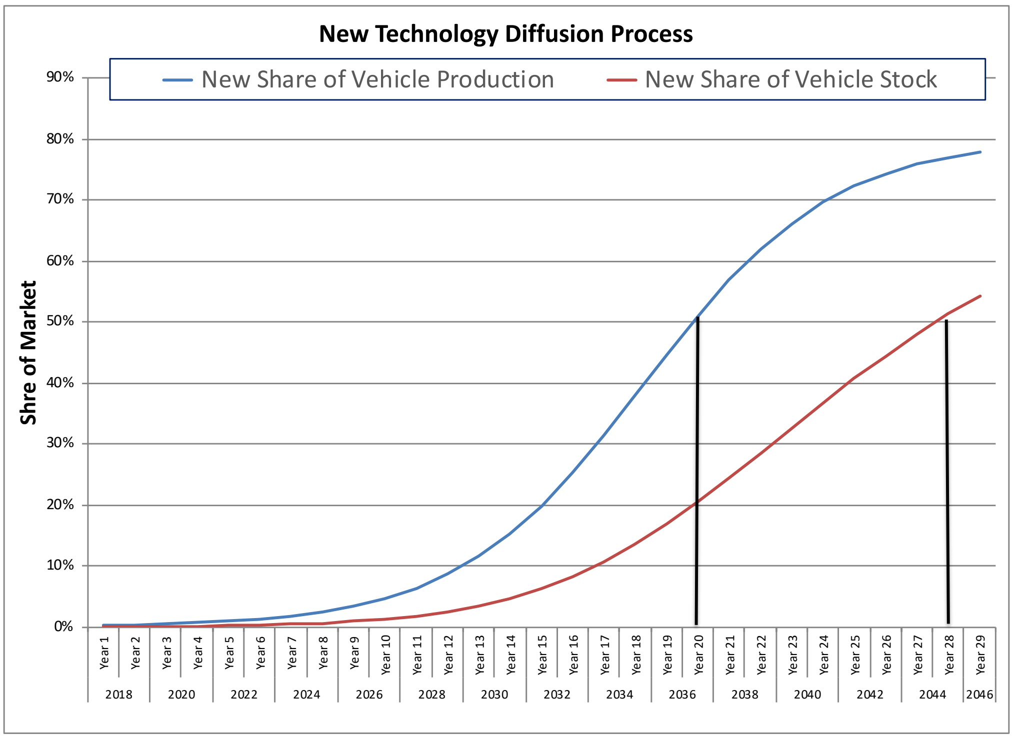
Honda provides an example. They began building a motorcycle plant in Marysville, OH in 1977, with assembly commencing only in late 1979. Work started on their first automotive assembly plant in 1980, and they benefitted from having experienced staff already in place, while the plant was to be the mirror of a plant in Japan, turning out an identical product. Even with those factors speeding the process, and engines and transmissions imported from Japan, it began operation only at the very end of 1982, and took until 1988 to produce its one millionth unit. The second assembly plant, located next door, commenced production in 1989. The move from early preparations to the completion of their second plant thus took a dozen years, even though they were assembling models that had already launched in a similar plant in Japan. As of 2018, Honda has expanded its footprint to 7 assembly plants in NAFTA (4 in the US, 1 in Canada and 2 in Mexico). Toyota's expansion is similar, occurring in stages over a 30-plus year period.

This is consistent with the standard logistics curve analysis of the diffusion of new technologies. It is visible in the increase in assembly plants in a particular market. It is seen in the spread of new technologies from their launch on low-volume, high-end vehicles as the industry modifies product characteristics on the basis of experience, improve production efficiency, moves from robust to lean engineering designs, adds capacity, and benefits from the entry of additional, competitive suppliers. Diffusion needs to be embedded in the replacement cycle of existing products (6+ years for pickup trucks, drivetrains and platforms, 4 years at the model level when based on an existing platform).

Even if a new technology diffuses fairly rapidly – half of new vehicles in 20 years, increasing to a maximum market share of 80% – it takes longer for the fleet to turn over. The graph below represents this process with a standard logistics curve, under the assumption that the overall vehicle market grows at 3% pa while the average vehicle lasts 12 years. In this case, while (as per the assumption) it takes 20 years for total output of a new technology to be on half of all new vehicles, the fleet turns over more slowly. It will

52. Data from interviews with auto industry capital equipment providers in 2017 over the possible liquidation value of Tesla's Freemont, CA factory.

thus be 28 years before half the vehicles on the road would incorporate the new technology. If we apply this to AVs we need to start in 2020, as there are currently none on the road. For BEVs, then under these assumptions we are 3 years into the process. BEV production hits 50 million vehicles in 2030, but because the total vehicle stock by that point would be 1.5 billion vehicles, they would comprise only 10% of the total stock of vehicles. Only in the late 2030s would half of all vehicles be electric – and as discussed above, due to the continued progress in ICE technology, the unsuitability of batteries for larger vehicles, and the existence of better alternatives in countries such as Brazil, BEVs might never reach 80% of the market, even with major improvements in battery technology. My judgement is that the business case for AVs is weaker, and the technology is not yet commercialized. This implies slower diffusion, in which case it will be 2050 before they comprise the majority of cars on the road.



Note: Author calculations using a logistics curve, loosely calibrated against several predicts for BEVs in 2025.

VII. Conclusion

> ***The auto industry may consist of dinosaurs. But the dinosaurs weren't wiped out by competitors, they were wiped out by a meteor that took out their competitors, too.*** ***the author***

Disruption is the exception, not the norm. It is unlikely to apply to differentiated goods, or consumer durables, or competitive industries. The auto industry is all of those, and has a long product cycle. Change in the industry is slow, not disruptive.

Christensen eventually defined "disruption" as a particular type of strategy, which might not succeed. Academic usage remains broader, and includes firm and technology displacement. This paper has not been about what sort of strategy is being employed by a specific firm. It has instead focused on whether, whatever the source, change at the industry level – including both automotive assemblers and components makers – is occurring fast enough to hurt multiple incumbents, or at least investors in them. Whether Tesla or Uber or Waymo will "disrupt" the auto industry is an issue of the speed of an outcome, rather than the nature of these players' strategy.

The auto industry is not amenable to any sort of rapid transition; the hurdles a would-be *de novo* producer faces are manifold. A strategy of "attack from below" will not work. Margins are thin, so using profits from selling inexpensive vehicles will not generate the funds needed for rapid growth. In a market for differentiated consumer durables, gaining share requires offering a portfolio of goods. The capital required to launch multiple models is huge and leaves a would-be startup no room for bad luck or inept management. The industry is also dynamic, and major players are used to bringing new materials, new production methods, and new features to market. Cars today are over twice as fuel efficient as they were in 1980, and emit a fraction of the level of pollutants while making it possible for occupants to routinely survive an accident at 40 mph. They are more durable, too, have higher intrinsic quality, and are laden with convenience features that did not exist in 1980, or even in 2000. Central to the industry is a global supply chain that provides a myriad of inputs into a large, complex, expensive assembled product. That, too, is a barrier to rapid change, as suppliers of new components must be capable of validating that their processes will deliver 99.9999% quality, and guarantee components will last 15 years. The core architecture is also fixed; steel and aluminum will continue to be used in large quantities, in order to provide a quiet, comfortable and safe container for passengers, independent of the drivertrain or electronics that bring it to life. There are multiple players for all components, most of which are engineered and manufactured by global companies with 50 or more years of experience. The top dozen have annual R&D expenditures of $1 billion or more. No single component firm dominates their segment, while the roadmaps suppliers develop with input from their prospective automotive customers mean the major players have a good picture of the sorts of technologies they need to be developing. As a result, no supplier can maintain a lead for more than 3-4 years. Within two model cycles carmakers throughout the world have access to new technologies at competitive prices. First to market provides at best a fleeting advantage; winners do not take all.

Since 1980, emissions and safety regulations led to the introduction of a host of new technologies: fuel injectors, catalytic converters and airbags, with their attendant sensors and software. In general these expanded the scope of the industry and did not displace incumbents. New materials had an impact, but even as the weight of steel declined while that of aluminum, magnesium, plastics and composites expanded, the value added of the steel that is used is over twice as high. There are exceptions for specific parts and processes and materials, but the suppliers of today typically have a long history in the industry, obscured by the many mergers and spinoffs post-1990. Globalization was chaotic, but it was not necessarily disruptive because it was gradual and relied upon acquisitions in the mature markets of North America and Europe. It is not unusual to find engineers who have been employed by 3 different suppliers, all while continuing to work in the same building.

At assemblers, much the same is true. In 1990 the industry consisted of the European Economic Community, the US and Canada (under their 1965 bilateral Auto Pact), and Japan. Eastern Europe had only just opened, and the Chinese market was for trucks, not passenger vehicles, and had yet to reach 1 million units. While several European firms were acquired by others – for example, Peugeot took over Citroën in 1975 and Chrysler in 1978, and VW took over SEAT in 1986 – essentially all of the players then present are still part of the industry, and in general with expanded footprints. The industry is configured differently today, with global vehicle platforms made on multiple continents and greater levels of cross-border trade reflecting product differentiation interacting with assembly plant-level economies of scale in a world with lower tariffs and inexpensive transport on roll-on/roll-off ships eased trade across borders.[53] That transition has been gradual, and overshadowed for investors and managers by the cyclicality of vehicle sales in major markets, particularly during 2008-2012. Transformation has not been disruptive.

Tesla

Tesla was founded in 2003, so is now 15 years old; Musk did not become CEO until 2008, while the firm was listed on NASDAQ in 2010. Production of the Roadster (2008-2012) was followed by the Model S (launched in 2012), the Model X (launched in 2015) and now the Model 3 (launched in 2017). After 15 years of existence it thus has only 3 models in production, and the Model S is now 6 years old and needs to be refreshed. Furthermore, all are modest-sized sedans, so while each comes in multiple versions, Tesla has a narrow lineup relative to the market as a whole, and sedans are a declining segment. Their planned Model Y will extend into the growing SUV segment, but it will require a second production facility. None is yet under construction, so it is unlikely to be available before 2022. Tesla, like any new entrant, faces a high hurdle in broadening their product lineup and adapting to changes in consumer tastes.

53. I use the term "platforms" throughout, even though firms are moving to sets of modules that facilitate adding a greater variety of "top hats." Ford currently has 9 global platforms (including the US-oriented F-series pickups), but intends to transition to 5 sets of modules, e.g., 5 front-ends that can be fitted to different middle sections. Like VW's MQB modular approach, fixing "hard" points allows air conditioning units and other key components to be shared across a wider range of vehicles.

Tesla's cars are lauded in the automotive press and have generated a cult-like following. Despite selling for $50,000 or more, the company has yet to make a sustained profit.[54] What purchasers view as wonderful cars have not prevented Tesla from losing $18,000 per car in 2018 Q2; to provide a reasonable return on assets they need to make $5,000 per unit (10% on sales). Add in the $7,500 Federal tax rebate, and purchasers to date have effectively bought their Tesla's at a $30,000 discount. No wonder owners are so enthusiastic about their car![55]

Meanwhile, Tesla's annual output has never reached the 240,000 units a year level typical of a modern, mass-market assembly plant. To borrow a favorite Musk phrase, Tesla represents mere mouse nuts in the 100 million unit-a-year global market, and they have no prospect for rapid expansion. Tesla has not and will not disrupt the industry; incumbent automakers did not feel compelled to rush BEVs to market. In fact, Renault showed a concept of its Zoe electric car in 2005, before the Roadster was on the market, and launched the Zoe in 2012, roughly contemporaneous with Tesla's first proper car, the Model S. Renault has found that the market is simply not there, even though in France its stickers for under US$35,000 and costs US$28,000 after subsidies. On another dimension, despite repeated promises Tesla has failed to date to launch an autonomous vehicle – but so has everyone else. If anyone leads, it is Waymo, but even they only have a small test fleet and have proffered no commercialization strategy (Welch and Behrmann 2018).

Other disruptors

There remain two potential sources of disruption. One is government policy. Until 2018, regulation widened the scope of the industry, by creating larger markets for emissions controls, safety features, and new materials for lightweighting. Specific materials and processes may fade from use–chrome plating, lead in bearings–but as often as not the new coating and bearing suppliers are the same as the old. Several national and local governments are pushing battery electric vehicles, or at least promising to ban internal combustion engines. This paper has argued that diffusion will be slow, and that while all major car companies will be ready to launch electric vehicles in the early 2020s, high costs will limit sales. Combined with the slow rollout of technologies intrinsic in the characteristics of the auto industry, global production of ICE vehicles will still be larger in 2030 than today. Indeed, BEVs will not even affect the profitability of engine component and transmission suppliers for over a decade, past the tenures of current managers or the time horizon of current investors.

54. Tesla's web site no longer refers to a $35,000 version, while the $7,500 will phase out from January 2019. The Model 3's actually for sale are out of reach for the majority of American new car purchasers.

55. To be fair, Tesla does not provide sufficient detail in their financial statements to make more than a crude estimate. This $18,000 figure includes losses on their non-automotive businesses, which account for 10% of revenues, as well as interest expenses, which reflect past losses.

Negative shocks are possible, such as an unraveling of the trade environment that enables cross-border trade in vehicles and components. Such a development would function as a very large tax on the industry, at least for firms for whom the US market is important, which is most of the industry. There is variation at the firm level, as Renault, PSA and the VW group are underweight in the US. It is very hard to see how this will work out, and President Trump has waffled on his position. In any case, it is probably better to think of the impact as one of chaos rather than a disruptive force that changes the industry's structure.

The second source of disruption, at least from the perspective of investors, is a self-created decline in profitability as the industry tries to compete with high-tech stock market valuations. In that sense Tesla has been a disruptor, with a market capitalization comparable to those of Ford and GM. So Boards of Directors and large shareholders are pushing top management at the major automakers to do what they can to recast themselves as technology companies and not as producers of cyclical, capital-intensive consumer durables. The result is an increase in investment in autonomous vehicle technologies, in New Mobility businesses, and in new powertrains. Since major revenues from autonomous vehicles are at best a decade away, BEVs do not sell, and ridehailing businesses all bleed money, the net result is a decline in profitability across the assembly end of the industry. Furthermore, even if these segments do pan out, everyone in the industry is a player.[56] With competition unchanged, no firm will increase its profits. This is playing out as a classic prisoners' dilemma game, where to play is to lose.

One caveat is that we are currently at peak auto, with strong sales in all major markets. Carmakers are flush with cash, and as in the past they find it difficult to set aside profits for the inevitable rainy day. If they don't spend money on R&D and acquisitions they must return it to shareholders in the form of higher dividends and share buybacks. Acquisitions might pan out; management obtains no lasting benefit from share buybacks. In the past, such cycles saw carmakers buy car rental companies, aerospace firms, and banks, or rush to add the biggest fins to their cars. If history is any guide, today's dubious acquisitions and trendy R&D projects will be pared at the start of the next business downturn. This disruption to profits is thus likely temporary, though investors should factor it into the price of companies caught playing the game, and reward those (Honda? Renault? PSA? FCA?) that are so far mainly observing.

Finally, suppliers will not necessarily be hurt. The major carmakers are in effect building a "field of dreams" in the hopes that business will come their way. Suppliers are more hard-nosed. Furthermore, driver convenience systems such as adaptive cruise control and parking assist are now common, backup

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56. Waymo is a potential entrant and may eventually generate revenue, but the major OEMs do not want to be beholden to a single supplier and are investing in alternative software systems, while Intel/Mobileye, NVDIA and others that stand to gain from a stair-step increase in sensors and in-vehicle computing power are likewise investing. The endgame will generate losers, not winners.

cameras were mandated effective MY2018, and AEB will be required for MY2022.[57] There is already a market for sensors, cameras and control systems sufficient to make them profitable for suppliers. Likewise, the growth of full and partial hybrids and 48V systems means that wiring and connector suppliers, power controls and electric drive motors have markets, even if pure battery electric vehicles do not pan out.[58] Informal observation over years of supplier visits suggests they have greater discipline in avoiding *ex ante* money-losing projects. The push for greater vehicle safety, lower emissions and fuel efficiency will not end. While stricter regulation may hurt assemblers, it is generally good news for suppliers. And suppliers are the bulk of industry employment (Klier and Rubenstein 2008).[59]

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57. Automatic Emergency Braking, mandatory in the US from MY2022. See the Wikipedia discussion of Collision avoidance system, including the reference to the DOT/IIHS announcement of a "voluntary" agreement by 20 automakers. Consumer Reports has a Guide to Automatic Emergency Braking, which provides a sense of the rollout as of June 2017.

58. Electric drive motors, for example, provide a way for car companies to offer on-demand 4WD systems in a technically clean manner amenable to packaging with lower parasitic losses that hard-link 4WD. Wards Automotive has a proprietary report AWD Electrified that contains a description of the current state-of-the-art and forecasts for future 4WD demand and electrification.

59. I have never looked at the aggregate capitalization of suppliers relative to car companies, and have no prior in that regard. A spot check suggests that many of the top 50 suppliers have modest valuations, with the total for 11 such firms coming to $200 billion as of late July 2018. Two of the top 10 suppliers, Bosch and ZF Friedricshafen, are not publicly traded.

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