THE FUTURE OF MOBILITY

Thaiha Nguyen, Investment Manager

BAILLIE GIFFORD

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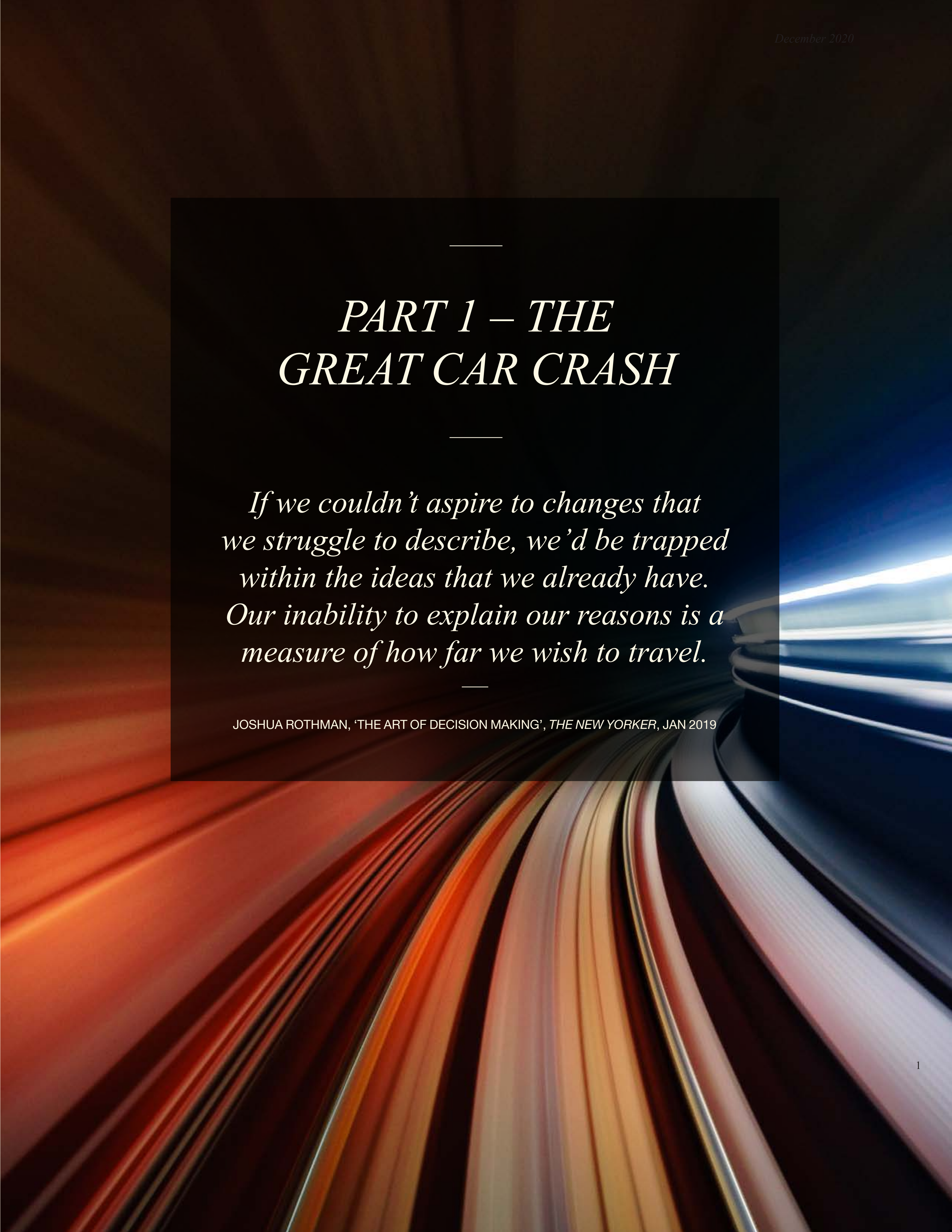


PART 1 – THE GREAT CAR CRASH

If we couldn’t aspire to changes that we struggle to describe, we’d be trapped within the ideas that we already have. Our inability to explain our reasons is a measure of how far we wish to travel.

JOSHUA ROTHMAN, ‘THE ART OF DECISION MAKING’, *THE NEW YORKER*, JAN 2019

Driven to disruption: winners and losers

Car manufacturers

Will be forced to retool themselves to make EVs and autonomous fleets

Oil and gas

Faces transport sector demand shock in 60% of fossil fuel market

Cargo and haulage

Human-driven industry could be undercut by driverless equivalent

Auto insurance

Potential demand collapse if AVs significantly cut accidents

Airlines

Driverless car journeys may displace short-haul domestic flying

Real estate

More leisurely commutes could boost suburban property values

Media

New opportunities may arise as commuting-time attention is freed up

Data infrastructure

Autonomous driving boosts demand for 5G, fibre and data centres

Utilities

Peak-load times will be transformed by mass overnight charging of EVs

INTRODUCTION

For the first time since the advent of the internal combustion engine, a complete transformation in car transport is underway.

Instead of personally-owned, gasoline-powered, human-driven vehicles, the advanced economies are transitioning to electric-powered and driverless vehicles, paid for by the trip or by subscription schemes. This great shift promises to solve the many problems arising from the way we currently get from A to B.

Car ownership as a condition of social inclusion and prosperity dates to Henry Ford and his dream to build a car "so low in price that no man making a good salary will be unable to own one". Not only did Ford make cars cheap, he enabled his own workers to buy them by introducing the $5-per-day salary in 1914.

In the US, Ford helped create a country where car ownership was a requirement, not just an aspiration. His mass-produced Model T coincided with the discovery of large reservoirs of crude oil in Texas and Oklahoma. The low price of energy-dense petroleum meant that the oil and automotive industries grew rich quick and were able to lobby government for more highways and fewer railways.

In the US today, 212 million licensed drivers own 252 million light-duty vehicles. They drive 3.2 trillion miles a year, burning more than 180 billion gallons of fuel, making up about half of total US oil consumption. Car and truck emissions comprise a fifth of greenhouse gases. The distance travelled by car keeps growing. Vehicle miles jumped as much as 50 per cent from 1990 to 2016.

Clocking up those miles is a horrendously inefficient business. Over 95 per cent of the cars sold in the US run on gasoline but less than 30 per cent of that energy is translated into motion. The rest is used to power headlights, radios and air conditioners or is wasted on heat and noise. Since cars typically weigh 20 times more than a person, that means a mere 1.5 per cent of the gasoline's energy is spent moving the driver from A to B.

Such shocking inefficiencies arise because cars are massively overbuilt. In the US, 85 per cent of travel is by automobile, with an average occupancy of just 1.1 people per vehicle commuting to work. Average speeds in cities are often less than 30 miles per hour and can run as low as 12 mph in congested areas.

Yet our cars are built for at least five adults with engines that can make the car reach 120 mph. Heavier propulsion and chassis systems drive up costs and increase risks. The World Health Organisation estimates that car crashes kill 1.35m people a year. That includes approximately 40,000 Americans – the equivalent of a 737 plane falling out of the sky every day.

Worse still, American automobiles sit unused about 95 per cent of the time and must be parked somewhere when idle. Towns and cities devote valuable real estate to car parks and garages, at the expense of green space, schools and hospitals. Parked end-to-end, Earth's cars would encircle our planet nearly 100 times – and that's just with the existing ratio of one vehicle for every eight humans.

Finally, traffic congestion is a global disaster. More than half the world's population lives in cities, a proportion expected to climb to 70 per cent by 2050. That presents big challenges in transportation, infrastructure and safety. Congestion costs each American an estimated 97 hours (four days) per year, or $1,348 annually, a total of $87bn in 2018.

At that rate, Americans will have lost $2.8tn to traffic jams by 2030. According to management consultants McKinsey & Company, congestion levels are reaching breaking point in many cities and can cost a nation as much as 2 to 4 per cent of GDP in lost time, wasted fuel and increased costs of doing business.

Henry Ford's dream has become a burden. The car is such an underutilised asset that the car industry is now one of the most disruptable businesses on earth. The forces of that disruption, meanwhile, are achieving unstoppable momentum.

THE FOUR-PART REVOLUTION

Oil dependency, safety, traffic congestion and global warming are all potentially solvable problems, but only by actors outside the existing car industry. The vested interests of the current stakeholders in the 130-year-old road transportation system, such as car, oil and insurance companies, mean they alone would never have catalysed the mobility revolution.

The period coinciding with the financial crisis of 2008–2009 was a disaster for the industry. While GM and Chrysler went bankrupt and Ford narrowly avoided the same fate, a handful of industry outsiders started to challenge the incumbents' dominance by converging new technology with innovative business models.

Google gathered the brightest minds emerging from the US Government's Defense Advanced Research Projects Agency (DARPA) challenge programme and launched its self-driving project. Upstart Tesla delivered its first Roadster in 2008, establishing the promise of high-performance electric vehicles. Shortly after that, Uber and Lyft established a vast market for ride-sharing, challenging the entire personal car ownership model.

A decade since these seeds of the mobility revolution were planted, we are seeing the emergence of a new mobility ecosystem that could offer faster, cheaper, cleaner, safer, more efficient and more personalised travel. Transportation is on the brink of being disrupted by the digital technology revolution – like retail, entertainment, finance and healthcare before it.

We are experiencing the dawn of the 'digital mobility' age, shaped by four concurrent trends (a glossary of new transport terminology is provided in the appendix):

1

Shared mobility

The shared use of a vehicle allows users to access transportation services on demand. The most common form of shared mobility is ride hailing, operated by companies like Uber and Lyft. But shared mobility goes beyond cars and encompasses micromobility, a rising trend of bike and scooter sharing. Some impacts of shared mobility include enhanced transportation accessibility, as well as reduced driving and decreased personal vehicle ownership. As a result, shared mobility programmes could yield environmental, social and transportation system benefits.

2

Electrification

Electric vehicles (EVs) first emerged in the mid-19th century, and the electric engine was the preferred propulsion system for motor vehicles until surpassed by the internal combustion engine, which has ruled for almost a century. In the 21st century, EVs saw a resurgence due to technological developments mainly in battery technology, an increased focus on renewable energy and various government incentives.

3

Autonomous driving

Autonomous vehicles (AVs) are driverless vehicles capable of sensing their environment and moving safely with little or no human input. They are equipped with a variety of sensors, such as radars, LiDARs (which stands for Light Detection and Ranging, a survey method using pulsed laser beams to detect distance and depth) and cameras operating as 'eyes' to sense their surroundings. Advanced computing systems, powered by artificial intelligence (AI) and machine learning then interpret sensory information to identify appropriate navigation paths, avoid obstacles and drive safely.

4

Urban air mobility

Urban transportation systems that move people by air are being developed in response to traffic congestion and ballooning urban populations. A new generation of aircraft called electric vertical take-off and landing vehicles (eVTOLs) hold the promise of replacing driving around cities, saving man hours by reducing time-consuming trips by road to short hops by air. The vehicles are designed to take off and land vertically in small areas, to be powered by electric engines and to operate on demand like road-bound ride-hailing services.

The chapters that follow consider each of these trends, highlighting their potential as well as the challenges to their wider adoption.

While uncertainty abounds, particularly about the speed of transition, it seems unlikely that the process will be stalled or reversed. The transition towards a new mobility ecosystem will have wide-reaching impacts spanning a host of industries, and we should consider in more detail what the wider impacts might be.

Transportation is on the brink of being disrupted by the digital technology revolution

THE IMPACTS OF FUTURE MOBILITY

The car industry touches nearly every facet of the US economy. It represents nearly $2tn in revenues, about 10 per cent of US GDP. The commercial trucking industry adds another $700bn to that figure. Almost seven million people work in the US car sector, with another four million employed as drivers. Those figures don't include the many additional jobs that rely on transportation provisions, such as warehouse workers, public works employees and those in delivery services. For that matter, the transition toward a new mobility ecosystem will have wide-reaching impacts that span a host of industries and players.

Even more exciting is the fact that all the disruptive forces in mobility are acting simultaneously, so magnify each other's impact. Ride-sharing couldn't reach its full potential without autonomous driving lowering costs per mile to be competitive with car ownership. Conversely, autonomous driving would take longer to get to market if people had not become more willing to share cars and still regarded cars as personal assets. Without the development of electric cars and battery technology, urban air mobility would remain a futuristic fantasy.

One of the biggest concerns about the future of mobility is job losses caused by autonomous technologies and their downsizing impact on the economics of the automotive and oil sectors. If we assume that the four million people employed as drivers work for 40 hours a week for 50 weeks a year that translates into 8 billion hours of paid work that we stand to lose.

It should be remembered however that America's 212 million licensed drivers drive their vehicles for 56 minutes a day on average. Nationally that translates into 72 billion hours a year spent driving. It would be unwise to obstruct technologies that stand to liberate 72 billion potentially productive hours a year for fear of losing 8 billion hours of paid driving work.

What sort of new jobs might emerge for the people who previously worked as drivers? Ride-sharing company Lyft's co-founder John Zimmer intends to evolve his on-demand mobility service to the point where it provides "rooms on wheels" – mobile chambers where concierges could provide meals, drinks or other services.

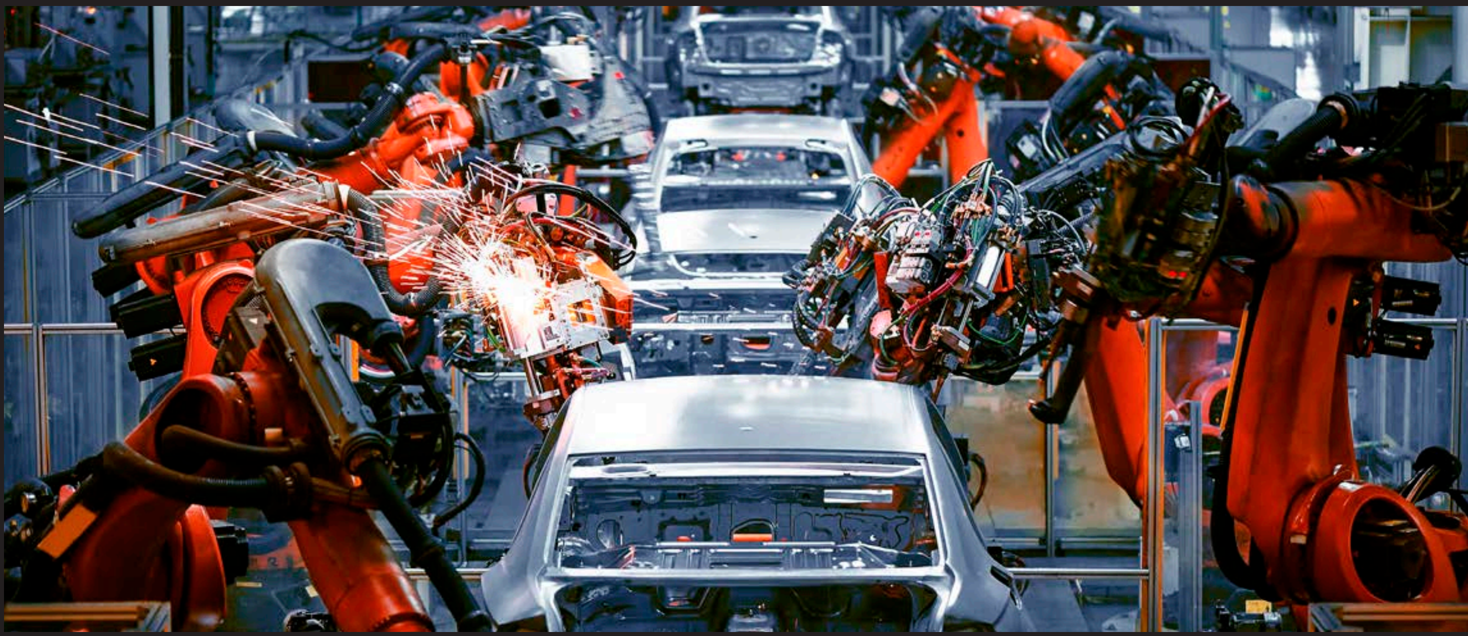
Logistics technicians will oversee the computer-controlled deployment of vehicles to ensure the fleets are properly dispersed, while the requirement for cleanliness – a potentially important differentiating factor in the shared mobility market – will require many more people to staff what used to be car washes.

There are many other potential new jobs to be created, in sectors such as mobility management, content creation for autonomous vehicle riders, cyber security for cars, eVTOL services and manufacturers of electric batteries.

The new mobility era will also affect job creation in other sectors. For example, online retail will become more prevalent as delivery costs fall. It should be possible to manage a likely period of high structural unemployment as people learn new skills, just as our forebears managed the transition from the age of horse-related industries, such as blacksmithing, to that of automobiles.

What follows is a summary of the industries likely to be affected the most by mobility disruption and a look at some of the investment implications.

CAR MAKERS



Known in industry jargon as original equipment manufacturers (OEMs), car makers are under intense pressure to keep their legacy business viable while pivoting to new businesses where they lack core competencies or the deep pockets needed for research and development.

They face enormous challenges: how to transition from internal combustion engines to EVs, how to evolve from being a product-selling business to becoming end-to-end mobility services providers, and how to acquire the technical expertise to prepare for the future of autonomous vehicles.

The industry's big concern is that the new vehicles will become commoditised. Automobile engineering will simplify when vehicles are electric, driverless and less accident-prone. Market differentiators are unlikely to be about added value from sleek design and cosmetic adornments, but more about the customer experience. This will be driven more by software and data than by traditional points of competition.

It is possible that OEMs will evolve like the PC industry, where further hardware innovation is limited, and most value will accrue to the software that will be developed by autonomous driving companies. Nowadays, few can tell the differences between Dell, HP, Samsung or Lenovo laptops. However, such a shift may be even more challenging for car companies whose pricing power is lower. Instead of selling to individual customers, they will sell cars to fleet operators with higher bargaining power and more demanding requirements. To stay relevant and profitable, there may be consolidation between car companies. For instance, we have seen German OEMs getting closer, from the three-way joint acquisition of Nokia's mapping division, HERE, in 2015 by BMW, Volkswagen and Daimler, to the joint venture between BMW and Daimler to develop ride-hailing, charging networks and parking facilities in 2019.

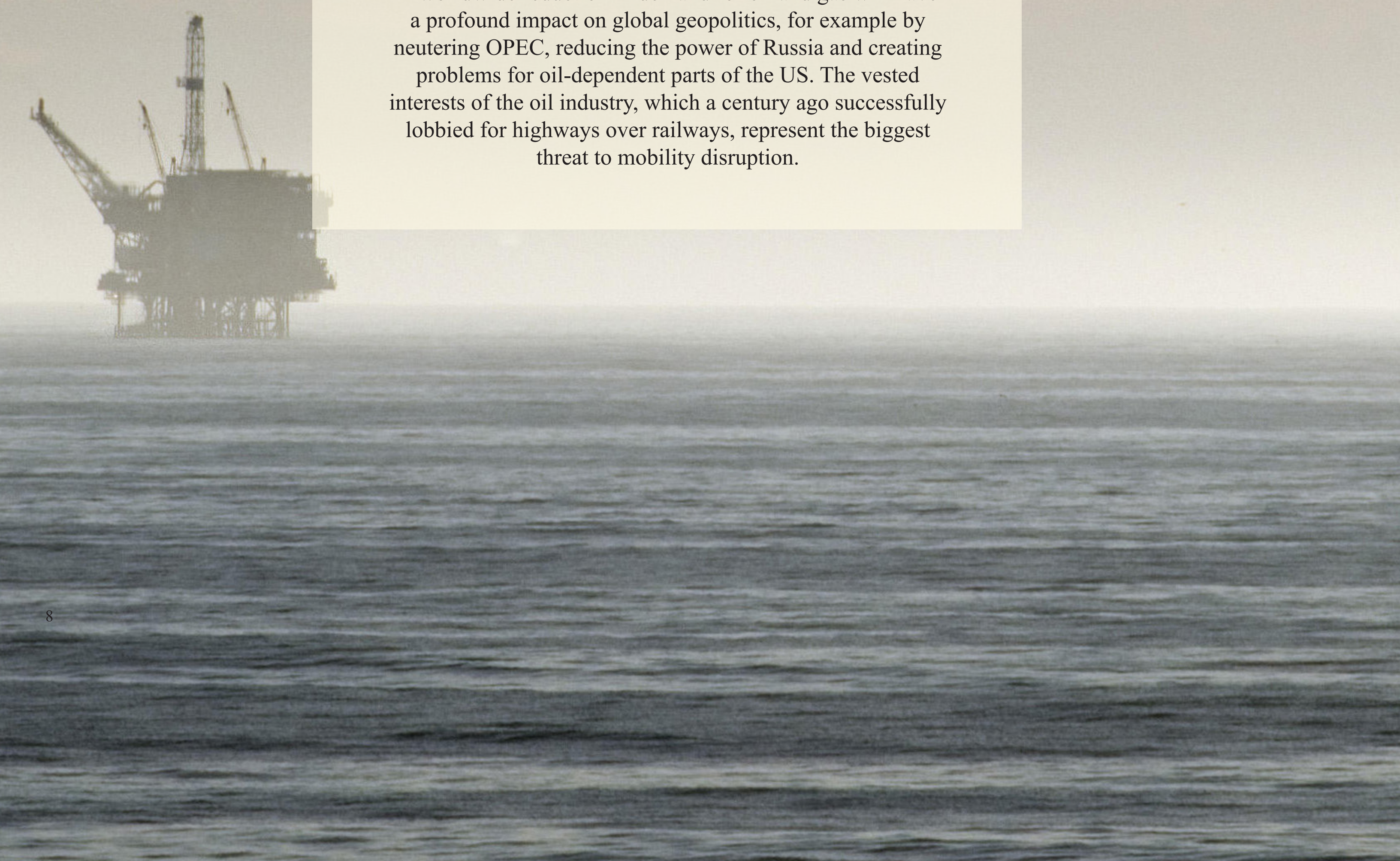
Also, Ford and Volkswagen recently extended their existing partnership from commercial vehicles and mid-size trucks to autonomous driving as they share an equal percentage of ownership in Argo AI, a self-driving company founded by Bryan Salesky, who was one of the top engineers at Google's autonomous driving division, Waymo, in the early days.

OIL AND GAS

As transportation accounts for around 60 per cent of global oil demand, the shift towards clean-energy transport will have a huge impact. Currently non-internal combustion engine vehicles, including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) account for a small percentage of the total fleet but a 50 per cent penetration in 20 years' time could remove 30 per cent of current oil demand.

The argument that the growing demand in many emerging market countries for increasing volumes of transportation will support increasing oil demand may miss the point that the new demand could be fulfilled by clean renewable energy, rather than by oil. In fact, China is the world's biggest supporter of EVs. Also, more efficient engines, smart routing and car sharing etc can all help to reduce oil usage.

A worldwide reduction in demand for oil and gas will have a profound impact on global geopolitics, for example by neutering OPEC, reducing the power of Russia and creating problems for oil-dependent parts of the US. The vested interests of the oil industry, which a century ago successfully lobbied for highways over railways, represent the biggest threat to mobility disruption.



CARGO DELIVERY AND HAULAGE

There is a strong economic case for self-driving trucks. The trucking industry faces a shortage of 50,000 drivers and is approaching a 100 per cent annual turnover rate. The average driver age is 49, compared to the overall workforce average of 42.

Driving a truck, especially on long-haul routes, is a gruelling and unappealing career choice. Also, due to safety regulations, drivers are legally restricted to 11 hours of driving a day and 60 hours a week. Self-driving trucks that operate around the clock, and with less fuel-burning braking, could dramatically increase revenues for fleet providers.

According to TuSimple, a San Diego self-driving truck company, driverless trucks could reduce operational costs to 20 cents per mile, from $1.80 per mile for human-driven trucks. The saving could significantly affect the overall profitability of truck operators and e-commerce players under increasing pressure to ship their products quickly and cheaply.

Most of the larger truck manufacturers, including Daimler and Volvo, are actively involved in developing highly automated solutions. However, as with passenger cars, automation is not their core expertise. There are many start-ups that are developing automated trucking solutions, for example TuSimple, Embark, Peloton, and Kodiak. However, the question is whether those companies will manage to capture the market before bigger competitors, such as Tesla and Waymo, shift their focus to the trucking industry.

AUTO INSURANCE

The US auto insurance market is worth roughly $300bn in annual sales, but if AVs reduce the number of accidents significantly, demand for insurance will decline. Currently, about 90 per cent of accidents are thought to be caused at least in part by human error, but the elimination of the human element in the driving process will shift the insurance burden to the fleet owner (in the event of ride-sharing services) or the manufacturer instead of the driver.

Since those companies will have more negotiating power, many may be able to get lower rates or to self-insure. Competition is also rising as the likes of Uber and Lyft are operating their own insurance businesses.

KPMG has predicted that the car insurance market will shrink by 70 per cent by 2050, losing $137bn of its value. Warren Buffett, whose Berkshire Hathaway owns the auto insurer GEICO as well as other insurance companies, acknowledged that self-driving cars would hurt the industry: “If they’re safer, there’s less in the way of insurance costs, [and] that brings down premiums significantly.”

OTHER INDUSTRIES

The above are just some of the most obvious industries vulnerable to mobility disruption. The impacts on many other industries are only limited by our own imagination. For example:

Airlines	While trans-continental driverless journeys don't appear to be on the horizon, domestic and short-haul flights could face a significant threat from self-driving cars. Once autonomous vehicles make car travel more convenient, many people might choose to take an on-demand car ride for shorter trips instead of enduring the inconveniences of air travel.
Real estate	Faster and easier commutes could shift residential property value from properties in urban centres to those in suburban areas. In commercial real estate, spaces currently predicated on human drivers could be converted to other uses.
Media and entertainment	The average American drives almost an hour each day. Without having to keep their eyes on the road, they could have more time to consume news and entertainment. Broadcasters could compete to provide video content that travellers would be able to consume without risking safety. For advertisers, it might also create a huge opportunity to present riders with location-based ads for nearby goods and services.
Data centres and internet infrastructure	Driverless cars will generate huge amounts of data and will need the infrastructure to support it. Intel estimates that an autonomous car could generate 4 terabytes of data per day, which will require widespread low-latency wireless connections, more data centres and more robust fibre networks. The current 4G networks do not provide the speed and reliability needed to process that much data efficiently. The advancement of 5G will help autonomous technology reach its full capability.
Utilities	The expected increase in EVs on the road and later eVTOLs will create a challenge for power companies. While EVs will not lead to a substantial increase in power demand, they will reshape the demand for electricity at different times. The most pronounced effect will be an increase in evening peak loads, as people plug in their EVs. Beyond peak-load increases, the highly volatile load profiles of public fast-charging stations will also require additional system balancing and real-time pricing.

Undoubtedly many uncertainties remain and we can expect a major power shift among industries. But while it is hard to predict the size of the impact, even being vaguely right in our predictions about the direction of travel will give rise to many exciting investment opportunities.

PART 2 – SHARED MOBILITY

Moving forward: multi-modal progress

	Car sharing	Micromobility	Urban air mobility
What's the problem?	— High cost of car ownership — Increased traffic congestion	— Lack of access to transport for first and last miles of journeys — Need for a clean mode of transport for short trips	— Increased urban population density — Lack of space for surface infrastructure
Where are we now?	— Less than 1% of miles travelled are shared — Still less cost-competitive than car ownership outside big cities	— Big opportunity. Over half US car trips cover less than five miles — Operators can't recoup the running costs of sharing schemes	— Attracting lots of investment — Regulations and technology in development
Where are we headed?	— AVs will reduce operating costs, making rides cheaper — Increased personalisation will cater to customer needs	— Integration with car ride-sharing will create a multi-modal transport network — Supportive regulation will increase safety and efficiency	— Demand for vertiport networks and services such as parking, loading and charging — Public education campaign will increase understanding and acceptance
Is it sustainable?	— Adds to urban congestion if merely replacing public transport systems — Transformative if it leads to car owners giving up their vehicles	— Emissions-free and economical on space — Replacing cars and buses for short trips reduces emissions and congestion	— Battery-powered or hybrid eVTOLS will be energy efficient — Widespread use will lower surface congestion and emissions

CAR SHARING

In the tectonics of transport, two giant plates – technology and consumer behaviour – are coming together. The traditional model of 'transportation as an asset' (TaaA), in which people buy, own, and drive their own cars, is shifting to 'transportation as a service' (TaaS).

With annual car ownership costs now at $9,000 (15 per cent of average US income) and rising at roughly 2 per cent per year, and with congestion worsening, the costs of ownership increasingly outweigh the benefits. Given the ease of ride-hailing apps, ownership is losing appeal, especially to the young. In the US, the number of light vehicles per hundred owned by 16-34 years old fell from 5 to 3.5 from 2000 to 2016. In the same period, the average age of new vehicle buyers increased by nearly seven years.

More surprising is the widespread adoption of ride sharing in China, where car ownership is seen as a mark of social status. In 2018, 550 million Chinese took over 10 billion rides via the DiDi app – almost twice as many as took Uber rides globally. DiDi's ambition is to achieve 8 per cent penetration of China's total mobility market by 2022. At the same time, growth in car sales has been decreasing since June 2018 – the first decline since the 1990s. Cost and convenience now come first.

That said, car sharing is still in its infancy. Even in the US, where ride sharing is best established, the service still represents only 1 per cent of total miles travelled. Globally, Uber has over 70 million riders and Lyft has 23 million, so it's not that ride sharing isn't widely known and accepted. The challenge for these companies and others is to increase the number of rides taken.

How to unlock new demand? For a start, ride sharing needs to compete better on cost. Although cheaper than the traditional taxi, it's still twice as expensive per mile as car ownership, particularly in suburban and rural areas, where parking costs are minimal.

Pooled services, where several riders are collected together on a single trip, could help reduce costs per rider, but the routing algorithms need to improve the matching of riders with journeys to reduce the time needed to walk to and from pick-up and drop-off points.

Ride sharing can only have a significant impact on the transportation system if more people actually share cars, reducing the number of cars on the road. Passengers are used to being crammed together on buses so, in theory at least, sharing a car shouldn't be a point of resistance.

Autonomous driving could also help, slashing costs by more than half, as drivers' pay accounts for over 70 per cent of the operational costs of ride hailing. That's why Uber's founder and former CEO, Travis Kalanick, got so worried about Google's Waymo when he heard in May 2014 that Waymo could potentially get into ride sharing with its driverless cars. "If Uber doesn't go there, it is not going to exist," Kalanick said.

Another reason for the low adoption of ride sharing is related to personalisation. For example, families might prefer cars fitted with baby seats. Others want them installed with their music playlist.

These are not insurmountable problems. Some Uber cars already have baby seats and can be customised for families or the disabled. Lyft has suggested that its drivers could turn into in-car service providers, helping riders with luggage or providing other functions.

With faster 5G wireless connectivity, riders will be able to access music and movies over the cloud. In Phoenix, Arizona, Waymo has been testing free in-car wifi and music streaming features. Users can listen to a pre-selected playlist or listen to their own playlist by linking their Waymo and Google Play music accounts. It's likely that ride sharing will gain more appeal if cars can become smart personal computers in the future.

In the meantime, there is unresolved concern about whether the rise of ride sharing helps reduce congestion and emissions if it encourages car journeys that would otherwise have been taken by public transport. A recent report by former New York City transport official Bruce Schaller, author of *Unsustainable*, an influential study of app-based ride-hailing services, found they were making urban congestion worse.

Ride sharing has added 5.7 billion vehicle miles to nine major urban areas over six years, and the trend is likely to intensify as the popularity of the service surges. Schaller also found that while options such as UberX added 2.8 new vehicle miles for each mile of personal driving eliminated, the inclusion of options such as UberPool and Lyft Line added to traffic at only a marginally lower rate: 2.6 new miles for every mile of personal driving reduced.

Lyft and Uber dispute Schaller's findings. Uber said that it had saved more than 315 million global vehicle miles in 2017 by shifting riders to its pooled service. Lyft argued that over 250,000 Lyft passengers had given up their own cars because ride sharing was available.

MAKING IT PAY

Ride hailing in its current form is unlikely to have a significant positive impact on the overall transportation system. It would take the rise of a multimodal integrated transport network, maximising the use of data analytics, as well as an altruistic commitment from ride-sharing companies, to steer travellers into the optimal modes that balance their convenience with the need to optimise the urban environment.

While ride-hailing companies such as Uber and Lyft have been significantly challenged by the Covid-19 pandemic, with revenues declining by more than 60 per cent at the worst point, we remain focused on the long-term picture. From an investment point of view, the two biggest questions are:

- Shorter term: can it be profitable?
- Longer term: what role will it play in autonomous driving? Or will ride-sharing become commoditised, allowing any car company to operate its own hailing service?

On the first question, there is increasing commitment from both Lyft and Uber to act rationally. Competition is moving from price discounts and coupons to product or consumer experience. Such competition could boost take rates and net revenues, while lowering sales and marketing costs. Encouragingly, Lyft has seen significant leverage from its sales and marketing, spending on which decreased from 41 per cent to 17 per cent of revenues over the last year before Covid-19.

Equally encouraging is growth on the revenue side. Lyft's pricing algorithms are improving. With more data on price elasticity to hand, it is now able to offer different products at various price points for customers to choose from. For example, there might be two prices for a shared ride, depending on how long customers were willing to wait for the driver. Lyft was previously unable to price for a demand surge. The price discrimination theory tells us that if companies can segment the market based on price elasticity and willingness to pay, they can extract more value.

Another pricing initiative that is building momentum is Lyft's enterprise business, partnering with the likes of Hilton, Disney, Delta, various US universities and even Medicare. Compared to the consumer business, the enterprise business has higher prices and lower price elasticity. In the case of Medicare, there is a huge potential market for non-emergency medical transportation. Billions of dollars are spent getting people to their appointments given the much larger costs of missed consultations. Lyft has signed a contract to provide Medicaid transportation in Arizona.

At the time of Lyft's IPO in March 2019, it was open to question whether Lyft would be able to pull on the two biggest levers of profitability improvement: take rates and sales and marketing. Since then, take rates are rising thanks to market rationalisation and pricing initiatives; and sales and marketing costs are leveraging returns. It's still early days but the company has already proved it can continue to drive down costs, even during challenging periods such as the Covid-19 pandemic.

The second question, on the long-term future of ride sharing, is harder to answer as there are so many moving parts. In the future, the service and user experience elements will become much more important and more of a point of differentiation. The cars themselves and the autonomous driving software may risk becoming commoditised, while the user experience may not. It's too early to tell whether Lyft or any other services will excel in user experience, but it's hoped that its co-founder John Zimmer's background in hospitality will help.

As mentioned earlier, Zimmer intends to evolve his on-demand mobility service to the point where the company will provide rides in what he describes as "rooms on wheels": mobile chambers where a concierge provides meals, drinks or other services such as massage. Logistics technicians will oversee computer-controlled deployment of vehicles to ensure the fleets are properly dispersed. Cleanliness, comfort and fun will be important points of differentiation in the shared mobility market.

MICROMOBILITY

Shared mobility goes beyond cars. The last few years have seen the rapid rise of so-called micromobility, with venture capital firms pouring big money into bike-sharing and scooter-sharing start-ups. There has also been a wave of acquisitions of these young companies by Uber, Lyft and Ford, which have tried to integrate them into existing ride-sharing platforms to create a multi-modal transportation network.

Most of those companies have similar business models. They use large cash reserves to build up a supply of ‘dockless’ bikes or scooters, then deploy them at scale across busy urban centres. While mass transit remains the most efficient means of moving large numbers of people long distances, getting people to and from this transit is a perennial difficulty: the much discussed first-mile and last-mile challenge.

The aim of micromobility companies is to help riders complete the first or final legs of their journey. Micromobility could also be a powerful tool in the fight to increase access to transport for traditionally under-served and marginalised communities, an important objective for many city authorities. Indeed, some survey data suggest that support for e-scooters tends to be highest among low-income users. But micromobility’s potential extends well beyond connecting people to mass transit. More than half the car trips taken annually in the US cover less than five miles, opening up those journeys to short-range alternatives, such as e-scooters and bikes.

Micro services have clearly resonated with consumers, as evidenced by their rapid adoption

The benefits of micromobility are obvious: for riders, they are cheaper and sometimes faster than cars. For cities, they are cleaner and take up much less space (although the picture is clouded by the need for conventional vans or trucks to collect, charge and relocate e-scooters and e-bikes).

These micro services have clearly resonated with consumers, as evidenced by their rapid adoption in such a short period. In China, the share of overall trips on bikes has doubled from 5.5 per cent to 11.6 per cent since the launch of dockless bike systems in 2015. Elsewhere, US-based companies Lime and Bird have introduced their services in more than 100 cities around the world (before Covid-19) and the adoption rate dwarfs car hailing in its early days.

Despite all these benefits and the spectacular early adoption rates, micromobility faces significant challenges. The first is the regulatory crackdown. Bike and scooter operators are entirely dependent on cities, many of which are now putting policies in place to restrict bike and scooter sharing for the safety of riders and pedestrians.

These vehicles may be small and light, but they can occupy a significant area of pavement space, infuriating pedestrians. Negative headlines about bikes and scooters being stolen, destroyed or dumped in lakes and oceans are common. The success of these services in the future depends on how well they cooperate with regulators. The Uber playbook of 'begging forgiveness rather than asking permission' can no longer be used.

The second challenge of micromobility is the viability of its business model.

The underlying problem is the quality of the scooters themselves: they don't last long enough to recoup costs. It's estimated that a scooter needs to be at least four months old to allow companies to break even, but on average they last for only a few months. In the early days, most companies bought the same cheap, low-quality Chinese scooters, designed for recreational use rather than as a heavy-duty commercial asset. Some companies now design them in-house, hoping that more durable scooters will reduce depreciation and maintenance costs. Lime has claimed that its latest version of scooter could last for five months.

There are dozens of scooter start-ups whose major distinguishing feature is their brand colours. Consolidation seems inevitable as these companies seek to gain scale and presence in different markets. For example, Bird's acquisition of Scoot allows it to operate in San Francisco. Spin has been bought by Ford, while Lime has been given an exclusive partnership by Uber.

It's hard to see bike-sharing and scooter-sharing companies becoming successful independent businesses. The barriers to entry are low and differentiation between services is virtually zero. It seems likely that they will work better under a transportation platform created by existing ride-hailing companies.


Uber
HYUNDAI | Uber
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URBAN AIR MOBILITY

Commuting in a large city can be frustrating and time-consuming. Traffic jams, train cancellations and roadworks can extend a short trip into one of a few hours or more. Urban populations are set to swell, putting greater pressure on existing transportation systems. In many places, there is simply no more space to build new surface transportation infrastructure, even if budgets allow it.

But what if our day-to-day travel was no longer restricted to road and rail networks? What if traffic could be extended beyond two dimensions? A new generation of aircraft known as electric vertical take-off and landing vehicles (eVTOLs) will soon enable us to redefine urban air mobility. Flying could replace driving in cities, saving people's time as trips that take hours on the ground can be reduced to minutes in the air, improving productivity and quality of life.

Although some eVTOLs may look like helicopters, they're likely to be powered by batteries, hybrid engines, or other new technologies that make them quieter and more energy efficient. Advanced avionics should enable eVTOLs to navigate with high precision, exchange information digitally and respond to changes in flight conditions autonomously.

When they are introduced, eVTOLs are likely to have pilots on board. With time, however, these aircraft will mature to a stage where they can operate autonomously. Although the technology is in its infancy, market segments are forming, regulations are being laid down, and technology is developing. In the sections that follow, I look at the path to market across four dimensions: vehicles, infrastructure, operations, and economics.

Vehicles

A big challenge in designing an eVTOL is transitioning from vertical take-off to forward flying while maintaining high stability. In 2010, Mark Moore, a 30-year veteran of NASA, former director of aviation at Uber, presented NASA with an eVTOL concept highlighting the potential of distributed electric propulsion (DEP) to enable cheap, quiet and reliable short-range VTOLs. Since then, more than 130 eVTOL concepts have been proposed by researchers, start-ups and major aircraft companies and more than $1bn has been invested.

EVTOLs require significantly different designs from helicopters for several reasons: (i) helicopters are efficient in hovering but slow in forward flying; (ii) they're very noisy: most helipads have now been shut down because of noise; (iii) they have high maintenance and fuel costs; and (iv) they require skilful pilots.

All these factors make helicopters unsuitable for large-scale urban transportation. Today various companies have demonstrated concepts that showcase ways to use DEP technology to achieve a variety of advantages (and penalties), depending on whether the designer favours cruise efficiency, hover power, vehicle control, design simplicity, payload or vehicle costs. It is too early to tell which design is best as it depends on the task the aircraft are asked to perform.

Another challenge with eVTOL design is the nature of the battery. For comparison, a 100kWh battery pack for the 2017 Tesla Model S can have a 300-mile range. But since vertical take-off and landing demands lots of energy, even a 150kWh battery pack can only support a 60-mile range for an eVTOL. Also, because of the high energy use during take-off and landing, eVTOL batteries must be able to discharge power at rates roughly 10 times faster than car batteries. This means batteries get a lot hotter, requiring special cooling systems – which in turn require more energy and weight. Battery safety is obviously even more important in the air than on the ground.

Significantly, no eVTOLs have yet been certified by the FAA (Federal Aviation Administration) or other regulators. Usually a new type of aircraft takes 5–9 years to be approved for use as it requires a new basis of certification. Aviation is the most heavily regulated industry in the world and has the highest safety standards, so it will take time to gather the concrete evidence needed before any aircraft is considered safe enough to commercialise.

The Uber Elevate Summit in Washington DC in May 2019 conveyed the sense that regulators, including the FAA, the US Department of Transportation and NASA, all seemed very supportive of eVTOLs and willing to collaborate with the industry to shorten time to market.

INFRASTRUCTURE AND OPERATIONS

To establish the large-scale deployment of eVTOLs, the infrastructure, rather than the flashier technology of eVTOLs, is likely to be the biggest hurdle. It requires the construction of thousands of 'vertiports' and associated parking, loading and charging capabilities. These are virtually non-existent today.

Industry players are conceptualising designs for ground infrastructure fit for residential buildings, highway plazas, parking areas and rooftops of high-rise buildings. Depending on pre-existing availability, space utilisation, functional requirements, and location, designs can range from 'vertistations' (one or two landing pads) to vertiports (located in busy districts, shopping centres, train stations and so on and integrated with other modes of transportation) and vertihubs (small airports for eVTOLs).

The costs of land or space acquisition and operational complications necessitate close public-private collaborations and large-scale partnerships. Companies in the space are establishing various partnerships with NASA, local authorities, architects and real estate developers to bring the concepts to life.According to Eric Allison, head of Uber Elevate[1], the company looks at movement data gathered from billions of trips taken by Uber cars (data show that where the demand is, how people like to travel, price elasticity etc) to decide where best to place those vertiports to maximise network flexibility and utilisation.

Besides infrastructure, robust air traffic management is a key challenge. How will eVTOLs operate in urban airspace, where they will have to fly much lower and closer to buildings than commercial aircraft do? They will have to detect a wide variety of obstacles, such as cranes, birds, drones, other eVTOLs or vehicles driving across landing sites. Another factor is that air taxis will not always have clear visibility but will have to operate in fog, drizzle, rain, snow and freezing conditions. Today, using Part 135 of the FAA's rules for helicopter and fixed-wing operations as the closest proxy, air-taxi aviation is twice as unsafe as driving. Half of a 'Part 135' crashes involved poor weather data and pilots not being where they thought they were.

Building a robust system that allows for the smooth and safe functioning of thousands of eVTOLs across thousands of vertiports in a dense urban air environment will not be easy. Today, even in cities with the largest commercial urban helicopter activities there is room for growth. For example, in Sao Paulo, Brazil, there are only 420 helicopters registered, supported by an infrastructure consisting of 193 active helipads. Those numbers will be dwarfed by the number of eVTOLs and vertiports demanded for the future of urban air mobility.

Operational complexity will be beyond the capabilities and parameters of current air traffic management (ATM), which is focused on commercial airlines flying between cities, and sUAS (small unmanned aircraft system) operation. It will call for a new urban air traffic management system (UATM) to be established by industry players and regulators.

Uber offers a helicopter service from central Manhattan to JFK airport to its Diamond and Platinum members. The costs are high, at $200 per trip, but the point is to understand the complexity of the network and the demand for multimodal transportation (integrating air taxis into the ride-hailing platform). As Eric Allison has said, it's a hard-core operational problem.

1. Uber Elevate was recently acquired by Joby Aviation.

ECONOMICS

Urban air taxis can only take off if the economics work. Only a very small elite will be willing and able to spend $200 on a flight from central Manhattan to JFK. Helicopters are expensive: on the basis of cost per pound of empty weight, they are as expensive as commercial aircraft (around $1,000/lb) due to low volume production (only around 1,400 units per annum globally) and lots of expensive critical parts. Initially, eVTOLs will be expensive but, as Uber estimates, if 10,000 units can be operational by 2030, economies of scale will bring costs down to $1m per unit or $250 per pound of empty weight.

For a helicopter, the baseline operating cost is around $1,800 per flight hour on the basis of 700 hours of flight annually. The biggest costs are maintenance and fuel (around 52 per cent of total costs), both of which will be much lower for eVTOLs. Uber's goal is to lower the costs by at least 35 per cent compared to helicopters, hence its target of an operating cost of $700 per flight hour.

If Uber were to make a 20 per cent profit margin and assuming a speed of 150 miles per hour and a full load of four passengers per trip, this translates to a cost of $1.40 per mile cost per passenger – putting it on par with Uber Pool. Of course, these figures will turn out to be loosest approximations but illustrate that air taxis need not necessarily be expensive.

There are grounds for optimism about the future of aerial ride sharing. It could be a time-saving solution to congestion and pollution. However, we are still at the earliest stage of the journey. It will require many things to happen simultaneously, from the advent of safe aircraft to the building of reliable infrastructure and robust airspace management system to realise the full potential of urban air mobility.

Also, in the period before full automation can be achieved, well-trained pilots will be required, creating a potential supply bottleneck. It could take at least a decade before eVTOLs are deployed at scale.

PART 3 – ELECTRIFICATION

Surprisingly enough, it was electric motors and battery engines, not the internal combustion engine (ICE), that had the upper hand in the early days of motoring. The first electric carriages were built in the 1830s in Scotland and the Netherlands. Subsequent breakthroughs in battery storage capacity led to the commercialisation of battery-powered cars in France and Britain in the 1880s and in the US in the 1890s.

The vehicles were quiet, clean and simple to operate. ICE vehicles by contrast were complex, noisy, dirty and dangerous.

What happened? A remarkable convergence of ICE technology, particularly the invention of the electric self-starter, which eliminated the hand-crank, made ICE vehicles easier and safer to start. Henry Ford's low-cost mass production techniques, the discovery of oil in Oklahoma and Texas, road development, public policy and consumer demand all conspired to enshrine ICE as the predominant power. EVs were banished to the fringes.

Over the years, there were sporadic attempts to revive EV technology, but they never surmounted high production costs, limited range (particularly in cold weather) and lengthy charging times. The most notable attempt was by General Motors (GM) in the late 1990s. It leased, and then promptly took back and crushed all its electric EV1 vehicles. Looking back, the former head of R&D at GM who was responsible for EV1 programme said:

"We blew it with the EV1…because of the short-term pressure of rewarding shareholders with appropriate returns, the health care and pension costs hamstringing us in the early nineties and the need to do a whole lot of spending on our fundamental business to get back in the game."

GM later regretted it, believing Tesla's first car, the Roadster, 16 years after EV1, was less innovative and that electric car technology would be a lot further along than it is today if GM had kept the programme going.

GM's troubles encapsulate the innovation dilemma faced by traditional carmakers and explain the slow transition to EVs. It was the challenge from Tesla and the tightening of CO_2 emissions rules around the globe that made the difference.

Roadblocks: barriers to breakthrough

Battery technology

Spurred by the limited range and high cost of lithium-ion batteries, the search is on for better batteries, including smaller, lighter 'solid-state' electrolyte alternatives. If manufactured at scale, EVs could compete on cost with petrol-powered equivalents.

Regulation

Support from regulators can transform the pace of adoption. China has led the way by subsidising EV buyers and mandating the car industry to produce EVs. By contrast, under President Trump, the US Government loosened emissions standards and reduced tax rebates on EVs.

Infrastructure

Proliferating charging stations and higher charging speeds will help reduce 'range anxiety'. The next technology leap will be around charging on the go, either wirelessly or by conductive rails.

REGULATORY SUPPORT

China has been at the forefront of promoting EVs. Whether its aim is to address a rapidly increasing pollution problem, to reduce reliance on imported oil, or simply to stake a leadership claim on the next era of global mobility, China is currently leading global EV sales, accounting for more than half of the total.
It is also driving the electrification of other types of vehicle, such as buses and two-wheelers, accounting for more than 99 per cent of these two modes of electric transportation stock globally. To meet its goal of becoming the undisputed EV champion by 2025, China is implementing a two-pronged approach: offering subsidies to EV buyers while mandating automotive companies to amass credits on the sales of EVs that can be transferred or traded.

India is another country heavily reliant on imported oil. In an effort to manage its massive oil bill, the government intends that by 2030, EV sales will account for 30 per cent of all new vehicle sales.

EV adoption is picking up in Europe. In the EU-15 nations (broadly, the western European countries) alone, the share of diesel engine-based vehicles declined from 56 per cent in 2011 to 45 per cent in 2017. This was set off by consumer reaction to the Volkswagen "dieselgate" scandal in 2015, when it was discovered the company had been rigging diesel-powered vehicles to cheat on government emissions tests. The subsequent decision by the German federal court to allow individual cities to ban diesel vehicles and the imposition of additional taxes on diesel vehicles in countries such as the UK are causing buyers to think twice before committing to ICE.

A few countries, including the UK, Norway, France and the Netherlands, have already announced plans to ban the sales of vehicles that run on conventional petrol and diesel fuel. This is planned over the next two to three decades, which should bode well for EVs.

North America, however, is likely to lag for some time. Consumers there prefer to drive vehicles with petrol (gasoline) engines, as the price of 'gas' is significantly lower there than elsewhere. Further, US Government policy has shifted to looser emissions standards and the government is tightening the screws on tax rebates. Together these policies have dampened EV adoption.

For example, President Trump wanted to end the federal tax credit of up to $7,500 on new electric vehicles and plug-in hybrids, to save (the White House claims) $2.5 billion over the decade. Right now, the credit is phased out to buyers once the manufacturer has sold 200,000 electric cars, removing some of the incentive for that company to further expand its EV offerings. Only Tesla and General Motors have breached that cap so far.

DEVELOPMENT OF BATTERY TECHNOLOGY

Customers' biggest concerns about BEVs are the driving range and the price premium, both related to the state of battery technology. The lithium-ion batteries in use today are iterations of a technology developed almost 40 years ago and commercialised by Japan's Sony Corporation back in 1991. As the years go by, we're squeezing more juice from the pack: energy density is rising by up to 8 per cent per annum, thanks to the continuing optimisation of existing lithium-ion cell chemistries, as well as the introduction of new battery cell materials. At the same time, advances in battery management systems contribute towards extending vehicle range while simultaneously improving safety and extending battery life. Many original equipment manufacturers (OEMs) have announced planned new BEV models with ranges more comparable to their ICE counterparts.

Battery prices have dropped by more than 80 per cent since 2010, from $1,160/kWh to $156/kWh in 2019. Battery prices are inversely correlated with production volumes. Historically, for every doubling of cumulative volume, there was an 18 per cent reduction in price. Based on this observation and battery demand forecasts, it is expected that the average price will be approximately $90/kWh by 2024 and $62/kWh by 2030. Experts believe that when battery costs fall to $100/kWh, EVs will be cheaper than ICE vehicles.

These are the average price figures. Tesla/ Panasonic's batteries are believed to be roughly 20 per cent cheaper. On Tesla's recent 'Battery Day', Elon Musk unveiled a plan to produce a newly designed battery in-house to dramatically reduce costs, and ultimately allow the company to sell its vehicles for the same price as gasoline cars. Musk anticipates that Tesla will deliver a compelling $25,000 passenger electric vehicle within the next three years.

But the 'super battery' hasn't yet been invented. At some point, we will run into the limitations of chemistry as well as of manufacturing efficiencies. Academic researchers and companies are racing to come up with new battery technologies.

Of all the possibilities, the solid-state battery is often the most cited and has received the most investment. This involves substituting out the liquid electrolyte found in lithium-ion batteries in favour of a solid electrolyte. For example, in 2019, Toyota announced a joint venture with Panasonic for a solid-state design; while Hyundai, Samsung, Ford and BMW all invested in Solid Power (a solid-state battery start-up). Interest is high because solid-state batteries are smaller and lighter, provide 50 per cent more power density and are less flammable than lithium-ion batteries based on liquid electrolytes.

An electric car with a solid-state battery could simplify the thermal management systems in favour of a larger battery, and thus achieve a longer range. However, the main barrier to its widespread adoption has been the search for a solid electrolyte with enough conductive capacity for large batteries, as well as a manufacturing method allowing economies of scale.

Although many breakthroughs are being claimed, we shouldn't underestimate the time it takes for a new technology to be fully commercialised in the car sector. Historically it has taken four to five years to develop a new vehicle model. The move to electrification is shortening these timelines but safely getting below three years is very difficult, even after the battery has been rigorously tested. Hence it is likely to take more than five years for any new battery technologies to reach commercialisation. J.B. Goodenough, one of the lithium-ion battery's creators, was criticised over his claims about a superior solid-state battery developed in his lab. Even Elon Musk, a specialist in bold claims, is a sceptic on battery development:

"When somebody has like some great claim that they've got this awesome battery, you know what? Send us a sample. Or if you don't trust us, send it to an independent lab where the parameters can be verified. […] everything works on PowerPoint. If you like, I'll give you a PowerPoint presentation about teleportation to the Andromeda Galaxy."

Overall, my take on this is that while it is important to track the development of solid-state batteries, they are not needed to enable electric vehicles to be competitive with petrol cars. Such a technology will arrive and push EVs forward, but in the meantime current incremental improvements in lithium-ion batteries will be sufficient to make EVs highly competitive and desirable.

DEVELOPMENT OF CHARGING INFRASTRUCTURE

Over time concerns about a lack of EV charging infrastructure will decrease for three reasons. First, the next generation of BEVs will have a greater range; second, charging infrastructure is rapidly being built; and third, charging time is falling dramatically.

Tesla has been building its proprietary charging network across the globe for years. Currently, there are over 20,000 individual Superchargers at over 2,000 stations. Last year, Tesla introduced its V3 Superchargers, which support a peak rate of up to 250kW and can charge up to 1,500 electric vehicles a day. This means that up to 180 miles of range can be added to the battery in just 15 minutes on a Model 3 Long Range. In June 2020, the German government mandated every filling station in the country to provide charging for electric vehicles.

But charging technology can go much further. A special route called eRoadArlanda has been built in Stockholm that charges modified electric vehicles as they drive along, thanks to a conductive electric rail. This is part of the Swedish government's plan to move from petrol and diesel and achieve a fossil fuel-free transport system by 2030. Another example comes from the European Union-funded FABRIC, which investigates the feasibility of wireless charging spots at car parks, road junctions and at traffic lights.

CONCLUSIONS

I started researching the automotive industry back in 2015 when I first looked at BMW. My conclusion at the time, gathered from conversations with BMW executives and industry experts, was that the time was not right for EV technology. I felt that fuel efficiency could be achieved largely through better engineering and aerodynamics, without the need for electrification. At that time, no major OEMs were committed to EVs.

Fast forward to 2020: BMW plans to mass produce 12 EV models by 2025. Daimler plans to unveil 130 electrified vehicles by 2030 and has budgeted $30bn for investment in batteries. Volkswagen will invest up to $91bn in battery and EV technology to electrify all 300 of its models by 2030. Ford will invest $11bn in green technology and has given guidance that it will produce 40 all-electric and plug-in hybrid vehicles by 2022. Volvo has committed to putting one million electrified cars on the road by 2025. The field is moving fast, and my conclusions of five years ago feel naïve and unimaginative.

Global sales of EVs have risen significantly over the last few years and will continue to grow, driven by government policies encouraging vehicle owners, along with tighter emissions standards and advances in lithium-ion battery technologies and charging infrastructure. Five or so years since I first looked into the automotive industry, I am convinced that the world is shifting to EVs faster than we imagined.

PART 4 – AUTONOMOUS DRIVING

At the societal level, it can save millions of lives, reshape our cities, reduce emissions, give back billions of hours of time and restore freedom of movement for everyone. At the individual level, we believe it will deliver safer, more convenient, more affordable and more accessible transportation.

Dan Ammann, CEO of Cruise

Switching to autopilot: levels of automation

Level 0
No automation

Level 1
Driver assistance

Car controls speed or steering under certain conditions but driver responsible for intervening and for all other tasks

Level 2
Partial automation

Car controls both speed *and* steering under certain conditions but driver responsible for intervening and for all other tasks

Level 3
Conditional automation

Car performs all driving tasks under certain conditions but driver retains responsibility for intervening

Level 4
High automation

Car performs all driving tasks under certain conditions and car is responsible for deciding when to hand control back to driver. Sometimes called ‘unreliable automation’, as the driver must remain ready to accept responsibility

Level 5
Full automation

Car performs all driving tasks under all conditions

THE STATE OF AUTONOMOUS DRIVING

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It was the 2007 DARPA Urban Challenge, an autonomous vehicle competition run by the US Defense Department's research body, that has led to today's self-driving technology. DARPA made things easier by eliminating pedestrians and cyclists from its simulation, but what the competing teams accomplished was still impressive. Most put their systems together largely from scratch in just 18 months.

At the time, the teams relied on rules-based programming techniques, which means the robotic systems of a decade ago tended to operate only in constrained environments assuming well-behaved road users who would not deviate much from established rules. In the past few years, the game has changed.

Advances in processing power, storage and artificial intelligence (AI) combine to allow computers to think through problems without a programmed 'script'. From massive volumes of data they learn to recognise patterns with astonishing accuracy, filtering out anomalous inputs from their sensors to focus on what matters.

The industry has come far over the last decade, but how close a truly autonomous vehicle (AV) is to realisation remains a big question. Industry morale spans a wide spectrum. At the optimistic end is Elon Musk, who has shared his vision for the roll-out of Tesla robo-taxis in 2021. At the other end are those who see the technology taking a decade to reach maturity.

Most, including the likes of Waymo, Aurora and Cruise are somewhere in the middle, assuming deployment in constrained environments within a few years. Great challenges remain at each step of autonomous driving, from perception to prediction to planning.

Perception

Autonomous cars must detect and classify the objects around them. This isn't easy. Even objects with the same functions come in various shapes and sizes, while weather, light and environment can interfere with sensors and reduce visibility. Also, things must be contextualised as well as identified. A stop sign on the road, on a bus, or held under the arm of a construction worker all mean different things.

Cars' sensors are their eyes and ears, but they can't 'understand' what they capture. A computer is needed to combine inputs from multiple sensors, then sort out errors and inconsistencies. Achieving a comprehensive, robust picture of the world for a computer to process is incredibly difficult.

Prediction

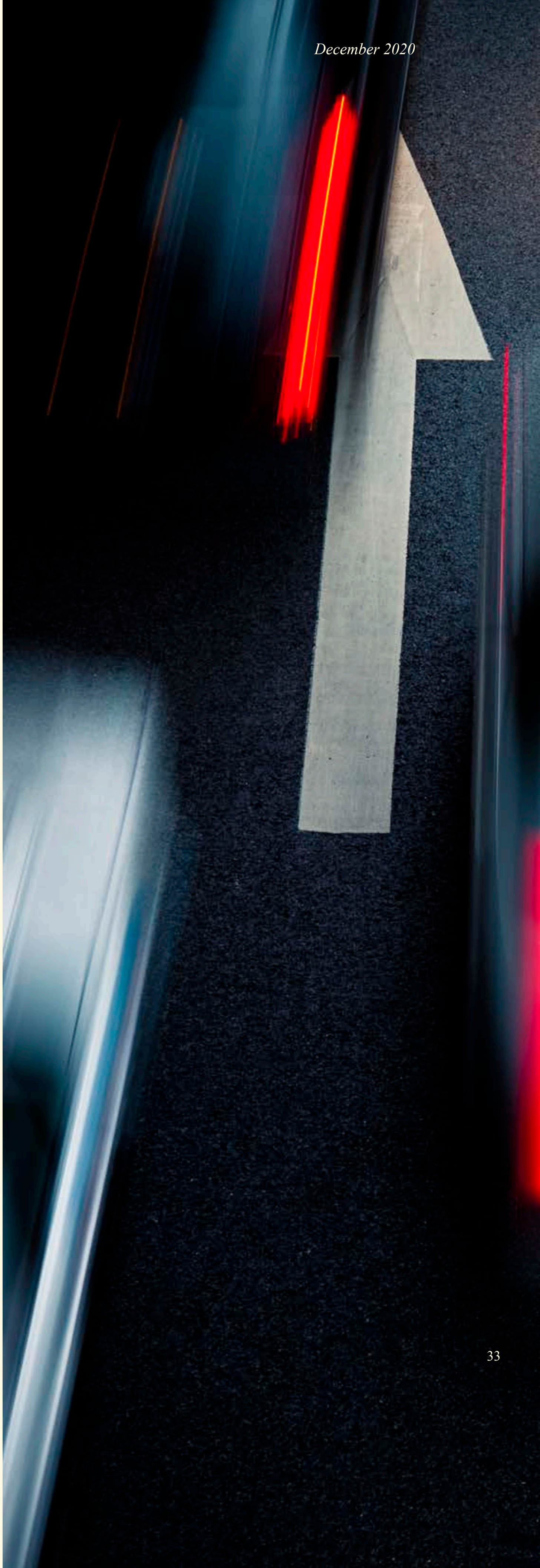
An AV must anticipate the next moves of objects around it and their interactions before they happen. The rules of the road set the pattern of the behaviours and speeds of different users, but people and things don't always follow rules and the accidental movement of one can have knock-on effects. Also, road users deploy all sorts of non-verbal cues to communicate. Getting computers to understand facial expressions, postures or hand gestures is challenging.

Prediction is seen as the hardest problem in autonomous driving. As Chris Urmson, former technical lead of Waymo and founder CEO of Aurora, put it: "If I could wave a magic wand, what part of the system would I make work today to accelerate it [autonomous driving] as quickly as possible ... it's really ... perception forecasting capability. So if tomorrow you could give me a perfect model of what is happening and what will happen for the next five seconds around a vehicle on the roadway, that would accelerate things pretty dramatically."

Planning

It's fiendishly hard to specify rules for every action a car might need to take under any circumstance. Right now, self-driving vehicle companies use a hybrid model, so that when the software fails to act, a human 'safety driver' can take back control. The alternative to this stand-by is programming extreme risk-aversion into the car, for example defaulting to pulling over to stop or seeking alternatives to a confusing or potentially problematic route. One piece of passenger feedback from the Waymo One service in Phoenix, Arizona, is that the car drives too cautiously, for example taking too long to make an unprotected left turn. The next step is to build in algorithms that tell the car when it's being too cautious, when it needs to 'nudge' forward in dense traffic or commit to an action consistently so that other road users can respond correctly.

One way around this difficulty is to get a computerised neural network to copy what humans do, a process known as 'imitation learning'. By feeding the computers lots of human driving data, the neural network will learn what we humans would do in similar circumstances. That said, further complications arise where there are ethical choices, as in the famous who to save? moral quandary known as the 'trolley problem'. The quandary is whether the onlooker should divert a runaway train from its current track, knowing that it will cause the death of one person working on the other line, to save five people working on the existing line. Professor Emilio Frazzoli, founder CTO at nuTonomy (acquired by Aptiv), makes the point that "the real Achilles heel for AVs is we don't know how human-driven vehicles should behave".



For all these challenges, there are grounds for optimism. First, sensors are getting cheaper and better. According to Aurora, LiDAR (light detection and sensing – a sensing system that uses pulsed laser beams to measure depth and distance to build up a 3-D map) can provide high resolution data from as far as 400 metres ahead. Its price has fallen dramatically, from $70,000–$100,000 to under $1,000. It will continue to fall thanks to continued technological progress and economies of scale.

Second, 'deep learning', AI that imitates our brains' neurological patterns, has advanced very rapidly in recent years. Since it requires lots of data to train the network, it will improve as more data are collected. Waymo has reached over 15 billion miles in simulation and 20 million miles in the real world; Tesla has nearly a million cars on the road driving billions of miles; and Lyft offered the public autonomous driving data from its 'level 5' (the highest level of vehicle autonomy) self-driving fleet to help democratise access to self-driving technology.

Third, according to Dmitri Dolgov, chief technology officer at Waymo, the benefits of intra-fleet communications will accrue once more autonomous cars are on the road. If one car 'learns' something about road closures, construction sites, or accidents it can instantly share that information with other cars in the network to allow them to react in advance. Today, there are only a few hundred Waymo cars on the street. With a lot more, perception, prediction and planning could be significantly improved.

Chris Urmson believes that the industry has crossed the '0–1 threshold' – the 'ah ha!' moment when self-driving cars can take to the road without safety drivers. At that point, the AV moves from being a mixed science-engineering product to a mixed engineering-commercialisation product. While further technological development is needed to improve safety, equally important questions include how to continue to scale, how to build the right business model and how the right customer experience could make autonomous cars more useful. Urmson is confident of large-scale autonomous vehicle deployment in 10 years' time.

WHAT WILL DEPLOYMENT LOOK LIKE?

Autonomous cars will initially be deployed in constrained environments. They will first appear on specified urban routes that are well mapped or in closed communities such as army bases, college campuses or retirement villages. Southern California and Arizona, areas with reliable weather where roads are in grids and pedestrians scarce, are likely to see self-driving cars materialise first. In Boston, New York City and other older settlements, driverless cars face more roadblocks.

But it will be hard to sell a consumer a vehicle that only works in some places. This fact, combined with high initial costs, means that most consumers' first experience in a driverless car is likely to be from using a ride-sharing network, such as Uber or Lyft. General Motors and Tesla also intend to offer their own ride-sharing service, to build direct relationships with consumers, and to create a market for their own driverless cars.

Besides, other applications than passenger vehicles, such as long-distance lorries and 'last-mile' delivery robots, are expected to be commercialised earlier. There are dozens of start-ups working on these applications, including those founded by former Waymo engineers such as Kodiak (trucks) and Nuro (delivery robots). The reasons are intuitive: the motorway is an easier environment than a town or a city; trucks and delivery robots do not carry people, so can readily 'sacrifice' themselves in case of emergency; and they don't have to factor in passenger comfort.

DIFFERENT APPROACHES TO AUTONOMOUS DRIVING

It's common to see different approaches to a single problem at the earliest stages of a technology's development. Three aspects are worth highlighting: one relates to the 'philosophical' approach to the technology, another to the technology itself and the third to the strategy to get the technology to market.

I. PHILOSOPHICAL APPROACH

There are two schools of thought on achieving full automation. One holds that shooting straight to level 4 autonomous driving, is flawed. The technology is not ready and there are already substantial incremental bene its to safety and drivers' comfort from 'level 2' automation, which is basically ADAS (advanced driver assistance systems, such as automatic emergency braking, lane departure correction and adaptive cruise control). Most carmakers, including Tesla with its Autopilot function, follow this approach.

By contrast, those currently aiming for level 4, notably Chris Urmson, believe that level 2 is not a stepping stone for level 4, and that the technologies should diverge. He believes that level 2 autonomy is at odds with human behaviour: people quickly trust technology that works. If encouraged to sit back and relax, it's hard for them to dip in and out of driving if a risk emerges.

There's also the challenge of context. Once drivers take back control, they don't always know enough about their surroundings to make the right decisions. So, while the active safety system is an important technology that should be integrated into vehicles, care should be taken on how level 2 is marketed and delivered.

For years, Waymo considered Tesla's Autopilot irresponsible. A fatal collision in May 2016 caused by over-reliance on the technology is often blamed on the company's gung-ho approach. The victim, 40-year-old Joshua Brown of Ohio, was a technology enthusiast so taken with Tesla's Autopilot mode that he posted dozens of videos of himself using it on YouTube. Despite Tesla's software warning him to resume control of the vehicle on seven occasions, he chose not to. His hands were on the steering wheel for only 25 seconds out of 37 minutes during which Autopilot was activated, resulting in him crashing into a lorry.

II. TECHNOLOGICAL APPROACH

Competition in autonomous driving has turned into 'Tesla versus the rest'. Tesla's approach uses cameras and computer vision while the others are based on LiDAR and high-definition (HD) maps. The differences are historical. When Waymo was founded a decade ago, 'deep learning' was not yet popular in the AI research community so cameras and computer vision weren't available solutions. In fact, Waymo only started to apply deep neural networks to pedestrian detection in 2015. Being part of Google meant that Waymo could tap into its parent company's expertise and resources, particularly Google Street View.

The Waymo team believed that, as well as providing directions, a detailed map of every street would hugely benefit autonomous driving. The argument is that if the system only has to process changes to a mapped area 1 per cent of the time, it can be up to two orders of magnitude safer than a system reliant on real-time perceptions of the world. Since other companies in the industry were founded by former Waymo engineers, they all follow a similar approach.

Tesla is the exception. Elon Musk has dismissed the LiDAR and maps combination as “crutches”. He argued that, as humans drove perfectly well without lasers on their foreheads, so too could computers. In his view, LiDAR sidesteps the fundamental problem of visual recognition needed for autonomy. Also, HD mapping is a laborious and expensive process, and systems that rely on maps are brittle and hard to scale up for multiple cities.

Tesla’s position makes sense for a company that can’t afford to install thousands of dollars’ worth of LiDAR equipment on cars it wants to mass produce. Tesla can also leverage the presence of nearly a million cars on the road collecting real-world data in diverse areas to train its computer vision. Waymo is constrained by gathering real-world data via a fleet of only 500–600 self-driving cars, currently only in Texas, California, Michigan, Arizona and Georgia. That’s why Waymo relies heavily on simulation. While this is a critical tool that helps quickly improve and iterate the system, it is questionable whether computers could ever simulate every real-world driving scenario. Musk may be right when he says: “If somebody can produce a driving simulation that matches the reality, that in itself [would be] a monumental achievement of human capability.”

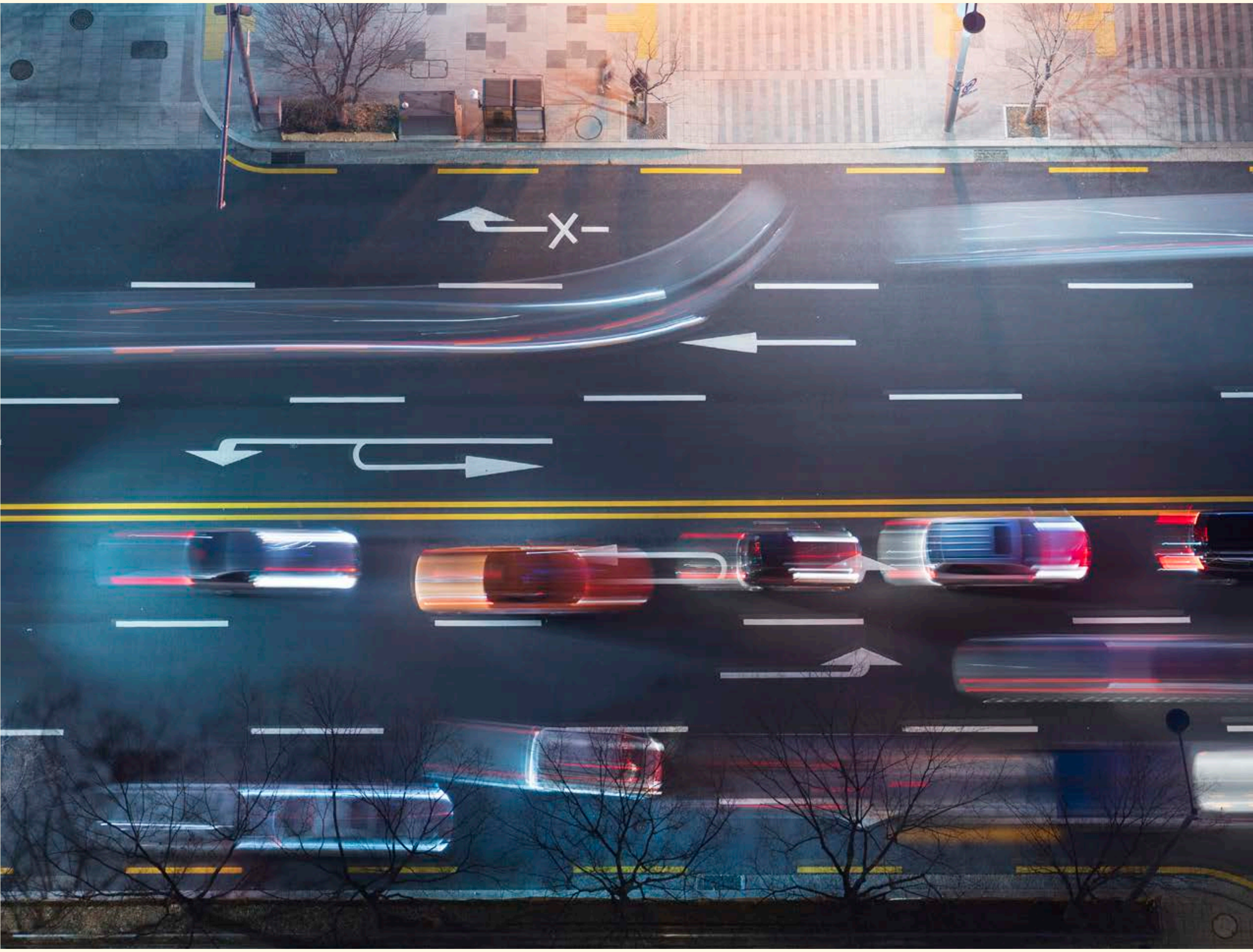
Tesla’s more purist approach seems riskier, though it is more likely to win in the long term if the company can master computer vision before the cost of LiDAR falls to the tens of dollars. Urmson agrees that LiDAR is a “crutch”, but no more so than petrol-powered hybrids are crutches on the path to electric vehicles. Any technology can be replaced by superior technologies in the future. Urmson sees the existing transport model as being so broken that any technology that can come to market and save lives is welcome. Furthermore, although LiDAR is not cheap, he believes that with the right business model (ride sharing), the costs can be absorbed.

III. GO-TO-MARKET STRATEGIES

Today’s autonomous vehicle landscape is a tangled web of partnerships, alliances and investment deals. There are three layers in the AV ecosystem: the cars, the self-driving software and the customer-facing service. Industry players differ over how many layers they are developing themselves.

Companies such as Aurora focus on software only. They want to build the ‘driver’ for driverless cars and rely on partner OEMs, such as Hyundai, for building the vehicles. Aurora sees OEMs as being more than mere “metal benders”. Designing and building millions of vehicles per year and having them operate in a vast range of circumstances for decades is a tough task best left to experienced carmakers, Aurora believes. It meanwhile can focus on building the software, a tremendously difficult task in itself. Besides its highly respected management team, Aurora’s pragmatism in collaborating with others in the ecosystem will increase its chances of success.

Waymo is less clear-cut as, besides software, it is attempting to create its own ride-sharing service with Waymo One, while also providing cars on Lyft’s network. Other companies such as Tesla, GM and Ford are trying to develop the ‘full stack’ or complete infrastructure. Building a commercial full-stack system requires massive resources and a huge range of technical talents. The economics are tricky: developers can’t gradually pay off the cost of development (billions of dollars) across other carmakers as no one wants to buy a competitor’s technology. Manufacturers, such as GM, are also wanting to expand into ride sharing, which is a highly competitive market and it’s not yet clear how it can be profitable. Such firms may be spreading themselves too thin. Nonetheless, despite the difficulties, the returns could be massive if they succeed. Each of the layers they are targeting is a market worth hundreds of billions of dollars.



WHO MIGHT WIN?

It's not yet clear which company's technology and business strategy is better. Put simply: Aurora and Waymo could become the default operating system for autonomous cars, similar to Android for smartphones or Windows for PCs. Those going for the full stack will face more challenges, but there are historical examples in which the control of an entire architecture brings success (for example, Apple and early BlackBerry).

To my mind, Tesla's model may stand the highest chance of success. Consider a comparison with Apple. Despite being a 'closed' system (only working on Apple products), iOS is still successful because it was developed for hardware devices that consumers desire. Apple is both a software and a hardware company, unlike other phone makers, and is capable of making devices that stand out from the crowd. iOS was developed to work exclusively and seamlessly with Apple hardware products, optimising itself to achieve the best user experience.

Isn't this exactly what Tesla is doing? Musk's company makes the electric cars that consumers love and one of its unique selling points is the integration between hardware and software (delivered via over-the-air upgrades).
As we move away from complex cars with simple software to simple cars with complex software, driven by electrification, Tesla with its strong software position could gain massive advantage.

Tesla's position in the electric car market remains strong, but we should be even more excited about Tesla's position in autonomous driving. With the largest fleet, driving billions of miles on real roads, the data volumes must give it a significant edge.

I am sceptical about incumbent car manufacturers developing autonomous driving software. If software is not their expertise and their hardware is not differentiated, the least a car company should do is to develop an integrated model. If history is any guide, a joining of forces between Ford and Volkswagen to develop self-driving software may go the same way as Symbian, the phone operating system developed by Nokia, Motorola and Ericsson that lost out to Android. The fate of Nokia might have been very different if it had abandoned Symbian sooner and followed Samsung's approach in adopting Android.

Similarly, it's better for incumbent car companies to partner with autonomous software companies such as Waymo and Aurora, and focus on what they do best: the mechanical engineering of motorcars.

AFTERWORD

Working on this piece about the future of mobility, drawing on history to imagine the future, has been as enjoyable as it has been fascinating. The challenge for the forecaster is that four fundamental disruptive forces in a trillion-dollar industry – autonomous driving, electric vehicles, shared mobility and urban air mobility – contain so many moving parts. Much of what has been discussed here will only happen at scale a decade from now at the earliest. Many of my attempts to envisage the future will fail miserably but I hope at least they will stimulate interesting new perspectives on the debate.

APPENDIX

New transport terminology: a glossary

ADAS	Advanced driver assistance systems such as automatic emergency braking, lane departure correction and adaptive cruise control
ATM	Air traffic management
AVs	Autonomous vehicles
BEVs	Battery electric vehicles
DEP	Distributed electrical propulsion
EVs	Electric vehicles
eVTOLs	Electric vertical take-off and landing vehicles
HEVs	Hybrid electric vehicle
ICE	Internal combustion engine
LiDAR	Light detection and ranging sensing system, which uses pulsed laser beams to measure depth and distance to build up a 3-D map of the environment
Micromobility	Transportation schemes designed for short distances, using lightweight, usually single-person vehicles, such as scooters and bikes
Non-internal combustion engine vehicles	This encompasses battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs)
OEMs	Original equipment manufacturers (carmakers)
OTA	Over-the-air updates for firmware and software, performed wirelessly rather than via cable
PHEVs	Plug-in hybrid electric vehicles
sUAS	Small unmanned aircraft system
TaaA	Transportation as an asset
TaaS	Transportation as a service
UATM	Urban air traffic management system
Vertihubs	Small airports for eVTOLs
Vertiports	Airports for VTOL aircraft
Vertistations	Pads for one or two VTOLs with minimal infrastructure
VTOLs	Vertical take-off and landing vehicles

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ABOUT THE AUTHOR

THAIHA NGUYEN
Investment Manager

Thaiha is an Investment Manager who joined Baillie Gifford in 2014. She is an analyst in the US Equities Team and has been involved in running the North American portion of the Managed Fund since 2020. She is also a Portfolio Adviser to the Positive Change Strategy. She is a CFA Charterholder and graduated BA (Hons) in Economics from the University of Cambridge in 2014.

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Calton Square, 1 Greenside Row, Edinburgh EH1 3AN
Telephone +44 (0)131 275 2000 / www.bailliegifford.com