October 2016

AN INTEGRATED PERSPECTIVE ON THE FUTURE OF MOBILITY

McKinsey&Company

Bloomberg NEW ENERGY FINANCE

An integrated perspective on the future of mobility

October 2016

EXECUTIVE SUMMARY

To view a city from above is to observe a world in motion. Trains carry people to and from work; taxis circulate in abstract patterns; trucks deliver goods and carry away garbage; pedestrians hustle down city blocks; cyclists zip through traffic. Mobility is the lifeblood of our cities and essential for urban life.

Yet, our desire for mobility has consequences: cities can be noisy, congested, and prone to smog. Far too many urban residents spend hours stuck in traffic; no one can escape airborne pollution. Mobility is also a critical economic factor, both in its own right and as the means of providing the goods and services that are the foundation of economic life. Finally, mobility matters to people, whether this is getting to work or school with ease, visiting friends and relatives, or simply exploring one's surroundings. In relatively few places, however, does the reality of what is available match the public's aspirations for safe, clean, reliable, and affordable ways to get from A to B—and back again.

We believe, however, that the way people move around the urban environment is primed for dramatic change. Already, new business models, as illustrated by organizations such as Uber and Didi Chuxing, are changing traditional mobility patterns. Technological innovations in the form of electrification, connectivity, and autonomy are on the horizon. Increasing urbanization and the growth of "megacities" with more than ten million people provide the conditions for change.

What, then, will be the future of urban mobility? A new report, An integrated perspective on the future of mobility, seeks to answer that question. To do so, it explores how a number of existing social, economic, and technological trends will work together to disrupt mobility at the local level.

The result is a radically different future based around three models of advanced urban mobility that are achievable by 2030. Inevitably, individual cities will make different decisions, based on specific local conditions, and go in different directions—and, globally, mobility systems in 2030 will on average look very much like they do today.

Yet there is a cluster of some 50 urban areas that could lead the way toward one of the three advanced-mobility models. These areas have the potential to demonstrate the profound effects of mobility innovation on everything from power systems to the use of public space, while simultaneously introducing a new city dynamism.

The mobility systems of the future are likely to be very different from what exists in most of the world today. The individual traveler is at the heart of this evolution, so consumers will need to be open to adopting new technologies and services. However, both the public and private sectors will have roles to play in paving the way.

THE VALUE OF AN INTEGRATED PERSPECTIVE

Numerous trends, ranging from energy decentralization to the Internet of Things, are likely to come together to create drastic changes in mobility systems over the next 10 to 15 years.

Predicting the future is perilous. In this case, however, two factors point us in this direction. First, several key mobility trends—electrification, shared mobility, and autonomy—are poised to take off. The costs of a lithium-ion battery pack fell 65 percent from 2010 to 2015, and they are expected to drop below $100 per kilowatt-hour over the next decade. Car-sharing and ride-hailing services are already at work in hundreds of cities around the world, enabled by smartphones and backed by substantial venture capital. An array of established automotive and technology companies, as well as intriguing start-ups like nuTonomy and Zoox, are testing self-driving capabilities, with the aim of providing door-to-door travel, with no human intervention required.

Second, and just as important, trends in related areas reinforce one another. Urbanization is expected to increase average city density by 30 percent over the next 15 years, stretching existing systems as demand rises. Urban planners and residents are putting livability and sustainability higher on their agendas. Increased connectivity is opening the door to multiple shared-mobility options and could also help to smooth traffic flows.

Looked at in isolation, each trend is significant. Their combined impact, however, will prove to be truly powerful. For example, more shared mobility could boost electric-vehicle (EV) sales because shared vehicles are used more intensively, improving the economics of ownership. In turn, higher EV production could accelerate innovation and reduce the cost of batteries. That opens up applications in adjacent systems, such as distributed storage. And the plummeting cost of distributed power generation could improve the greenhouse-gas abatement potential of EVs, because they would get more of their juice from low-carbon sources. In these and other cases, there is a powerful dynamic of mutual reinforcement at work. It's not just one oar in the water—but lots of them, all pulling in the same direction.

THE FUTURE OF MOBILITY IN THREE MODELS

Today, a small number of cities, such as Amsterdam, Singapore, and Stockholm, are singled out as having effective mobility. With varying degrees of emphasis, they have efficient public transit, encourage cycling and walking, and have managed to limit congestion and pollution. By 2030, we expect a number of additional systems to be at the leading edge of the next phase of advanced mobility.

In broad terms, the best will combine shared mobility, autonomy, and electrification with integrated energy systems, public transport, and infrastructure. In specific terms, cities will navigate these possibilities differently. Local conditions—such as population density, wealth, the state of road and public-transit infrastructure, pollution and congestion levels, and local governance capabilities—will determine what changes occur, and how quickly.

For the near future in cities leading the advance, we envision three mobility trajectories, with trends such as sharing, autonomous driving, and electrification all moving forward at a different pace. Each is suited to a specific type of metropolitan area, whether it be a dense developed city, a suburban sprawl, or an emerging metropolis.

Clean and Shared. Delhi, Mexico City, and Mumbai are examples of densely populated metropolitan areas in developing countries. They are all experiencing rapid urbanization, and they all suffer from congestion and poor air quality. For cities like these, the widespread use of self-driving cars may not be an option in the short or medium term, because of poor infrastructure, interference from pedestrians, a variety of vehicles on the road, and a lack of clear adherence to traffic regulations. The approach most likely to apply is a shift to cleaner transport, in the form of EVs, while also limiting private car ownership, optimizing shared mobility, and expanding public transit. In conjunction with some connectivity and autonomy, traffic flows and safety could be enhanced. According to our research, if relevant Asian cities move toward this model, by 2030 shared vehicles could account for almost half of passenger miles due to a combination of greater utilization and more passengers per trip.

Private Autonomy. There are many cities around the world where development and commuting patterns have increased sprawl significantly. In such cities, having a car is all but essential. That will likely remain the case for the foreseeable future. However, there are genuine costs to this way of life; congestion in Los Angeles costs the city an estimated $23 billion per year.[1]

To do better, we envision consumers in these cities embracing new vehicle technologies, such as self-driving and electric vehicles. Dedicated road space, for example, could be allocated to self-driving vehicles. Connectivity could make it easier to implement demand-driven congestion charges, which could increase road capacity while limiting new construction. Car sharing and ride hailing could emerge as complementary options but would not replace the private car on a large scale.

There is a possible drawback to this scenario: with lower marginal costs to travel an extra mile in an EV, and without requiring a driver's attention thanks to autonomy, the demand for mobility could increase and thus add to congestion. Passenger miles traveled could grow 25 percent by 2030, with the majority attributable to additional autonomous travel in private vehicles.

Seamless Mobility. This is the most radical departure from today's reality. In the near term, it is likeliest to emerge in densely populated, high-income cities such as Chicago, Hong Kong, London, and Singapore.

In this system, mobility is predominantly door to door and on demand. Travelers have many clean, cheap, and flexible ways to get around, and the boundaries among private, shared, and public transport are blurred. Mobility is delivered through a combination of self-driving, shared vehicles, with high-quality public transit as the backbone. EVs become far more common, spurred by economics, consumer interest, incentives, and the creation of low-emission zones. And all this is enabled through the use of smart software platforms that manage multimodal traffic flows and deliver mobility as a service.

1 INRIX National Traffic Scorecard Annual Report, Centre for Economics and Business Research and INRIX, 2013, inrix.com.

In a seamless-mobility system, people would potentially travel more—likely by 20 to 50 percent—because it is cheap and easy. However, the number of cars would likely remain the same or decline, due to the high level of sharing and significantly higher utilization. EVs could account for as many as two-thirds of vehicles on the road, while those capable of self-driving may exceed 40 percent.

KNOCK-ON EFFECTS

Combined, these three models could apply to around 50 urban areas globally—representing some 500 million people—but the majority of cities are expected to develop more incrementally. Cities are most prone to accelerated uptake based on a ranking of metrics, including income, population, government effectiveness, level of public-transit development, congestion, and pollution. Each model can deliver significant benefits, such as saving time, reducing congestion, and improving air quality. We quantified the possible cumulative societal benefits of each model until 2030: $2,800 per person for clean and shared, mostly in the form of improved safety; $3,300 for private autonomy (boosting 2030 GDP by 0.9 percent); and $7,400 per person for seamless mobility (boosting 2030 GDP by 3.9 percent).

To take full advantage of these benefits and avoid the pitfalls, the public and private sectors would need to work together, while city officials would need to be willing to reconsider how they conduct their own business. For example, sharing and autonomy could cannibalize public-transport systems, and cities may consider whether it makes sense to partially shift ownership to private shared-mobility providers. Governments may also want to rewrite fuel and power taxation and to use the opportunity of connectivity to revisit how infrastructure is priced.

These new mobility models will also require a number of sectors to do some hard thinking in order to find new opportunities—and to avoid some major risks. In the power sector, for example, EVs could represent 3 percent of electricity demand globally, and nearly 4 percent in Europe, by 2030. Differentiated time-of-use rates and investments in charging infrastructure could help utilities to mitigate negative grid effects from EV charging. EVs could also play a role in reducing curtailment as solar-photovoltaic and offshore-wind generation increase.

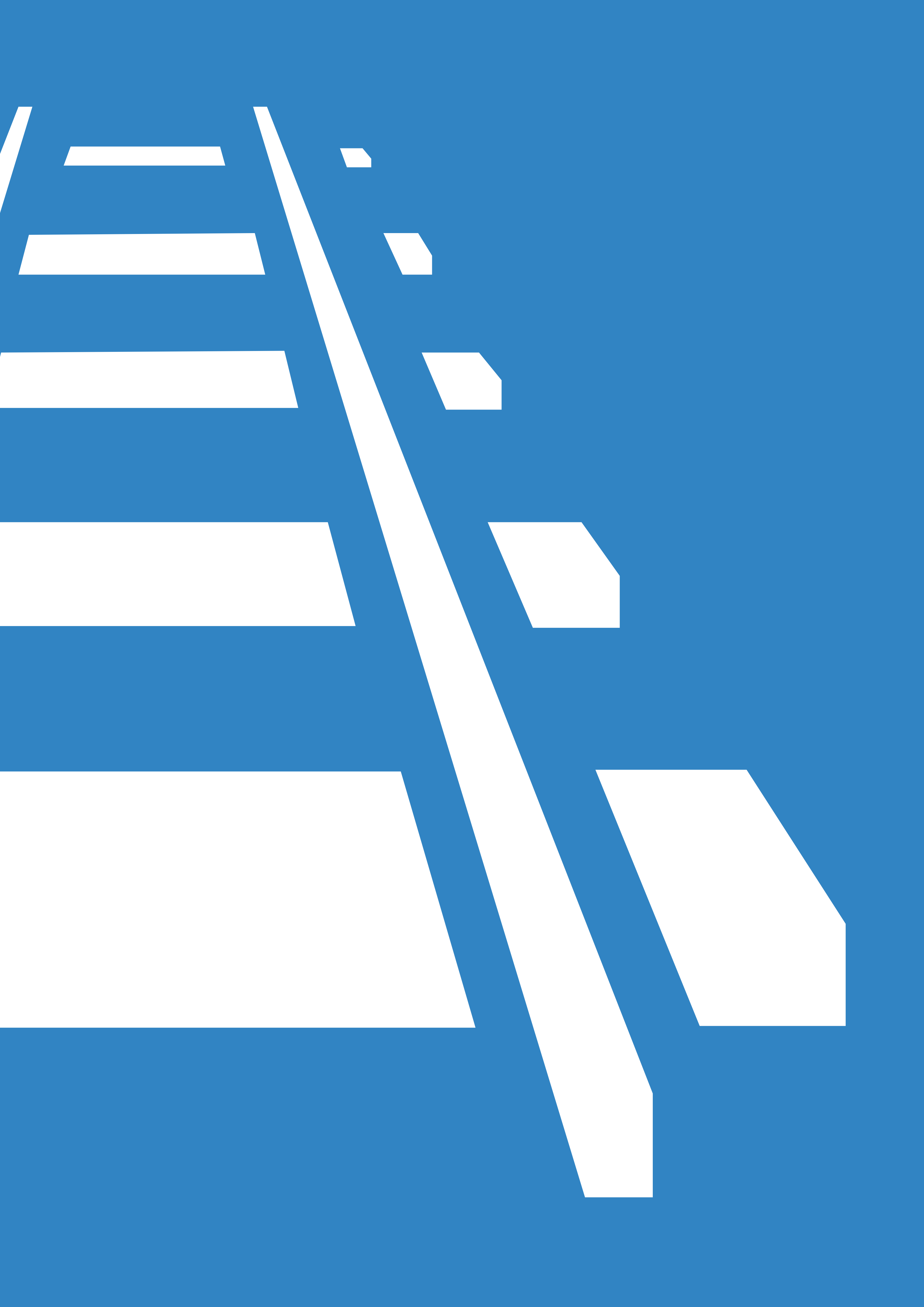
The automotive sector faces a future that could be fundamentally different from its past and may need to consider moving from using a pure product-ownership model toward providing a range of transportation services. EVs, of course, are a direct threat to the internal-combustion engine. Gasoline retailers should be thinking through how to further monetize current assets and how to capture future value through new propositions around convenience retail, the connected car, fleet services, and electric charging. For tech companies, the three mobility models offer a world of opportunity. As the use of connectivity and autonomy increases, so, too, does the need for sensors and software. The data generated could be highly valuable in and of itself.

MOVING INTO THE FUTURE

In cities from Tokyo to Vancouver, the reality of changing mobility is already apparent. More shifts are coming. These changes will allow people to travel more efficiently, more cheaply, more often, and in different ways. But the future is not set, and there is a strong role for the public and private sectors to help avoid pitfalls associated with increased congestion, air-quality concerns, and other potential negative outcomes.

To best capture the benefits, the public and private sector—at a local and global level—need to prepare for the future, not wait for it. Governments may want to anticipate these new mobility models by crafting regulations consistent with consumer-friendly technological developments that also promote larger public goals, such as clean air and reduced congestion. They need to think ahead, with regard to both replacing the possible loss of fuel-tax revenue and reviewing their connection with the private sector. Strong partnerships that make it easy to blend public transit and private mobility will likely produce the best solutions.

Why does this matter? Because getting mobility right could be a significant competitive advantage for cities. This shift can help clear the air of pollution and reduce traffic deaths. It is an opportunity to improve the quality of life—day in, day out—for billions of people.



INTRODUCTION

Mobility is the lifeblood of our cities: every day, metropolitan transport systems bring people to work and to play; vehicles deliver food and essential goods, and carry away waste. Mobility is what keeps our urban centres functioning. At the same time, mobility is a critical factor in every country's economy both as an important sector in its own right and as a significant growth engine (or blocker) for many other industries, including the automotive, civil engineering, energy, technology, and telecom sectors.

Today, new business models introduced by companies such as Uber and Lyft are changing the way we view mobility systems, while technological innovation in the form of electrification, connectivity, and autonomy is set to bring additional opportunities to business and urban areas. There could also be advantages for wider society: advanced transport could resolve environmental issues and improve citizens' health. Too often, though, our mobility systems cease to function efficiently: streets become clogged – blighted by congestion and pollution – and less safe as increasing numbers of vehicles stress the available infrastructure.

These issues will come more sharply into focus as cities and suburbs expand. By 2030, 60 percent of the world's population will live in metropolitan areas.[2] The number of megacities with more than ten million people will continue to grow and with them traffic density, energy consumption, pollution, and congestion.

This combination of metropolitan expansion and rapid innovation will inevitably drive significant change – but what will the future of mobility systems look like? This report seeks to uncover some of the key trends by addressing the following questions: how will advanced mobility take shape in different urban environments? Will society be better or worse off, and what will the main drivers be? Do changes in local mobility systems have global impact? If we are to reap the economic and societal benefits of advanced mobility systems, how could we accelerate our move towards them?

2 McKinsey, Automotive Revolution – perspective towards 2030, January 2016.

CONTENTS

MANY FAST-MOVING TRENDS AFFECT MOBILITY

The first part of this chapter discusses various fast-moving trends that influence mobility systems. Some are core mobility trends – vehicle electrification, shared mobility and autonomous driving – while ancillary trends include connectivity and the Internet of Things, urbanization and other macroeconomic trends, and the decentralization of power generation and storage.

On an individual basis, each of these trends will have a major impact on specific aspects of the mobility sector. More significant, however, is their combined impact and potential to reinforce and magnify one another, which in turn affects the broader mobility system. Thus, later in this chapter we explore these reinforcing effects and discuss why it is important to take an integrated perspective.

VEHICLE ELECTRIFICATION

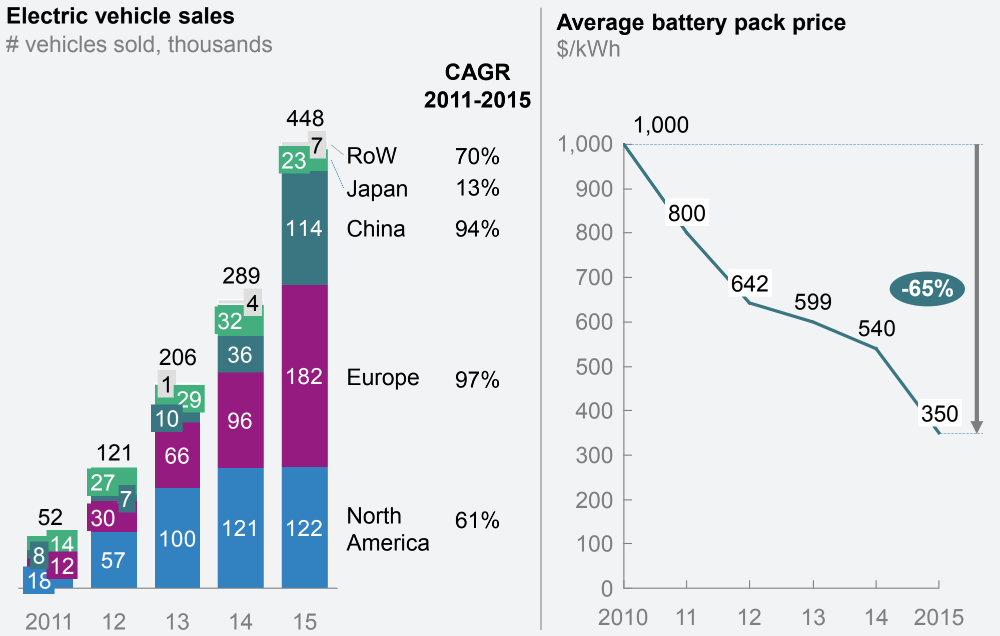
Global electric vehicle (EV) sales have risen quickly over the past five years, fueled by generous purchase subsidies, falling battery costs, fuel economy regulations, growing commitments from car companies, and rising interest from consumers. Sales rose 60 percent in 2015 alone to nearly 450,000, up from 50,000 in 2011 (Exhibit 1). While many of the early adopters were in the United States, Europe and China have since ramped up significantly. In most markets, though, EVs still represent fewer than 1 percent of total vehicles sold, but pockets of much higher penetration exist – including Norway, where electric vehicles represent more than a quarter of new vehicle sales.

The average price of lithium-ion battery packs used in EVs fell 65 percent over the period 2010–15 – from $1,000/kWh to $350/kWh – and continues to drop, driven by scale, improvements in battery chemistry and better battery management systems.[3] Costs have fallen further and faster than many had expected. They are now forecast to drop below $100/kWh in the next decade, and could possibly fall as low as $50/kWh–$60/kWh in the longer term, if semi-solid electrolytes and silicon-infused anodes are implemented, along with

3 Throughout this report, the term "Electric Vehicle" or "EV" is used for battery-electric vehicles and plug-in hybrid electric vehicles. Hybrid electric vehicles without a plug are not addressed.

EXHIBIT 1

ELECTRIC VEHICLE SALES HAVE RISEN AND BATTERY COSTS HAVE FALLEN RAPIDLY



NOTE: Plug-in hybrid electric vehicles and battery-electric vehicles; light duty vehicles only. Excluding low-speed vehicles and hybrid electric vehicles without a plug. Battery prices are an average of BEV and PHEV battery packs

SOURCE: Bloomberg New Energy Finance

other advancements that come with economies of scale and purchasing power.[4]

These changes will make private EVs competitive with comparable internal combustion engine (ICE) vehicles by the mid-2020s on a total cost of ownership basis, and even earlier for high-utilization vehicles such as delivery fleets and taxis. Already today, consumer interest is rising: Tesla's Model 3 launch in 2016 attracted over 400,000 reservations and deposits for a vehicle that will not be available until late 2017 at the earliest.

Global and national fuel economy regulations are playing a major role in pushing hybridization and electrification of the vehicle fleet: the United States, the European Union and China in particular have set aggressive targets for automakers to meet. Much of this will be achieved through improvements to ICE vehicles, but this is likely to become increasingly difficult as standards tighten further in the 2020s, and all types of electric vehicles will benefit from the growing emphasis on improved fuel economy. Car companies have responded to these pressures and are dramatically increasing the number of plug-in and electrified vehicles they intend to offer over the coming years.

SHARED MOBILITY

Shared mobility has evolved rapidly over the past few years, as ride-hailing services now vie with more traditional car-sharing and car-pooling providers.[5] Companies such as Uber and Lyft have enjoyed rapid uptake and compete head-to-head with local taxis, but increasingly also public transit and car ownership. Exhibit 2 highlights a few examples of shared business models, from car sharing to more specialized applications that allow drivers to monetize their own cars when idle.

Ride hailing in particular has grown rapidly, with a large number of venture-backed start-ups springing up around the globe. Investments into ride-hailing companies topped $11 billion in 2015, and total $21 billion to mid 2016 (Exhibit 3). Many are currently competing heavily for market share in contested regions. China, with the largest number of urban commuters in the world and low vehicle-ownership rates, has

4 Bloomberg New Energy Finance estimates based on bottom-up modeling of a large scale lithium-ion battery pack manufacturing plant.

5 Bloomberg New Energy Finance, Carsharing in Europe: automakers take the spotlight, September 2016.

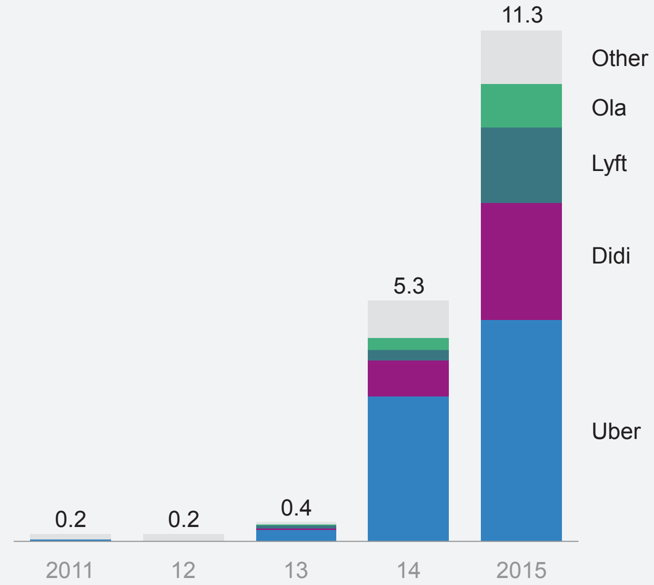
EXHIBIT 2

Company type	Example companies	Description	Flexible desti-nation/return?
Operator car sharing	zipcar	Offers a fleet of cars with fixed parking spots that can be rented by the hour	✗
	CAR2GO	Offers a 'floating' fleet of cars that can be located on an app and rented for one-way trips within defined city centers	✓
On-demand ride-hailing	UBER	Matches private drivers with passengers for intra-city trips on demand	✓
	Gett	Matches licensed taxis with passengers through a mobile app	✓
Peer-to-peer car sharing	easyCar club	Peer-to-peer marketplace that matches car owners with renters on an hourly basis	✗
	FlightCar	Peer-to-peer marketplace allowing car owners to rent out their vehicles from airport parking, mainly competing with car rentals	✗
Peer-to-peer ride sharing	BlaBlaCar	Matches drivers with passengers for intercity drives	✓
	scoop	App-based matching of pre-booked commutes with people working in the same area	✓

EXHIBIT 3

INVESTMENTS IN SHARED MOBILITY HAVE TAKEN OFF

Investments in ride-hailing companies
$ billion



SOURCE: Bloomberg New Energy Finance; Crunchbase experienced particularly high growth. Local ride-hailing company Didi Chuxing, following its acquisition of Uber China, now has over 50 million active users and provides more than 100 million rides a week.

AUTONOMOUS DRIVING

Autonomous driving technology is advancing rapidly due to road safety concerns, potential cost savings, and technology innovations. The current state of technology along with expected improvements and the already-announced plans of several large OEMs and others, make it likely that full self-driving vehicles – level four autonomous driving capability – will be available by the mid-2020s. Level four is the highest level of autonomous driving technology, according to the US National Highway Traffic Safety Administration categorization (Exhibit 4).

Automakers and new market entrants are competing to roll out the technology for widespread use. Tesla and Google's early autonomy efforts attracted significant attention, and Tesla has announced that its customers would be able to summon a car across the country by 2018. From public sources it is known that managers at incumbent manufacturers such as BMW, Ford, General Motors, and Volkswagen are expecting the first self-driving cars (typically L3 or L4) on the market in 2020–21. Additionally, numerous other players have announced or are already running pilots (Exhibit 5). Just as significant is the understanding that these statements are backed by substantial investment, in-house initiatives, and partnerships with insurers, telecom companies, and start-ups.

Autonomous driving capability is a computational problem, solved at IT pace

Automotive-grade in-vehicle computers are powerful: based on the architecture commonly found in supercomputers, they are already capable of merging data from multiple sensors to achieve full surround vision, a key component in the development of fully autonomous vehicles.

As part of the effort to achieve full autonomy, various start-ups are working on components ranging from imaging and sensing hardware to communication modules for wireless connectivity, mapping, and driving data storage, as well as rental and insurance services optimized for a world with autonomous cars. These companies have been extensively courted not only by OEMs but also by technology and telecommunication

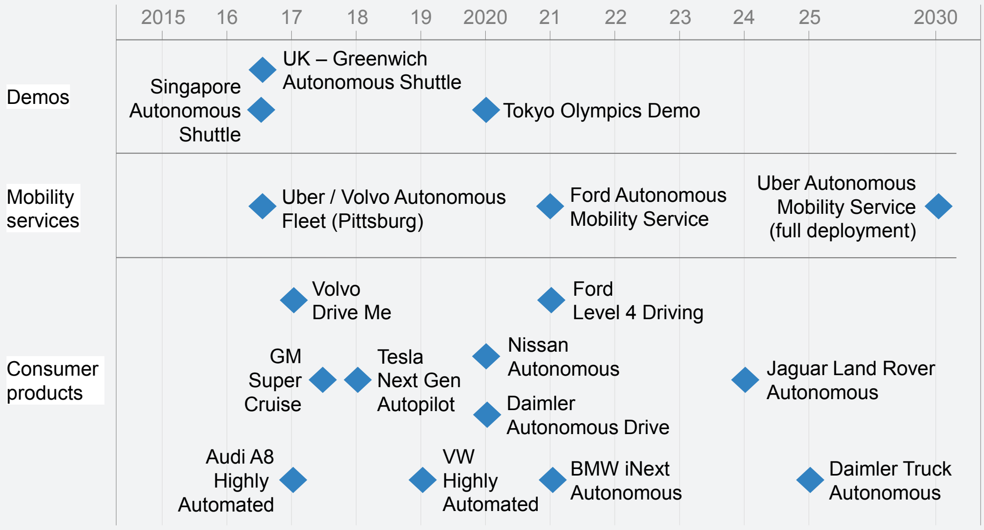
EXHIBIT 4

Level 01	Level 02	Level 03	Level 04
Function specific automation	**Combined function automation**	**Limited self-driving automation**	**Full self-driving automation**
Covers one or more specific control functions	At least two primary control functions designed to work in unison. Driver available and in control most of the time	Vehicle is in control most of the time, but the driver is expected to be able to occasionally retake control with reasonable transition times	Vehicle is in full control and driver/passenger is not expected to take control at any point
Example Automatic assisted breaking	**Example** Adaptive cruise control combined with lane management	**Example** Google's self-driving car	**Example** None commercialized as yet

EXHIBIT 5

AUTONOMOUS DRIVE LAUNCHES

Timeline of events



SOURCE: Press search; Company websites

players; examples include a $2.4 billion cloud-based platform acquired by Verizon and a LIDAR and 3D mapping solution backed by Samsung (Exhibit 6).

Fully autonomous cars are not just another driver-assistance feature

Full autonomy is likely to be taken up quickly, both by fleets and consumers, and to rapidly establish itself as a new technology platform for innovative businesses and applications, some of which we cannot yet imagine. Ride-hailing businesses are known to be keenly anticipating, and in some cases, actively participating in the development of fully self-driving cars, as autonomy can cut labor costs. The same holds true for trucking companies and shorter-range delivery firms.

Self-driving vehicles have the potential to free up time for many of us, during commutes and other routine trips. Reconfigured interiors and new in-vehicle entertainment systems are likely to be just the start of keeping occupants comfortable on journeys. Additionally, if cars are allowed to operate without occupants, a significant proportion of trips that today require a driver – for instance, to pick up or drop off family members or friends – could be made without one. As a consequence, families might find it more convenient to operate a single car that shuttles from one ride to another instead of owning multiple vehicles. Parking concerns may then be replaced by more pressing questions to redefine what a car is allowed to do, as it becomes cheaper to let a car roam or park further away rather than pay for prime real estate.

However, these new operating models may cause vehicle miles to increase, leading to increased congestion and, for ICE vehicles, additional emissions.

CONNECTIVITY AND THE INTERNET OF THINGS

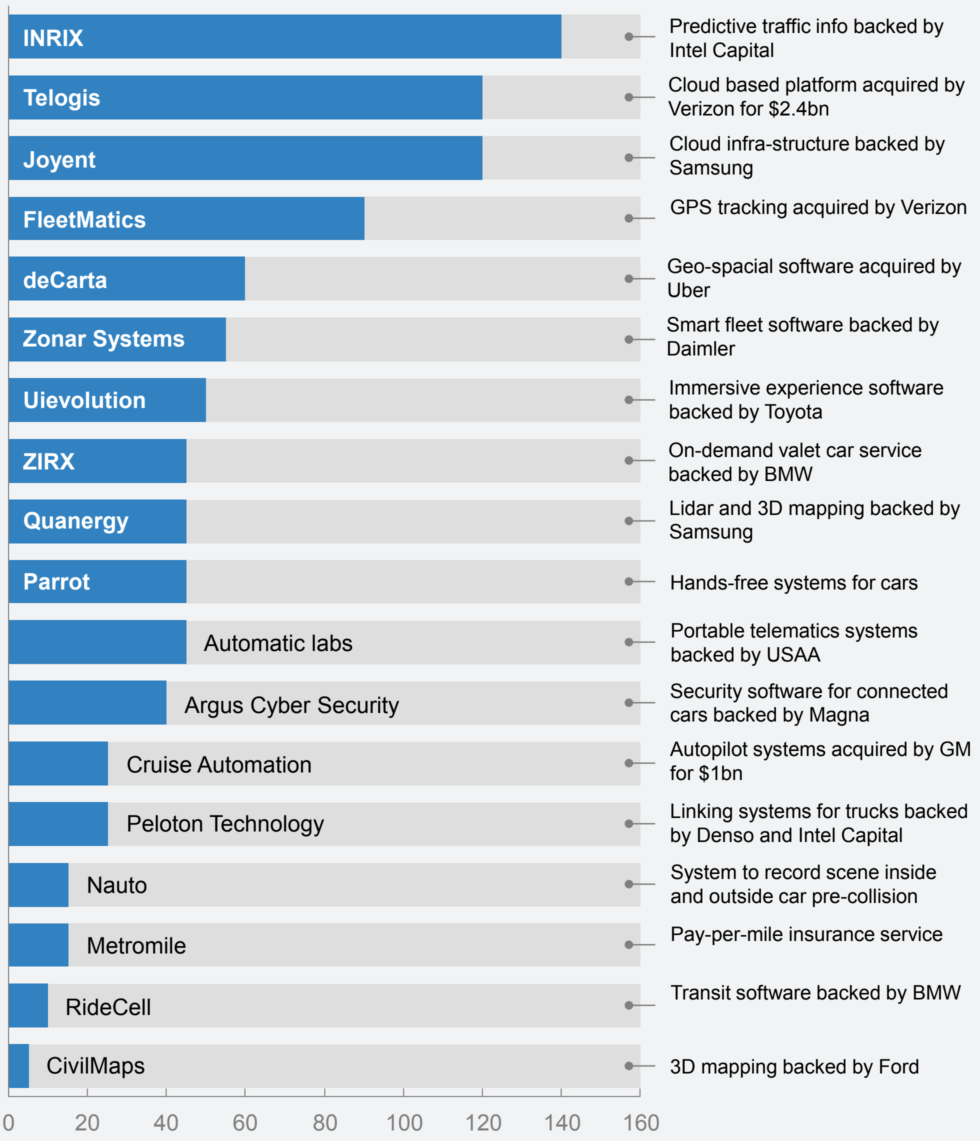
The "Internet of Things" (IoT) is defined by three characteristics: the presence of sensors, connectivity to networks, and the ability to rapidly compute incoming data.[6] IoT applications are quickly spreading into mobility. Meanwhile, infrastructure connectivity and other "hardware" elements enable further smoothing of traffic flows. Volvo is piloting a machine-to-machine social network that enables cars to warn one another about road conditions and other hazards. Tesla updates its vehicles smartphone-style – remotely over the air – including for such critical updates as automatic

6 McKinsey, Unlocking the potential of the Internet of Things, June 2015.

EXHIBIT 6

INVESTORS HAVE HIGH INTEREST IN COMPANIES DEVELOPING AV TECHNOLOGIES

Acquisitions of and investments in autonomous driving capabilities
$ million



SOURCE :Bloomberg New Energy Finance; Crunchbase

emergency braking, an approach which may spread within the automotive sector.

Customer demand for car connectivity is increasing rapidly: the share of consumers willing to switch their car brand for better connectivity reached 37 percent in 2015, with China particularly keen at 60 percent.[7] Contrary to many expectations, data privacy does not appear to be a major obstacle, with 76 percent of customers willing to send vehicle data to manufacturers.

7 McKinsey, Competing for the Connected Customer – perspectives on the opportunities created by car connectivity and automation, September 2015.

Note, however, that the connectivity trend does not apply only to vehicles. Especially in developing countries, growing smartphone penetration makes shared business models more easily accessible. For example, in Kenya the mobile payment penetration rate is more than 70 percent.[8] Mobile data usage in India is expected to increase from 1.8 Exabytes per month to 20.6 Exabytes per month in 2020.[9]

PUBLIC TRANSIT

Across the world, cities are enhancing and expanding public transit networks. Eventually, autonomous features may reduce operating costs while network optimization can yield significant benefits in terms of reliability and capacity. New shared-vehicle networks solutions could help cities reduce the cost of underperforming public transport routes, as is being explored in Florida, where Pinellas Park's transportation agency is offering 50 percent discounts on Uber rides along two bus routes that were recently eliminated. Furthermore, on-demand services provided by minivans and buses create the opportunity to improve first- and last-mile options, and so channel more passengers onto existing routes.

LIVEABILITY AND SUSTAINABILITY

In many metropolitan areas, concerns over air quality have grown – in particular, the health impacts of particulate and NO_x emissions. Metropolitan areas such as Greater London and Amsterdam are continuing to introduce a wide range of measures that favor low-emission vehicles over the coming years.

In addition to air quality, urban planners are increasingly seeking to focus on liveability and sustainability, while reclaiming urban space and revitalizing cores with inner-city parks. Investments in cycle lanes and public infrastructure may reinforce a shift away from car ownership, as using a mix of public and shared transit becomes a more compelling option.

URBANIZATION AND OTHER MACROECONOMIC TRENDS

Urbanization and population growth will increase the average density of metropolitan areas by at least 30 percent between 2015 and 2030.[10] As a consequence, in developing dense metropolitan areas demand for mobility may nearly double if passenger miles travelled per person remain stable and car ownership follows its historical relationship with GDP growth. This will certainly put significant additional strain on mobility systems that are already stretched today, reducing the attractiveness of private car ownership.

Local policy around liveability and sustainability may also accelerate electrification of the vehicle parc, further enforced by national and global emission regulations and support for renewable energy.

DECENTRALIZATION OF THE ENERGY SYSTEM

In the past decade, the cost of renewable power generation has decreased significantly. If costs continue to decline rapidly, intermittent distributed generation, as well as batteries and demand response assets, will play an important role in global power-generation over the next 15 years (Exhibit 7).[11] This trend could accelerate electric vehicle uptake by lowering power prices at peak times and resolving specific grid issues that currently inhibit electric vehicles locally. In some cases it may establish a maximum price that consumers will pay to charge their vehicles. Managed EV charging can also prevent curtailment of renewable generation during peak hours.

In sunny areas, residential PV and storage systems could mitigate the negative impacts of EV charging on the grid as consumers opt to charge using their own generation facilities rather than at retail electricity rates. An illustrative example of a residential household in San Diego, California, shows that a distributed generation and storage system could provide electricity well below average residential prices for grid power. Assuming a 6kW solar PV system, coupled with a 10kWh battery storage system, the levelized cost of electricity for the combined system could be around \$0.10/kWh–\$0.12/kWh by 2030. This is below current residential power prices in California, which were \$0.174/kWh on average as of May 2016.[12] A system of this size could provide 70–90 percent of the electricity needs for average

8 McKinsey, Sub-Saharan Africa: A major potential revenue opportunity for digital payments, February 2014.

9 Cisco, VMI Mobile Forecast 2015 – 2020.

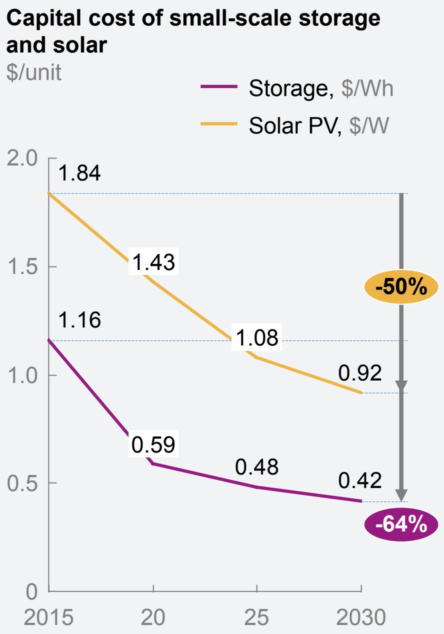
10 CityScope, McKinsey Global Institute.

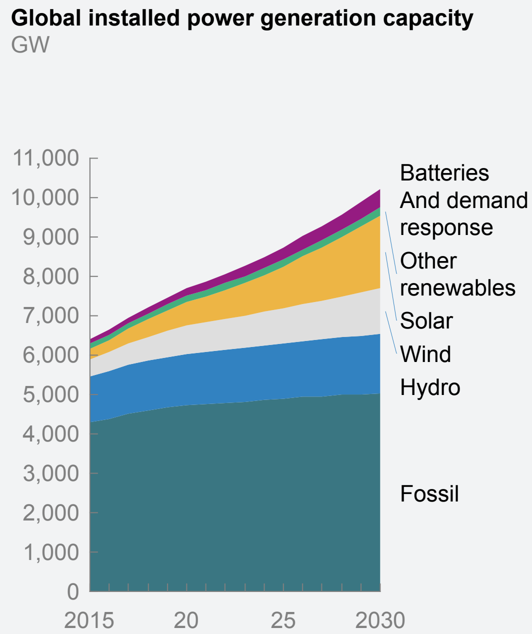
11 Bloomberg New Energy Finance, New Energy Outlook, June 2016.

12 EIA.

EXHIBIT 7

RENEWABLE PENETRATION INCREASES AS THE COST OF DISTRIBUTED GENERATION AND STORAGE FALL





NOTE: Residential system costs
SOURCE: Bloomberg New Energy Finance

daily driving and residential consumption, while still maximizing home consumption from the PV system.[13] Distributed PV and batteries may also be used for workplace parking lot charging, and in other areas without space constraints.

It is worth noting that the $0.12/kWh charge cost of a distributed combined system is still higher than many off-peak grid rates, particularly those aimed specifically at EV owners. However, as the penetration of solar PV on the grid rises, the daytime power price will continue to fall, pushing prices well below the levelized cost of electricity of the distributed system outlined above.

REINFORCING EFFECTS AND THE NEED FOR AN INTEGRATED PERSPECTIVE

To understand the future of mobility systems, we must evaluate these individual trends together. In this section we will detail eight key areas of mutual reinforcement between trends, which over the next 15 years may play out at a different pace and scale across mobility systems (Exhibit 8).

1. An uptake in shared mobility will accelerate vehicle electrification

Relative to ICE cars, electric vehicles have high upfront costs – the battery – offset by lower marginal costs: electricity is generally a fraction of the price of gasoline and maintenance costs are lower. Consequently, the higher mileage driven by shared vehicles helps advance the point at which electric vehicles become cost competitive.[14] Vehicles used for ride-hailing accumulate a similar or even higher annual mileage than taxis – typically around 70,000 miles – versus 13,500 miles for an average private vehicle in the United States (Exhibit 9).[15]

At the same time, the higher mileage experienced by a typical ride-hailing vehicle will also reduce its lifespan, accelerating the transition to next-generation vehicles that are both electric and autonomous. For every 10 percent increase in shared mobility as a proportion of the total, the cumulative number of electric vehicles sold in 2015–30 could increase by up to 5 percent.[16]

13 Bloomberg New Energy Finance PVStore model. Assuming household consumption of 8,400kWh/year, average driving distances of 9,400–13,600 miles per year and conversion efficiency of 0.3kWh/mile.

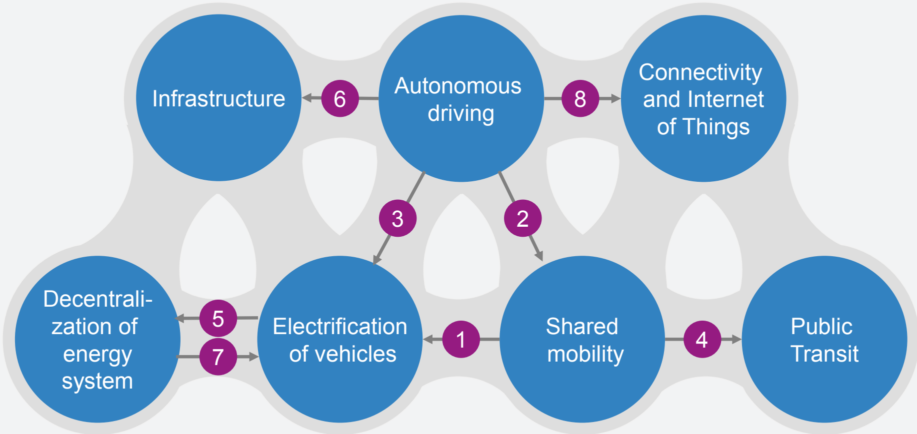
14 BNEF and McKinsey estimates.

15 New York City Taxi & Limousine Commission, 2014 Taxicab Fact Book.

16 McKinsey analysis.

EXHIBIT 8

Key trends



Reinforcing effects

1. An uptake in shared mobility will accelerate electrification, as higher utilization favours the economics of electric vehicles
2. Self-driving could merge shared mobility business models into a single proposition competitive with private car ownership and public transport
3. Self-driving – private and shared – vehicles are likely to increase mobility consumption in which case electric vehicles offer lower total cost of ownership
4. An uptake in shared mobility will affect public transit
5. Electric vehicle production at scale would accelerate battery cost reductions, with multiple effects
6. Self-driving electric vehicles will have different usage and hence requiring different requirements for charging infrastructure
7. Increasing renewable power generation will make electric vehicles more attractive as a means to reduce the carbon intensity of the transport sector
8. Self-driving vehicles might accelerate the uptake of IoT applications

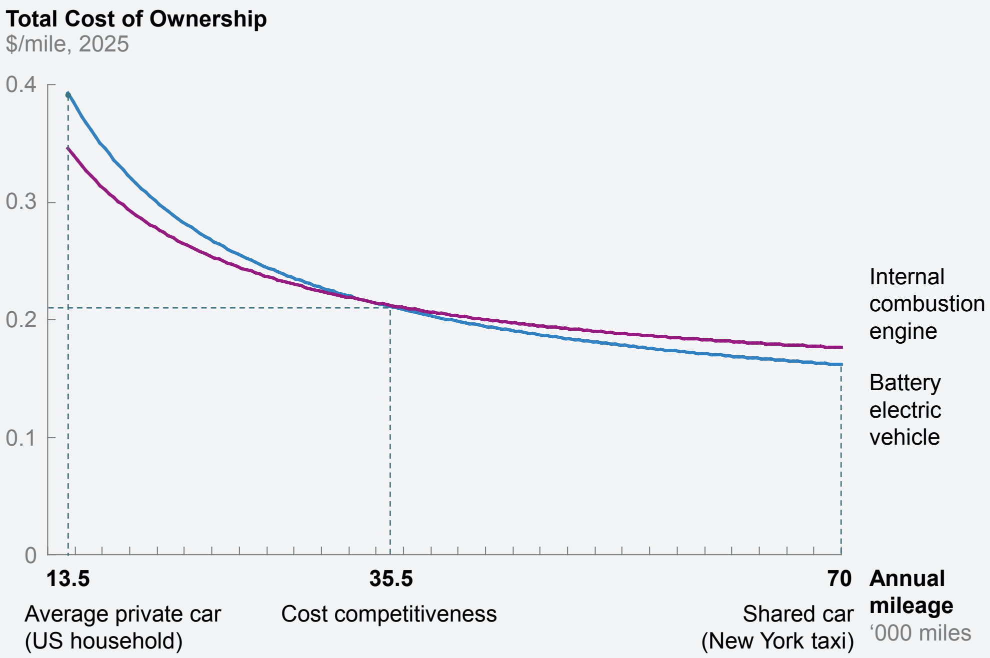
2. Self-driving could merge shared mobility business models into a single proposition competitive with private car ownership and public transport

With current technology, ride-hailing is unlikely to be cost competitive for commuter trips compared with private vehicles in most locations. Even low-cost offerings that match passengers with similar journeys and split the costs demand a 140 percent premium over private car ownership for the average traveler (Exhibit 10).

However, adding self-driving vehicles to the mix could have a disruptive effect in the context of shared-mobility business models and private car ownership. The cost difference between a privately owned car and a hailed ride would shrink dramatically. On average, a private car could still be cheaper as it can avoid paying taxes and margins to fleet and platform operators. For many drivers ride-hailing would nonetheless become the economic alternative. An on-demand, self-driving vehicle could also replace most current shared-mobility

EXHIBIT 9

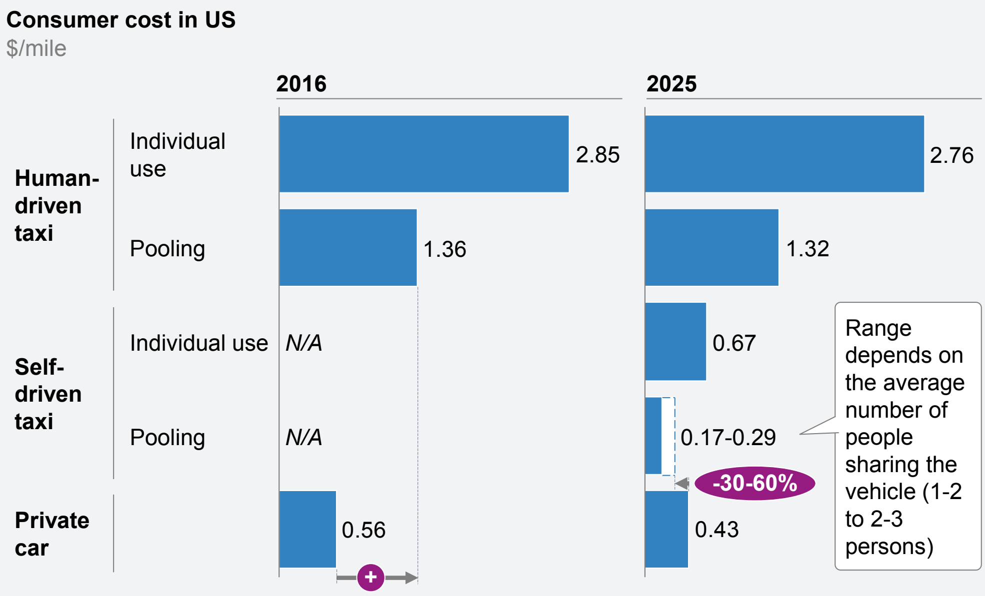
HIGH MILEAGE IMPROVES THE RELATIVE ECONOMICS OF EVS



SOURCE: Bloomberg New Energy Finance; McKinsey

EXHIBIT 10

BY 2025, A POOLED SELF-DRIVING TAXI COULD COMPETE WITH A PRIVATE EV



NOTE: all cars are modeled as battery electric vehicles
SOURCE: Bloomberg New Energy Finance; McKinsey

business models such as car sharing, carpooling, and ride-hailing: it could drive itself to the next customer, to a designated parking space, or back to the point of origin.

If a private consumer were open to sharing a ride with another traveler, the economics become even more attractive: on average, using a self-driving, electric, pooled taxi could be 30–60 percent cheaper per mile than a private vehicle, depending on the number of people sharing the ride. By 2025, a private car would cost $0.43/mile, whereas a consumer could use a self-driving, pooled taxi for as little as $0.17/mile–$0.29/mile.[17]

Compared with public transport, it appears that in various US cities public transport remains about as twice as cheap as human-driven taxi pooling with a cost of $0.64/mile in 2015.

3. Self-driving vehicles, both private and shared, are likely to increase mobility consumption, in which case electric vehicles offer lower total cost of ownership

As outlined above, the costs of a pooled self-driving taxi could be 30–60 percent less than a private vehicle. Moreover, this model may offer additional consumer utility: the enjoyment of on-demand access to a variety of vehicles for door-to-door transport, without the upfront cost or responsibility for maintenance attached to vehicle ownership. Alternatively, a privately owned, self-driving vehicle may be more expensive but could be summoned by other family members for trips that perhaps otherwise would not be made.

At lower cost and with increased utility, it is likely that self-driving vehicles would not only replace trips from other transport modes, but would also create entirely new demand for mobility. This is similar to a price elasticity effect whereby demand increases as prices per unit of mobility go down. In this paper we assume that demand increases by 12–24 percent if costs per mile fall 30–60 percent, using historical price elasticity curves for rail and private cars.[18] Additional demand may also come from groups such as youth or the elderly, who are currently dependent on other drivers or transit, and may therefore represent a significant pool of suppressed demand. As shown in Exhibit 9, at higher mileage, electric vehicles become attractive on cost.

4. An uptake in shared mobility will affect public transit.

Today, the impact of this rise in shared mobility on public transit seems positive. There is evidence that car sharers use public transit 40 percent more often than people who don't share cars.[19] Other research indicates that the more people use shared-transport modes, the more likely they are to use public transit.[20]

However, in the 2020s, the costs of commuting via public transit versus shared, self-driving vehicles may converge. Some travelers could decide to shift – occasionally or structurally – from public transit to shared mobility, as the convenience of a door-to-door on-demand offering is compelling. In some locations, shared mobility could fulfill first- and last-mile needs – connecting homes with the public transport network – or it could replace less utilized routes. In other locations, the speed and reliability of traveling by public transit, particularly rail, may offer an unrivaled service compared with driving.

5. Electric vehicle production at scale would accelerate battery cost reductions, with multiple effects

A high uptake – and corresponding production increase – of electric vehicles could accelerate a reduction of battery prices. This would in turn improve the relative economics of EVs and speed up their adoption. This could also unlock new battery applications including home energy storage. The expected cost reduction per cumulative doubling of manufactured volumes of EV lithium-ion batteries is around 16–20 percent, in line with historical

17 Costs are estimated based on the total cost of ownership, assuming 70,000 miles driven annually, average driver salaries, 10 percent overhead costs and a 10 percent required rate of return on invested capital for the fleet operator. We assume a utilization factor of 50 percent for taxis and 70 percent for pooled cars. This does not take into account a price premium for any additional journey time required to pick up multiple passengers.

18 GIZ, Transport Elasticities: Impacts on Travel Behaviour. Historical price elasticity analysis for other sectors (mobile data, air travel) indicates increases in demand could be much more significant if price declines by 50 percent.

19 Transit Cooperative Research Program, Report 108: Car Sharing, Where and How it succeeds, 2005.

20 American Public Transport Association, Shared Mobility and the Transformation of Public Transit.

trends. If such rates were to hold, the production volumes of electric vehicles discussed later in this paper could drive battery costs down to below $100/kWh in the next decade, even before any additional technology breakthroughs.[21] This could enable more renewable generation to be added to the grid, improving the emissions profile of an electric vehicle.

6. Self-driving electric vehicles – private and shared – will change the requirements for electric vehicle charging infrastructure

Having the right charging infrastructure available could have a reinforcing effect on the uptake of EVs, and vice versa. However, the locations and types of charging infrastructure would clearly be different for private EVs versus future shared, self-driving vehicles. The latter would have higher utilization, favoring fast-charging methods, and could drive autonomously to charging locations in low-cost locations. Equally, a lack of appropriate infrastructure could slow the electrification of shared vehicles.

7. Increasing renewable power generation will make electric vehicles more attractive as a means to reduce the carbon intensity of the transport sector.

Even in areas with high amounts of coal generation, such as China, electric vehicles already have lower CO_2 emissions per mile driven than the average ICE vehicle (Exhibit 11). Even with very aggressive assumptions about improvements in internal combustion engine technology, electric vehicles will still have lower CO_2 emissions per mile by 2030.[22] Moreover, this differential will increase after 2023 as the share of renewable power generation grows faster than ICE engines can improve. This makes electric vehicles an attractive means to reduce the carbon intensity of the transport sector.[23]

8. Self-driving vehicles may accelerate the uptake of vehicle connectivity and IoT applications

Vehicle connectivity has been rising steadily in recent years. Self-driving vehicles – as well as the charging and fuel infrastructure serving them – will require much more than contemporary vehicles and infrastructure. This demand will boost the uptake of vehicle-to-infrastructure technologies to enable aspects such as road pricing, traffic flow optimization, and accident-prevention systems. In parallel, as self-driving vehicles free up the driver's time, an opportunity will arise for connecting the occupants with online retail and media offerings during the trip.

Travellers will be able to spend time productively during their journey, and one can envision vehicle interiors that could enable occupants to connect to online retail, offering location-based personalised offers. There could be opportunities for streaming media and videos, providing entertainment to the passengers during their journey. Vehicles in the future could also connect to smart appliances at home, and seamlessly provide an experience to consumers that is an extension of their homes.

21 Bloomberg New Energy Finance battery cost model and McKinsey analysis.

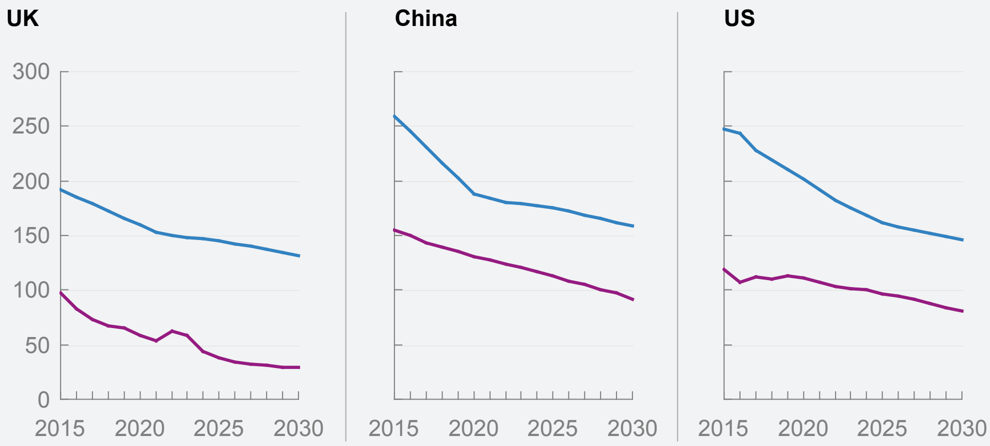
22 Bloomberg New Energy Finance, Do EVs emit less than internal combustion engines?, August 2016.

23 Emissions from associated generation only, excludes manufacturing emissions.

EXHIBIT 11

DESPITE FUEL EFFICIENCY, ICE CARS REMAIN MORE CARBON INTENSIVE THAN EVS

Average emission from different powertrains[1]
gCO2/mile, 2015-2030



1 Based on ICCT, normalized to NEDC cycle
2 Including indirect emissions from power generation
SOURCE: Bloomberg New Energy Finance, ICCT

ACCELERATED UPTAKE IN CITIES

Today, a few cities globally – such as Hong Kong, Singapore, Stockholm, and Amsterdam – are frequently cited as prime examples of how to organize mobility systems, differentiated by the availability and reliability of their public transit, integration of cycling and walking, but with varying levels of congestion and pollution. The maturation and reinforcement of mobility trends provides the potential for some cities to accelerate away from the pack. In these places, mobility in 2030 could look significantly different to the global or regional average. It is these break-away mobility systems which this paper will categorise and explain.

Such divergences have already started to appear. For instance, Norway has laid out plans for all private car sales to be electric from 2025 onwards.[24] Meanwhile, Singapore's Land Transport Authority recently signed partnership agreements to test shared, on-demand, door-to-door, first-and-last-mile, and intra-town self-driving transportation. Uber has signed a deal with Volvo to jointly invest $300 million in an autonomous taxi fleet, with testing that began in Pittsburg in September 2016.[25]

McKinsey's Automotive Revolution – perspective towards 2030 outlined how the specific type of city – in terms of factors such as population density and income profile – is set to be a prime indicator for citizen and local authority uptake of new mobility models, including shifts in the role of the private car.[26] In this paper we build on the same city archetypes, using population density, economic development, and prosperity as first dimensions of segmentation. Future states are laid out for three of these archetypes, where high wealth or increasing density can be a driver for change.

Each of the following three potential trajectories exhibits distinctive characteristics, linked to a specific type of city environment:

- A "**Clean and Shared**" system, more applicable to low-income, dense metropolitan areas where continuing rapid urbanization and pressing problems of congestion and pollution increase the urgency of shifting to cleaner transport and optimizing shared mobility in conjunction with public transit. Fully fledged autonomy is less likely in this system.
- A "**Private Autonomy**" system, more common in high-income, suburban sprawl, in which the private car remains a central element. Autonomy and electrification could make travel more convenient, safe, clean, enjoyable, and lower its cost.

24 Norwegian Government, National Transport Plan 2018-2029.

25 Press search, "Uber and Volvo to develop self-driving cars," Financial Times.

26 McKinsey & Company, Automotive Revolution – perspective towards 2030, January 2016.

- A "**Seamless Mobility**" system, most likely in high-income, dense metropolitan areas, in which the trends of autonomy, electric mobility, and shared mobility all move forward rapidly and are used to deliver "seamless mobility." These would be technologically advanced and stable mobility systems predominantly offering a door-to-door, on-demand, multimodal service.

This vision is neither intended as a prescription of the future nor as a definitive forecast, but rather as one possible version of it. Moreover, it relies on rapid technological advancement, evolving consumer preferences, and regulatory foresight to bring it to fruition. There is an economic case for metropolitan areas to consider interventions toward a desired future state.

CLEAN AND SHARED – LIKELY FOR DEVELOPING, DENSE METROPOLITAN AREAS

The Clean and Shared model is characterized by shared multimodal trips centered on human-driven cars, two-wheelers, and mini-buses which are increasingly electrified, as well as expanded provision of public transit. The application of self-driving cars may not be viable in dense, developing metropolitan areas, where the state of the infrastructure is poor and the general traffic situation is more complex.

Pollution-driven electrification. Dense developing metropolitan areas already face severe air-quality concerns and may use mandatory electrification to curb increasing pollution, especially pollutants impacting health such as PM2.5 (particulate matter with a diameter of less than 2.5µm, one of the most harmful pollutants for human health) and NO_X. Advances in decentralized renewable power generation – such as solar PV – as well as decentralized storage may be crucial to enabling this move to electrification. In many developing cities the central power grid is already running at near maximum capacity and is not able to fully absorb extensive electrification of transport. In areas with sufficient unused rooftops, private vehicle owners may use decentralized generation and storage to power their household and vehicles, and to be less vulnerable to brownouts. Operators of delivery and ride-hailing fleets may find it easier to secure their own charging infrastructure using decentralized energy, and they may be the first to significantly embrace electric vehicles due to the attractiveness of their reduced running costs at high mileage.

Ridesharing and shared mobility. Population growth may increase mobility demand, in particular from private cars, to unsustainable levels. Ride sharing and high-capacity public transit may be strongly incentivized over private vehicles. Consequently, a range of tailored shared-mobility models may emerge, ranging from on-demand rides on two-and three-wheel vehicles, to combinations of already-common informal transit options such as shared minibuses with modern app-based ride-hailing and consumer information systems.

Low-speed vehicles. Emerging cities may see an increasing number of low-speed electric vehicles designed particularly for city centers or non-highway driving. With falling battery costs and fewer moving parts than comparable ICE vehicles, such niche designs are already becoming a competitive option for local mobility for an emerging middle class.

Keeping the human driver. Low labor costs, poorer road conditions, governmental concern about unemployment and a more complex traffic situation make autonomous vehicles less attractive and harder to operate in dense, developing metropolitan areas. Autonomous driving capability may still find a niche within private luxury vehicles, but is unlikely to experience wider uptake. The core of the vehicle parc would remain human driven.

Improving traffic flows. Basic infrastructure improvements, from lane structures to dynamic traffic lights, may help to improve throughput over today's roads. Lower levels of vehicle autonomy and driver assistance will reduce accidents, but full self-driving functionality may have limited applications.

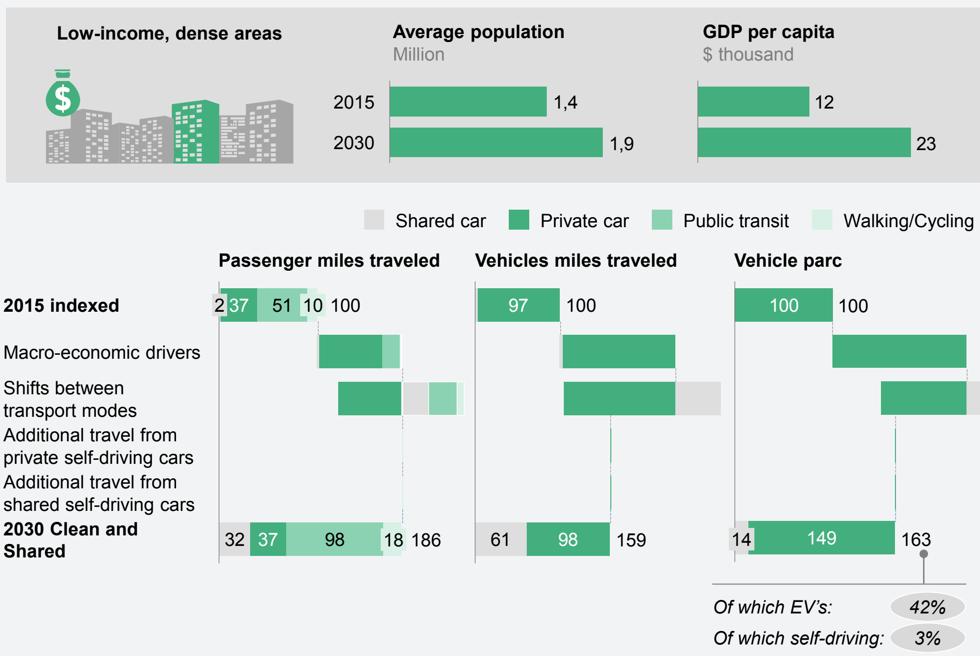
Supporting public transit. To release the pressure on the mobility system, metropolitan areas may build out high-capacity transport networks at a faster rate than the increase in demand for mobility. Rather than expensive underground systems, rapid buses on dedicated lanes and above-ground light rail transit could provide additional capacity. Middle-class users may consider high-quality ride pooling in air-conditioned cars for the first and last mile, combined with a trip on a high-capacity local train, as an attractive alternative to private car ownership.

Potential impact. In the average developing, dense metropolitan area in Asia, population is likely to grow by 50 percent and GDP by 90 percent from now to 2030 (Exhibit 12).[27] In a Clean and Shared system, the corresponding increase in passenger and vehicle miles would be offset by a high degree of sharing and more public transit. By 2030, shared light vehicles – thanks to a combination of greater utilization and more passengers per trip – could account for a third of vehicle miles travelled. Rapid uptake of electrification is likely to result in nearly 40 percent of vehicles on the road being electric; however, the penetration of self-driving vehicles is set to remain very low.

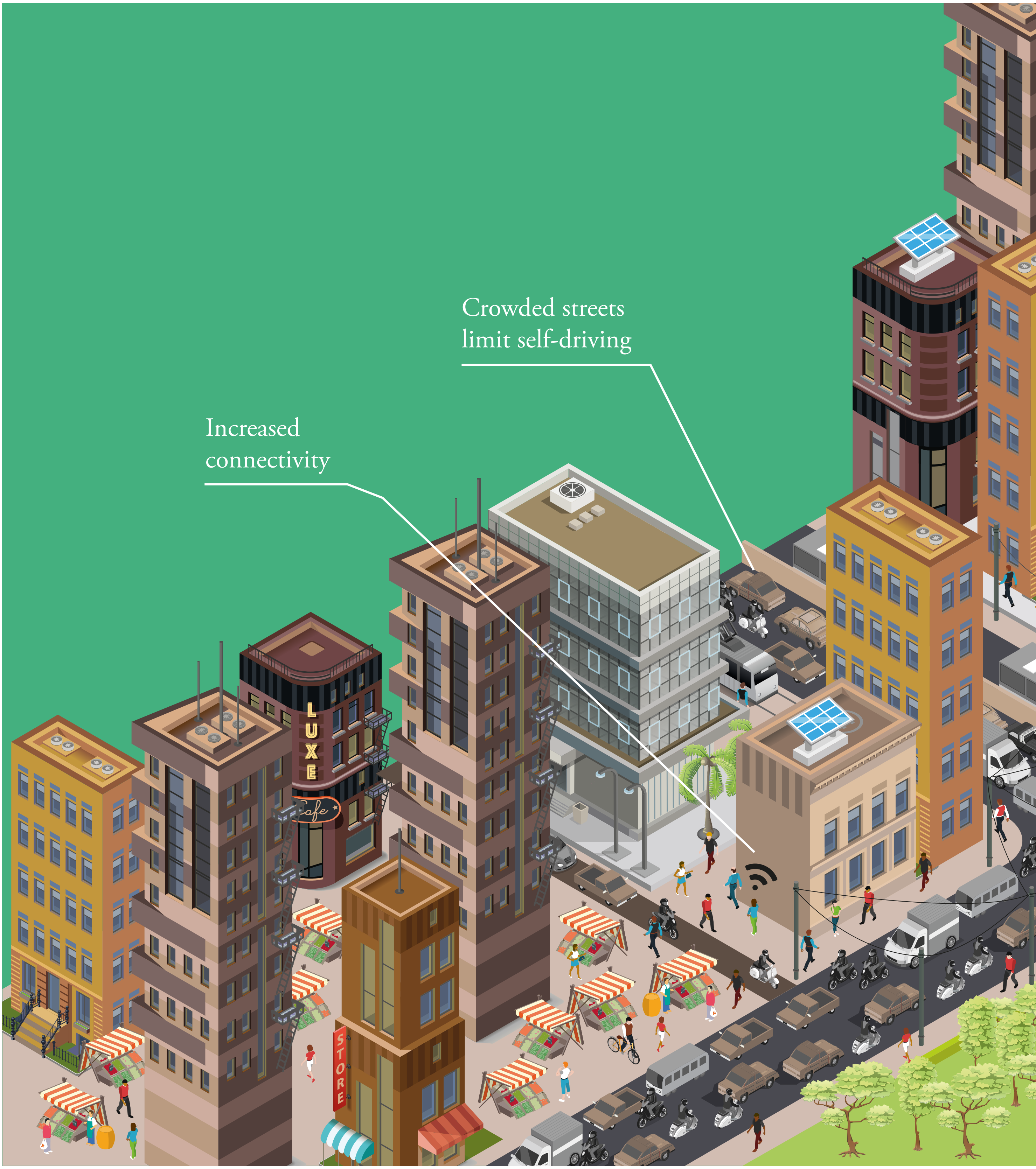
Where? A transition to a Clean and Shared system would be most likely for emerging, dense cities. Of all developing, dense metropolitan areas, about 15 may be in a position to be early adopters – including Istanbul, Delhi and Mumbai – based on criteria such as population size, above-average GDP per capita, historical implementation of public projects, and urgency of pollution and congestion issues today. Exhibit 12 shows how several key indicators could change for an average low-income, dense city as it transitions to the Clean and Shared end-state.

27 McKinsey, McKinsey Global Institute.

EXHIBIT 12



SOURCE: McKinsey Global Institute; McKinsey


Crowded streets
limit self-driving
Increased
connectivity
LUXE
Cafe
STORE


Busy system including motorbikes and pedestrians
Rapid bus systems

PRIVATE AUTONOMY – LIKELY FOR DEVELOPED, SUBURBAN SPRAWL

In a Private Autonomy system, the private car would maintain its dominance as the central element of mobility. Autonomy and electrification might allow passengers to use time in traffic for business or pleasure. The system as a whole may be stretched by increased demand, as vehicle ownership is expanded even further and empty vehicles are sent on errands or to roam for parking.

The attractiveness of the private vehicle. The advent of desirable and highly personalized cars – which would frequently also be electric – may maintain consumers' appetite for a private vehicle. In this vision of the future, consumers are likely to value both their privacy when travelling and the independence of owning their own car. Accordingly, car sharing, ride hailing, and ride sharing remain complementary options but do not replace commutes on a large scale.

The convenience of autonomy. Most commuting patterns may originally remain unchanged with vehicle autonomy offering people the opportunity to enjoy movies or catch up on emails while driving. Meanwhile, additional consumers who were previously not part of the addressable market for vehicle manufacturers may purchase or use (autonomous) cars: they include the elderly and teenagers below driving age who could "summon" vehicles belonging to other family members when they were not being used, for school or social trips.

With lower marginal costs to travel an extra mile in an electric vehicle – and without a driver's attention required – demand for mobility is likely to increase. Depending on the increase, this could generate more congestion. In the longer term, this may contribute to more urban sprawl as acceptable commuting distances increase. Demand for vehicle miles could grow even more than passenger miles, as people send their cars to roam or park remotely to avoid high charges. Zero-occupancy rides may quickly become a common sight in this future state, with the potential for competing interests as idle cars occupy road space desired by other people.

Consumer-driven electrification. Consumers may prefer an electric car, which in combination with home or workplace charging is a convenient option. Vehicle charging based around decentralized solar panels and battery storage systems may result in lower prices than retail power options in many locations.

Optimized road infrastructure. The road network may grow, but mostly around the edges of the sprawl. A more productive – or at least more comfortable – commuting experience, coupled with better road utilization and higher average speeds, thanks to the intelligent capabilities of autonomous vehicles, may mean that people are willing to commute for longer distances. Initially, existing road capacity may suffice thanks to higher traffic density; however, with lower costs and more car users increasing the total number of trips, infrastructure will eventually require further investments to tackle capacity bottlenecks. To ensure improved road carrying capacity, city authorities may seek to further separate autonomous vehicle driving lanes from pedestrians and non-autonomous cars.

Demand management. Municipal programs to carve out dedicated road space for autonomous vehicles could be complemented by more sophisticated demand-control measures. Highly connected vehicles may lead authorities to implement demand-driven congestion charges or – privacy concerns notwithstanding – even geo-fence areas to automatically block cars from entering certain localities at specific times. In suburban areas or on highways, dedicated autonomous-vehicle-only lanes could maximize road capacity; in some places, car settings could automatically pay for priority road access in congested areas.

Public transit. Meanwhile, rising suburban sprawl may make it harder for last-mile public transport systems such as buses to compete in outer areas, even as dynamic routing and on-demand pick-up significantly improve service levels. Instead, family vehicles are likely to be used with increasing frequency to provide mobility for people who cannot drive – for example, autonomous cars can be dispatched to collect the elderly from shopping trips or drive school kids to after-school events, or move the physically challenged – so blurring the boundaries between an exclusively used vehicle and one that is privately shared. Rapid public transit that is already in place is likely to maintain its position.

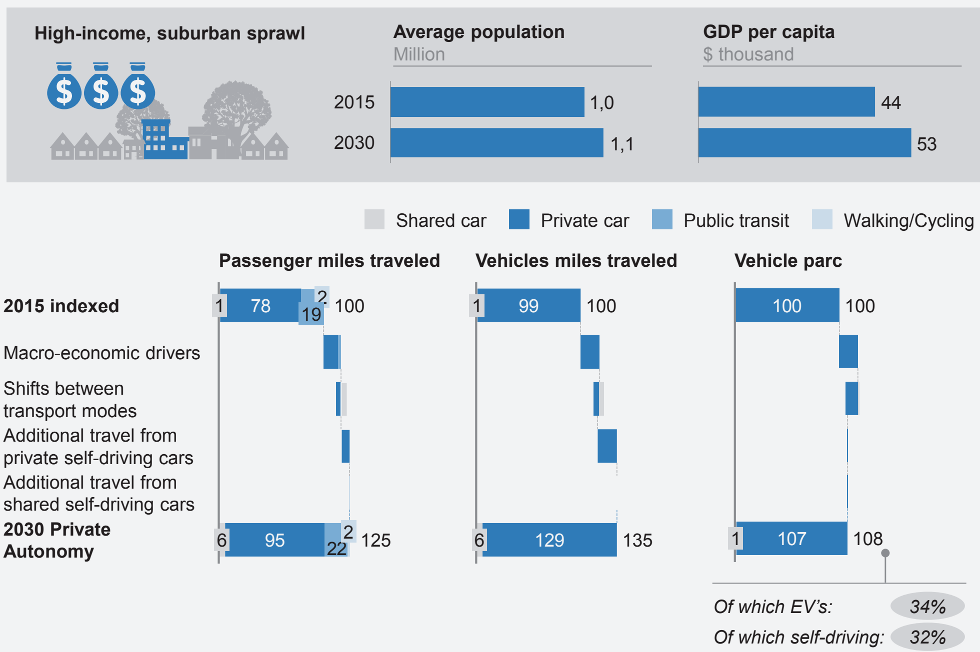
Despite the continued supremacy of the private car in this future end-state, for low-income groups innovative shared models may offer compelling alternatives to traditional car ownership. In Dallas and Phoenix, "Dollar Vans" already go head-to-head with public buses, with more daily passengers than buses. Evidence suggests that this mode can be more efficient that bus networks.[28] In regions where public transport provides an inferior service to travelling by private vehicle – for instance, in the United States the average public transport commute is 53 minutes compared with 22 minutes by private vehicle – then this shift represents more equitable access to transport for those who do not own a private vehicle. [29] Accordingly, automation of these shared-mobility services, while attaining a small modal share overall, could improve access to transport for low-income groups.

Potential impact. In a typical European or North American suburban sprawl, passenger miles traveled may grow by 25 percent versus 2015, with the majority of this increase attributable to additional autonomous travel in private vehicles (Exhibit 13). Miles travelled by private autonomous vehicles would increase as additional journeys and zero-occupancy rides become commonplace. On the other hand, households will need fewer vehicles on average due to the additional flexibility of a private AV vehicle – the net effect will be a similar number of vehicles traveling 35 percent further. Both EV and AV technologies are likely reach market penetration of 30–35 percent of the vehicle parc in those cities – far above the global average.

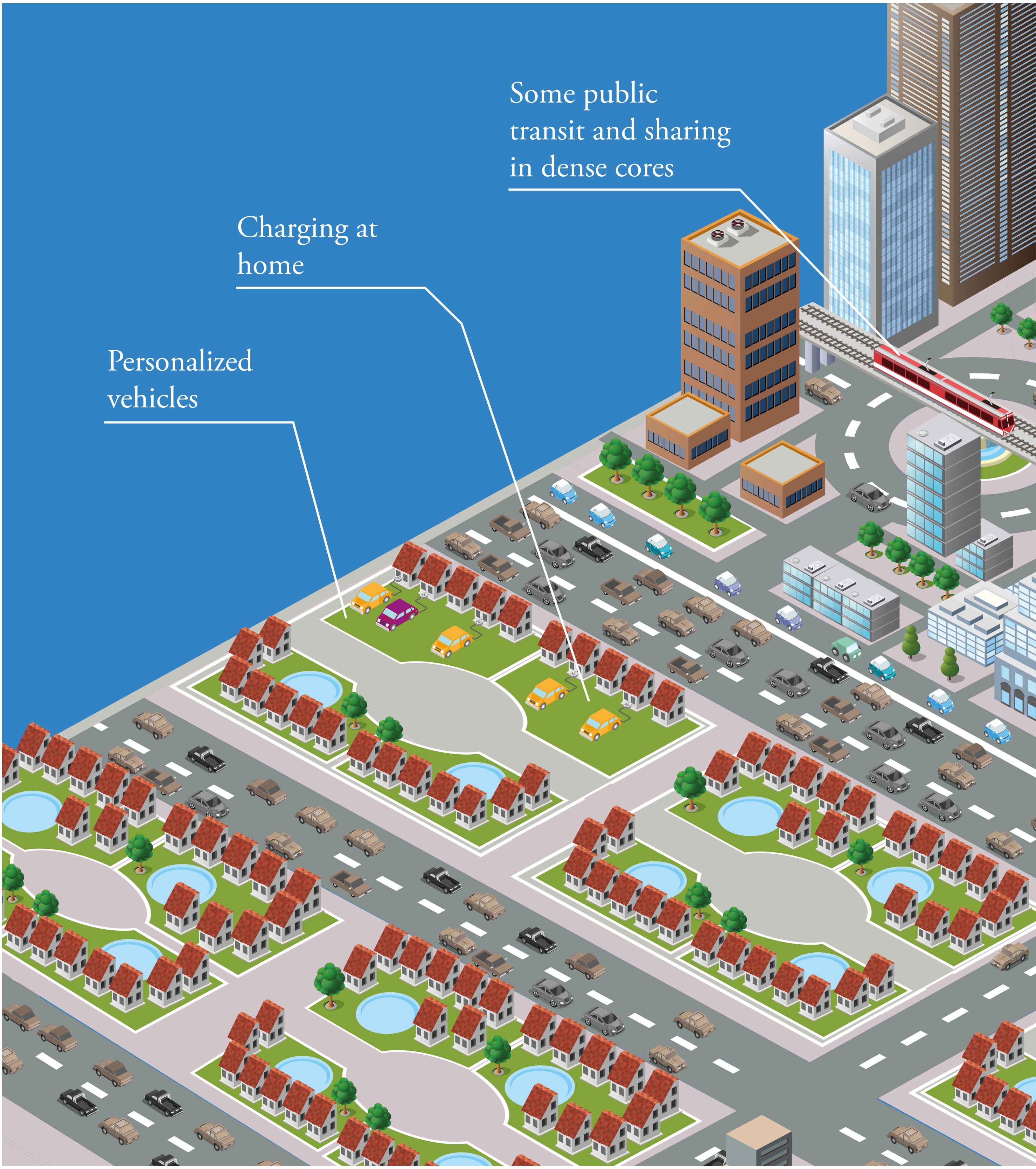
28 The Economist

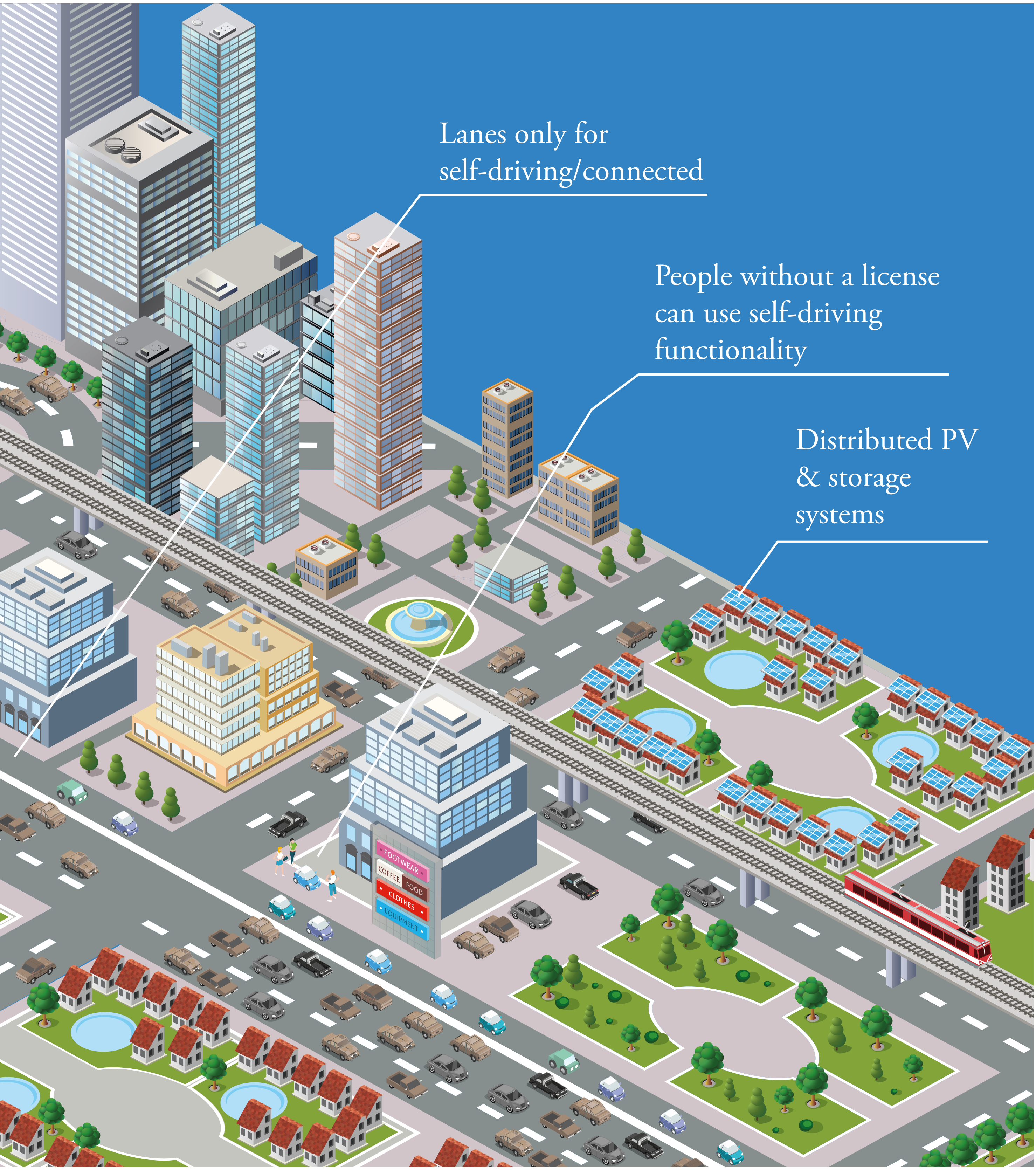
29 U.S. Department for Transportation, 2009 National Household Travel Survey.

EXHIBIT 13



NOTE: Vehicle parc figures include the expected impact of private AV ownership on the number of vehicles owned per household
SOURCE: McKinsey Global Institute; McKinsey


Some public transit and sharing in dense cores
Charging at home
Personalized vehicles


Lanes only for self-driving/connected
People without a license can use self-driving functionality
Distributed PV & storage systems
FOOTWEAR
COFFEE
FOOD
CLOTHES
EQUIPMENT

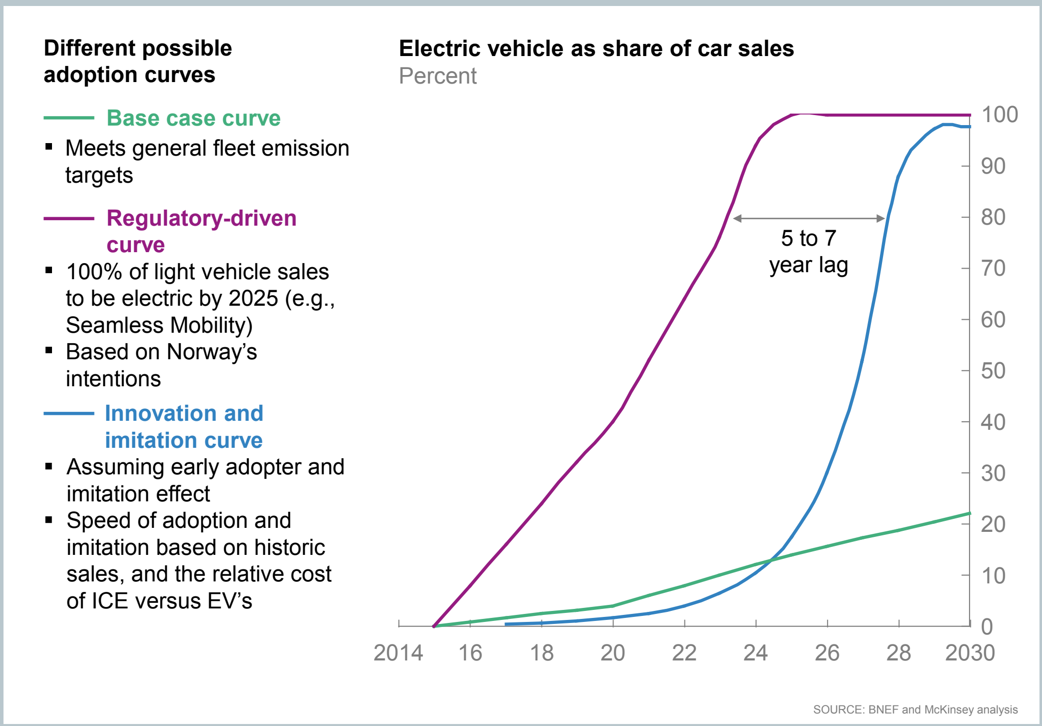
Could aggressive electric uptake be consumer driven?

The Seamless Mobility system assumes that electric vehicles will comprise nearly 100 percent of light vehicle sales by 2025, driven by a mix of economics, consumer demand, and strong regulatory intervention. This is modeled on the intentions and aspirations Norway put forward in its long-term Transport Plan, with a more detailed plan to be published in 2017. However, what if demand for electric cars does not require any regulatory intervention or support and is entirely driven by consumer demand? EVs may be able to compare very favorably on various performance metrics (acceleration, noise, and servicing requirements) within the given timeframe, separate from any economic or environmental motivating factors. Could early adopters stimulate a large group of imitators via word of mouth, causing a snowball effect in electric vehicle uptake?

Bass-diffusion modeling is an alternative to looking at regulatory-driven approaches to EV adoption. The Bass model describes the process of how new products are adopted and imitated throughout a population. The Bass model depends on two things: the primary rate of adoption (early adopters) and imitation of others. Both of these drivers are also influenced by price elasticity of demand for competing products. When EVs are relatively expensive this acts as a dampener due to price elasticity, but the moment EVs become cheaper, this goes into reverse and price elasticity helps drive adoption. If this happens in parallel to when the imitation effect kicks in, the rate of increase in overall addition can be very sharp.

Based on the speed and timing of adoption and imitation on historical electric vehicle sales, and the relative cost of ICE versus EVs, we see a consumer-driven adoption curve that takes off five to ten years later but then accelerates rapidly to near 100 percent sales (Exhibit 14). However, meeting such aggressive timelines would present significant challenges for scaling up manufacturing capacity.

EXHIBIT 14



Where? Private Autonomy systems would be most likely in developed suburban sprawl areas, where the car remains a necessary element to get around and where inhabitants have sufficient wealth to afford electric and autonomous features. Within developed suburban sprawls, about 20 areas globally may have the potential to reach Private Autonomy status ahead of the pack, including Sydney, Houston, and the German Ruhr area. These early adopters are selected for their high relative GDP per capita, historical implementation of public projects, and openness to adopting new technologies.

SEAMLESS MOBILITY – LIKELY FOR DENSE, DEVELOPED METROPOLITAN AREAS

In a Seamless Mobility system, mobility may increasingly become a door-to-door, on-demand, multimodal service with blurred boundaries between private, shared, and public transport.

Sharing meets autonomy. The collision between shared mobility and autonomous driving could trigger a whole new transportation model: a fleet of shared, self-driving, electric cars providing on-demand, door-to-door mobility. Such vehicles may exhibit considerable variation in size and specification – basic, luxury, from 2 to 20 passengers – in order to meet disparate demand from different user segments. The shared mobility fleet may be able to provide mobility at much lower cost than privately owned vehicles, a factor that would likely drive additional demand. Shared mobility may be further incentivized through priority access to the city over private cars.

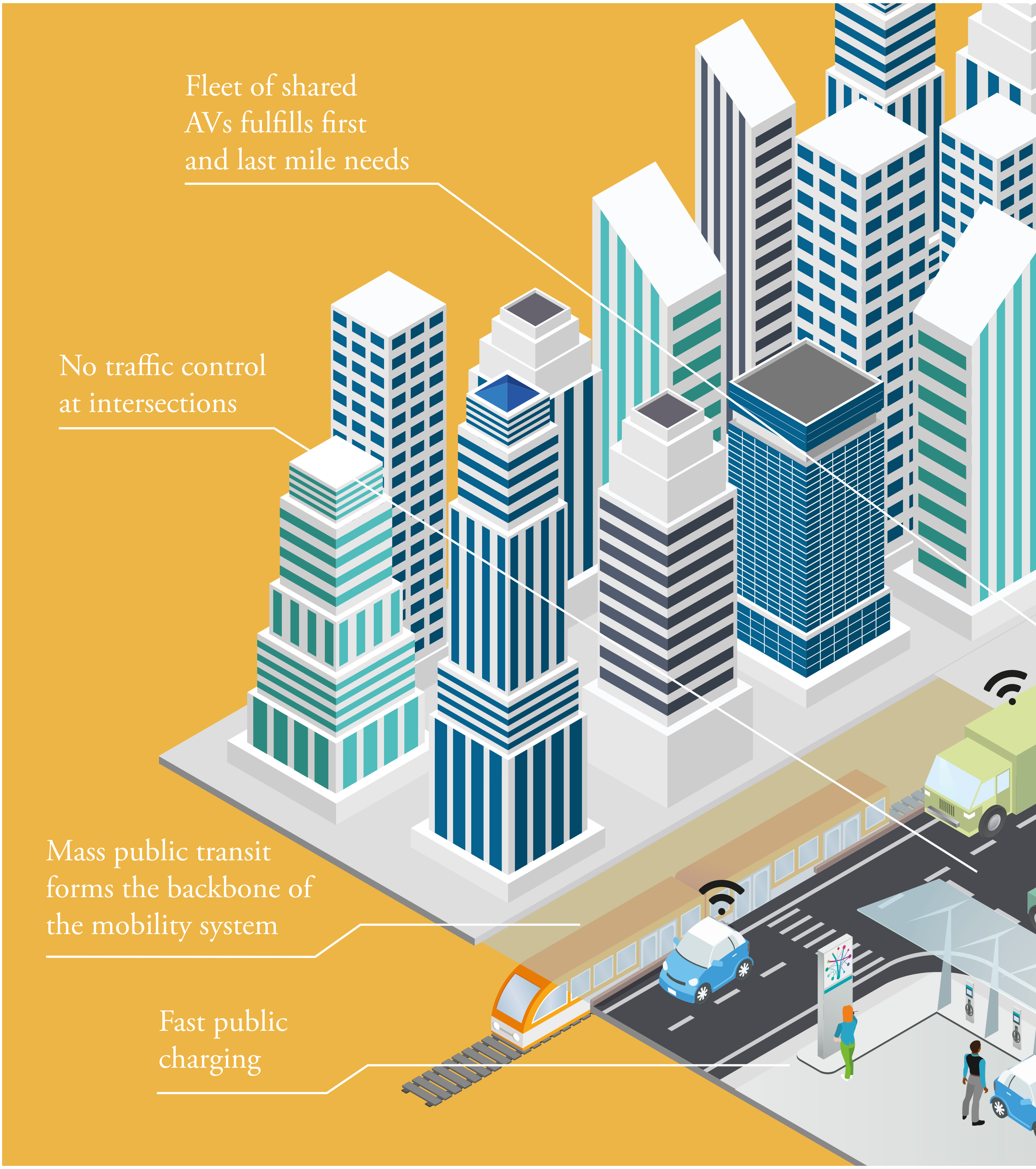
Zero-occupancy driving may be restricted for private autonomous vehicles to avoid congestion caused by empty private cars roaming for parking or driving to serve other family members. Meanwhile, advanced congestion pricing and demand-management models may be introduced – with differentiated rates based on time, occupancy, and location – and enabled by the increasing connectivity of vehicles.

An increase in shared and autonomous vehicles opens up opportunities for urban planning. There may be less need for parking facilities, which could be turned into urban green or other public space. However, urban planners may want to consider zoning to accommodate drop-offs and pick-ups.

Incentivized electrification. The economics of a high-mileage shared-vehicles model favors electric vehicles, while electrification of the private vehicle parc is likely to be accelerated in response to tightening fuel economy regulations and introduction of low-emission zones in urban areas. In selected countries or metropolitan areas electrification of all new cars sold may even become mandatory. As a consequence, by 2030 electrification levels in the vehicle parc in Seamless Mobility regions may have reached as high as 60 percent. In parallel with mandatory electrification, public and semi-public charging infrastructure may be built out quickly, while negative impacts on power markets and the grid are mitigated through time-based payments, smart charging, and differentiated power tariffs.

Fast public transit as a backbone. The shared fleet may partially substitute buses, providing more first- and last-mile options, especially in the outer ring of metropolitan areas. Mass-transit rail systems – in combination with walking and cycling – would remain a vital and essential part of the mobility system, as the speed and capacity of such systems remains unrivaled.

Enabling infrastructure. In this system, mobility infrastructure increasingly becomes a mix of physical components and software, with mobility used more and more as a service. Consumers would likely rely


Fleet of shared
AVs fulfills first
and last mile needs
No traffic control
at intersections
Mass public transit
forms the backbone of
the mobility system
Fast public
charging

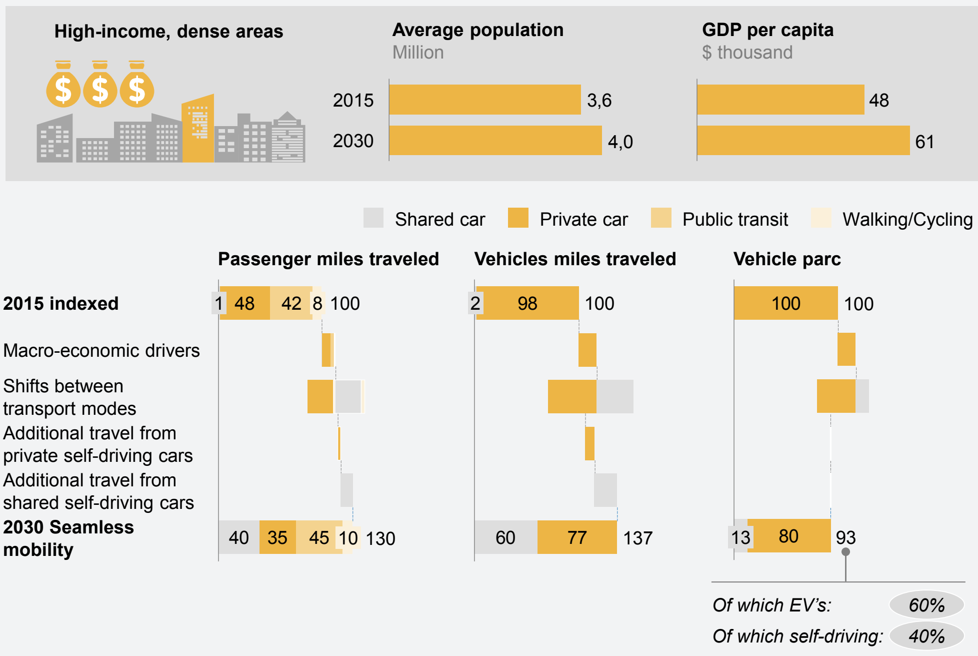

Mobility as a service via an integrated platform
V2V and V2I communication
Low emission zones
Parking spaces converted into public green, walking & cycling
subway
CO_2

on a single integrated software platform to compare travel modes and prices, and to pay for transport across different options, independently of whether public or private transit is used. Cities could leverage the smart routing and dispatch algorithms of specialized providers to replace first- and last-mile bus services with licensed or subsidized ride hailing – or even install a central dispatch platform that smooths traffic flows. Meanwhile, physical infrastructure improvements, in combination with autonomous and connected cars using interoperable protocols, would also ensure optimal traffic flows via a vehicle-to-infrastructure (V2I) intelligent transport system.

Potential impact. In a Seamless Mobility system, we estimate that people may travel more – up to 30 percent more miles, spread across all modes, in an average North American or European dense developed city (Exhibit 15). The largest increase in passenger miles would be with shared vehicles, unlocked by the drop in costs of shared, autonomous vehicle fleets. Due to the high level of sharing, the vehicle parc in a European or North American city stops growing despite the increase in passenger miles. Nonetheless, it is possible that more miles driven may still lead to more or at least constant congestion in urban bottlenecks. In this future system, the penetration of EVs and self-driving vehicles could reach levels far beyond what is achievable globally. Electric vehicles may make up three-fifths of the car parc, while vehicles capable of self-driving may exceed 40 percent penetration in the car parc by 2030 in specific Seamless Mobility cities.

Where? Seamless Mobility is most likely to occur in high-income, dense metropolitan areas, as well as in some European and North American suburban sprawl areas. Fifteen metropolitan areas worldwide are best positioned to accelerate first, including London, Singapore, and Shanghai. These areas combine high historical implementation of public projects and GDP, and a track record of willingness and ability to invest into public infrastructure at pace and scale. In addition, these areas have high-quality mass public transit, which could form the backbone of a multimodal system.

EXHIBIT 15



SOURCE: McKinsey Global Institute; McKinsey

ACCELERATED LOCAL UPTAKE IS GLOBALLY RELEVANT

Adding together the figures cited at the end of each future state description results in a total of approximately 50 metropolitan areas that could be early contenders to "make the leap" to one of the three future states we have described (Exhibit 16). They represent nearly 500 million people based on today's population.

THERE IS A COMPELLING CASE TO ACCELERATE

It is unlikely that individual metropolitan areas will be able to choose which future state they would prefer. Local conditions and circumstances may determine which of these potential trajectories can be reached and whether the respective benefits can be reaped. For example, the high uptake of shared mobility assumed in Seamless Mobility and Clean and Shared is not viable for areas of suburban sprawl; equally, poor infrastructure, inadequate road regulation, and crowded streets will prevent rapid uptake of autonomous vehicles in most developing metropolitan areas.

Nonetheless, metropolitan areas should consider steps to make the most beneficial vision of the future more likely, not least because there are significant potential benefits and pitfalls to be avoided by moving quickly. These benefits kick in when metropolitan areas move beyond incremental change to step up to truly radical change within the mobility system. There are various benefits to be gained from an integrated view of the system, including the following:

- **Environmental footprint – reduced pollution.** A combination of electrification and modal shifts could reduce CO_2 tailpipe emissions by as much as 60 percent in 2030 in specific urban areas.[30] Other emissions such as NO_X and PM2.5 have serious detrimental health impacts that would also be significantly mitigated by electrification and modal shifts.[31]
- **Citizens health & safety – improved safety.** Human error is responsible for approximately 94 percent of vehicle accidents.[32] Automation can eliminate many human errors that previously contributed to accidents; yet, automation itself may introduce new accident patterns, including sensor failure, improper maintenance, and algorithm misinterpretation. However, such failures are likely to be much less common than human error. World Health Organization statistics indicate that 1.25 million people died in road crashes in 2015 and potential to reduce traffic accidents represents a welcome benefit to society.[33]

30 Including indirect emissions from power generation, this figure decreases to 45 percent.

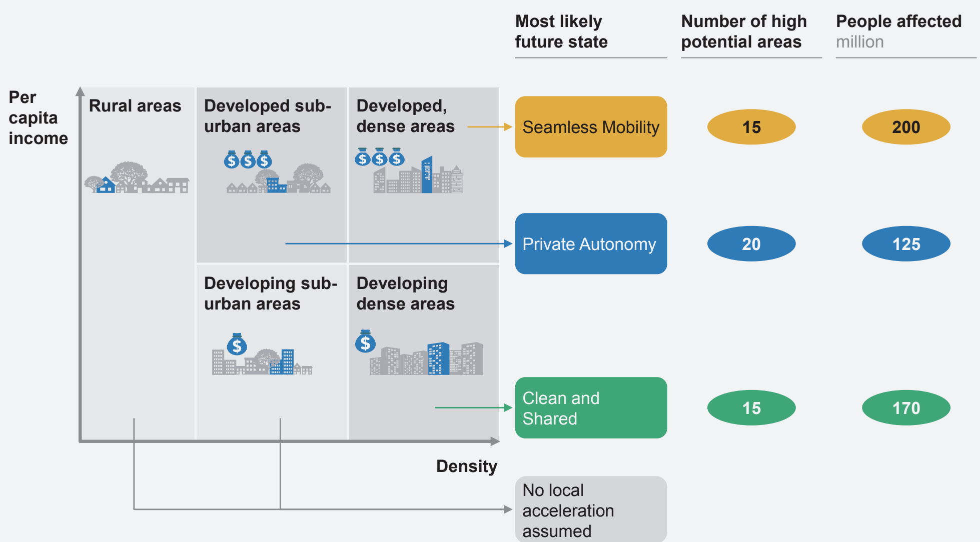
31 Torfs et al, "Health Impacts of particulate pollution in a Megacity," Environmental Development, April 2013, 2007.

32 National Highway Traffic Safety Administration.

33 World Health Organisation.

EXHIBIT 16

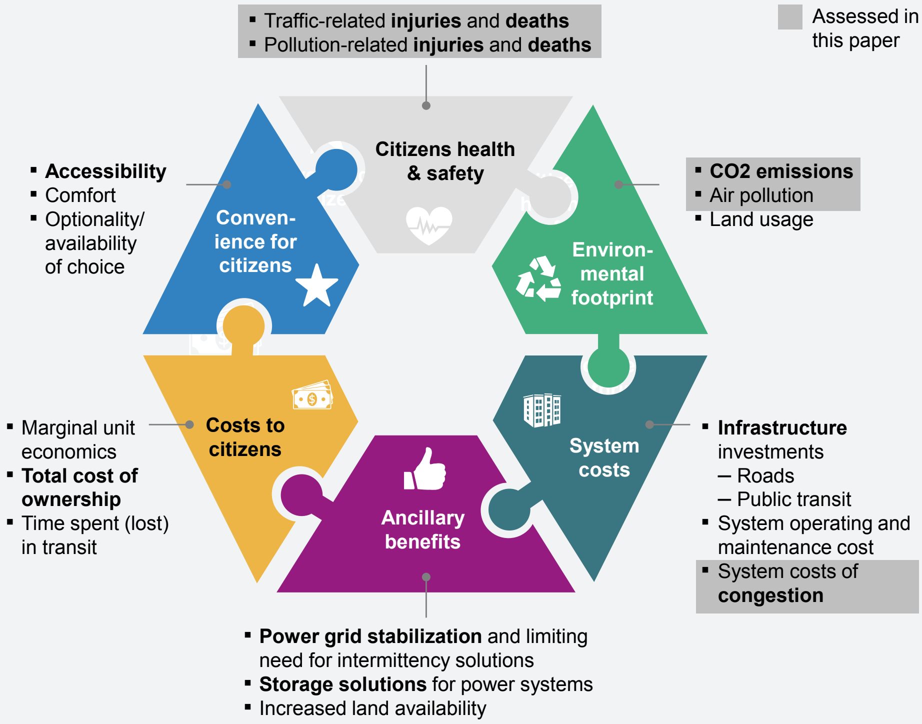
AROUND 50 LARGE METROPOLITAN AREAS HAVE THE HIGHEST POTENTIAL TO ACCELERATE



SOURCE: McKinsey analysis

EXHIBIT 17

COSTS AND BENEFITS EMERGING FROM AN INTEGRATED VIEW OF MOBILITY SYSTEMS



SOURCE: McKinsey Analysis

- **System costs – reduced cost of congestion.** Congestion costs more than 1 percent of GDP globally.[34] This problem can be addressed through costly supply-side levers or demand-management levers: for instance, dynamically priced traffic lanes. Autonomy and modal shifts, if properly managed, will allow for additional throughput without additional infrastructure investments.
- **Convenience for citizens – access to mobility.** Local disruption could improve the access to mobility. New mobility will enable opportunities to travel for the elderly, adults unable to drive, and youth, which would not otherwise have existed. Additionally, shared mobility – due to reduced cost for the individual – is likely to provide more equitable access to transport in urban cores by increasing mobility for lower-income segments of the population.
- **Cost to citizens – freed time.** Autonomous vehicles will liberate hours currently spent driving to be used however consumers choose to spend them.

These benefits do not represent an exhaustive list, and others will emerge over time. Exhibit 17 provides a framework for how the associated costs and benefits might play out.

We have quantified the potential benefits that an average city in each future state could expect from achieving the most applicable mobility future, assuming a cost for the different benefits mentioned: for example, a price of CO_2/ton[35] of $36 in 2015 and of $50 by 2030; costs of ~$20,000 for light injuries in the European Union/North America; congestion cost per km of $0.058.[36] Seamless Mobility systems may achieve the highest absolute benefits, reaching $2.5 billion by 2030 and increasing 2030 GDP by up to 3.9 percent

34 McKinsey analysis based on Centre for Economics and Business Research, The Future economic and environmental cost of gridlock in 2030, July 2014.

35 Metric tonne

36 EPA, World Health Organisation Data, McKinsey calculation based on various city case studies.

(Exhibit 18).[37] Over the period 2015–30, benefits per inhabitants would be up to $7,400 and $30 billion–$45 billion for the average developed dense city, mostly from improved road safety. As autonomy is introduced and shared self-driving vehicles become commonplace, resulting congestion and safety strains on the system could temporarily limit the benefits.

Moving to Clean and Shared by 2030, an average-sized developing, dense city could see societal benefits of $0.6 billion cumulatively, increasing the local GDP by 2.9 percent. Over the timespan 2015–30, benefits could be up to $2,800 per inhabitant and up to $4 billion at a city level.

Societal benefits in a Private Autonomy system are similar: up to $3,300 per inhabitant and $3 billion for an average-sized suburban sprawl over the period 2015–30. By 2030, benefits for each area of sprawl could reach $0.5 billion, boosting GDP by 0.9 percent in 2030. In this scenario, benefits mostly accrue from safety improvements from the rise of private self-driving vehicles.

If the complete set of 50 metropolitan areas with early adoption potential were able to accelerate early, this would yield cumulative global societal benefits of up to $0.60 trillion. There would also be significant impact on other sectors – for instance, increasing power demand and additional vehicle sales – which we outline in the next chapter.

The benefits shown are sensitive to the amount of additional travel generated by (shared) self-driving vehicles (See sidebar, "Sensitivity to additional travel assumptions").

Just as the pace of disruption may be unevenly distributed, so too are its benefits. For example, congestion in Los Angeles costs the city $23 billion per year, representing a fifth of total US congestion.[38] Meanwhile, air pollution in Delhi is among the worst worldwide, shortening the average life expectancy of its inhabitants.[39] In such cases, the benefits to society may be higher than average. There is an opportunity for significant impact, and both policy makers and industry

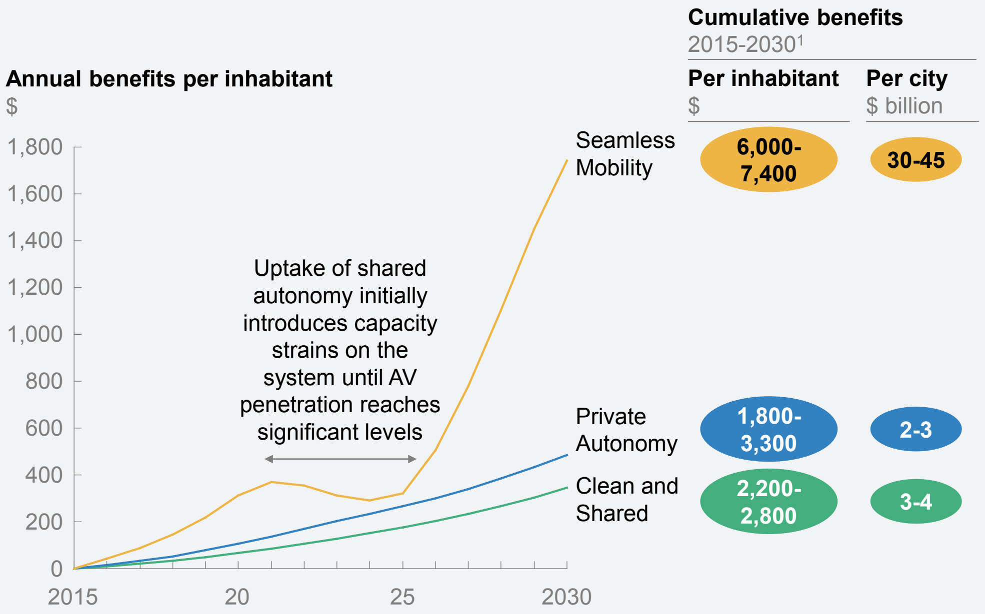
37 This figure includes total calculated system benefits which may include elements not additive to GDP.

38 Centre for Economics and Business Research, The Future economic and environmental cost of gridlock in 2030, July 2014.

39 World Health Organisation.

EXHIBIT 18

SOCIETAL BENEFITS ARE HIGHEST IN SEAMLESS MOBILITY



1 Ranges depend on regions
SOURCE: McKinsey Analysis

players can take actions to help bring about the potential future states that may lead to these societal benefits.

There is, however, a risk that the rapid changes in the mobility sector will have undesirable effects. For instance, planning charging networks without considering shared and autonomous vehicles may lead to poorly located chargers. Failure to co-ordinate between the development of shared mobility and urban planning could result in congestion around drop-off points and low public transport utilization. Unrestricted private AV use may exacerbate congestion through the increase in zero-occupancy rides. At the same time, lack of investment in the right infrastructure will reduce the benefits of autonomy. An integrated perspective can ensure cities avoid such pitfalls.

Sensitivity to additional travel assumptions

In combination with shared-mobility business models, self-driving cars could change our demand for mobility by boosting convenience and the driving experience. People could travel door to door while still being free to work or be entertained; such vehicles could be of any size, for private use, or pooled with other travelers, which would be at much lower cost.

Throughout this whitepaper we have assumed that demand for shared autonomous vehicles would follow historical price elasticity for travel. Historical analysis shows that a 10 percent reduction in the price of car travel induces 4 percent extra demand. The costs of a shared autonomous vehicle could be 30–60 percent lower than a private vehicle (Exhibit 19). If the basic price elasticity curve of car travelers holds, this would induce additional demand of 12–24 percent. For our Seamless Mobility system we assumed 20 percent additional passenger miles by car, due to the introduction of shared autonomous vehicles. In addition, we have assumed private autonomous-vehicle owners travel 20 percent more miles due to increased convenience and from the possible applications of zero-occupancy rides.

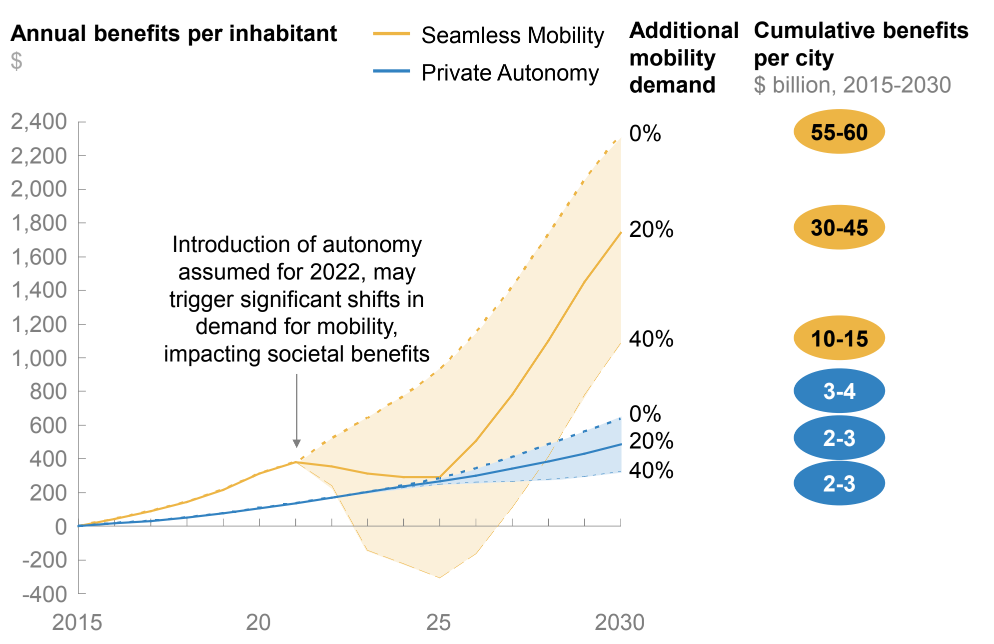
Yet demand for travel may be less elastic than expected – it is still time spent in a vehicle. This would have an upside in terms of societal benefits: less travel means reduced energy consumption and emissions, fewer accidents, and less congestion. However, a more compelling case to consider is: what if increases in demand for mobility are much larger? In other industries, such as telecom and air travel, demand for mobile minutes, data, and air travel increased by up to 150 percent in periods of 50 percent price declines.

We have modeled a sensitivity in the increase in passenger miles, ranging from zero – as if demand for mobility is insensitive to price changes – to 40 percent additional travel. This would significantly vary the societal benefits: changes in miles traveled would affect the congestion benefits and, before electrification and self-driving capability reach high penetration, also environmental and safety benefits.

For example, at a 40 percent demand increase, cumulative benefits for an average city could decrease to $10 billion in a Seamless Mobility system (Exhibit 19). However, this drop does not acknowledge the value – to consumers and to business – of the additional mobility enabled.

EXHIBIT 19

SOCIETAL BENEFITS ARE SENSITIVE TO THE ADDITIONAL MOBILITY DEMAND UNLOCKED



SOURCE: McKinsey Analysis

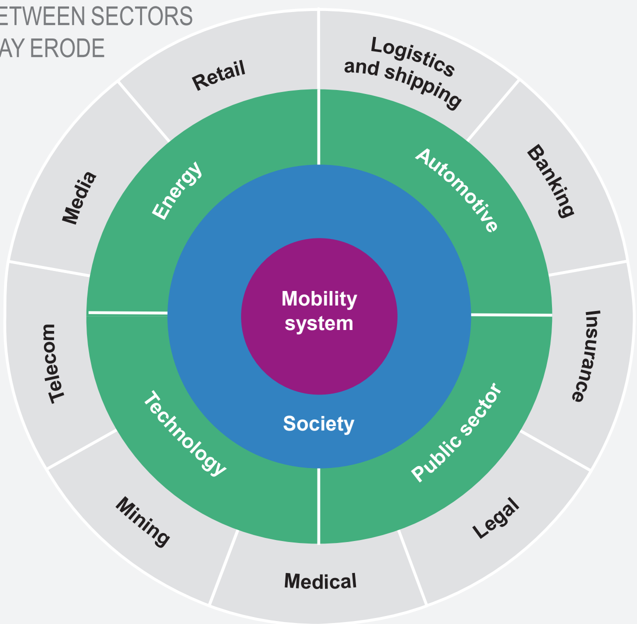
KNOCK-ON EFFECTS ACROSS SECTORS

BLURRING BOUNDARIES

Changes in the mobility system may erode the boundaries that exist today both within and between sectors (Exhibit 20). New business opportunities look set to emerge in various areas, including autonomy platforms, autonomous services, and decentralized power generation, storage, and charging.

EXHIBIT 20

BOUNDARIES BETWEEN SECTORS MAY ERODE



The shift to electrification may blur the boundaries between utilities, downstream oil and gas, and potentially other operators of charging infrastructure – a trend that we see has already started today with utilities such as Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric moving to the charging infrastructure market. Within the mobility sector itself, an on-demand self-driving taxi could replace most current shared-mobility business models. Adding a self-driving component to car-sharing operations, ride-hailing services, and taxi services makes the business models indistinguishable.

A shift to mobility-as-a-service enables a role for an integrator, sitting in between the public transit or fleet operator and the consumer, to provide an information and service delivery platform across modes. Already today, users of shared transport are one-and-a-half to two times more likely to use third-party information applications and websites than traditional public transit users.[40]

40 American Public Transport Association, Shared Mobility and the Transformation of Public Transit, March 2016.

In terms of market structure, a spectrum of systems may emerge across the globe: these may range from examples where the public sector owns the central platform, and manages public transit and the fleet of self-driving vehicles, to multiple-operator systems where public transit providers and numerous businesses coexist.

POWER SECTOR

Electric vehicles will have a limited impact on the power sector for the next 15 years, but this looks likely to rise quickly thereafter in selected regions. By 2030, electric vehicles could represent 3 percent of global electricity demand – assuming all 50 metropolitan areas marked as potential early adopters accelerate to the future states outlined in this whitepaper, and that the rest of the world's vehicle parc electrifies more gradually. In Europe, electric vehicles could represent 4 percent of the total electricity demand, offsetting a general decline in demand for other uses. (Exhibit 21). In Asia, the additional electricity demand from EVs would be small in comparison with overall demand. Electric vehicles are expected to begin making a larger contribution to demand from 2030 to 2040: Bloomberg New Energy Finance's New Energy Outlook 2016 shows light electric vehicles would add 8 percent to global electricity demand by 2040.[41]

Operating charging infrastructure may be a natural opportunity for utilities. However, the extent and composition of public charging infrastructure needed is still unclear and will likely remain so until there is more certainty on average vehicle range. The upcoming generation of purely electric vehicles with a range of over 300km increases the number of trips achievable with overnight charging at home, reducing the need for public or workplace charging of private vehicles. Extremely high utilization of autonomous electric taxis in Seamless Mobility and a lack of driveways and garages would still require investments in public fast and slow charging.

An increase in electric vehicle charging – at home, work, or via public charging infrastructure – also offers the potential to reduce peaks in electricity demand and improve average utilization of the power system, provided most vehicle charging takes place during off-peak periods. Conversely, uncontrolled charging could exacerbate demand spikes.

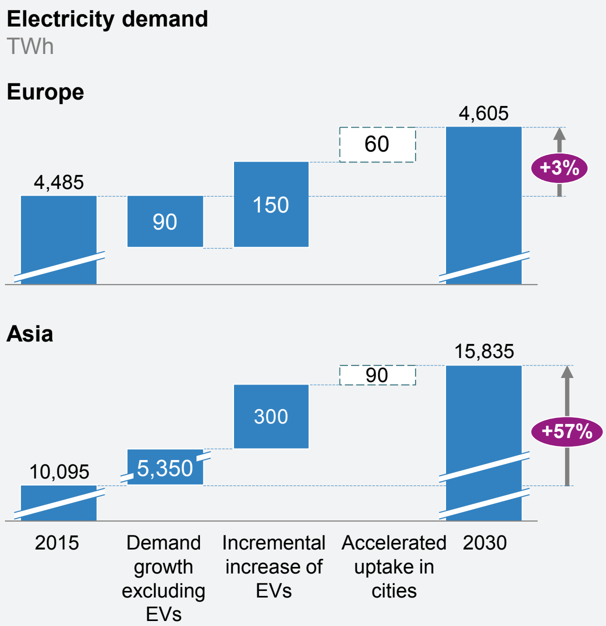
Electric vehicles are typically not charged uniformly throughout the day. The majority of charging for privately owned vehicles – and some of the commercial vehicle fleet – will take place at night. Utilities could use incentives, such as time-of-use pricing, to deliver a strong price signal in favor of off-peak charging, so mitigating the contribution of EVs to peak demand. Today, over 20 US utilities already offer time-of-use charging tariffs aimed specifically at EV owners; peak prices are typically two to five times higher than off-peak rates.

For areas with increasing solar PV penetration, utilities may also have to adjust rate structures in step with the build-out of PV. To best capture the benefits from a system-efficiency and emissions perspective, utilities and regulators in these areas may consider rate-based public or workplace charging infrastructure investments. California is in the early stages of this approach today with all three investor-owned utilities making or proposing investments in charging infrastructure funded through electricity rates. This approach could also help reduce curtailment of renewable power generation.

41 Bloomberg New Energy Finance, New Energy Outlook 2016, June 2016.

EXHIBIT 21

EVS MAY REPRESENT 3 PERCENT OF GLOBAL ELECTRICITY DEMAND BY 2030 IF CITIES SEE ACCELERATED UPTAKE



Share of total electricity demand
Percent

	2015	2030
Europe	0.03	4
North America	0.03	3
Asia	0.01	3
Rest of World	0.00	0.2
Global	0.02	3

SOURCE: Bloomberg New Energy Finance and McKinsey

The local impacts of EV charging: UK example

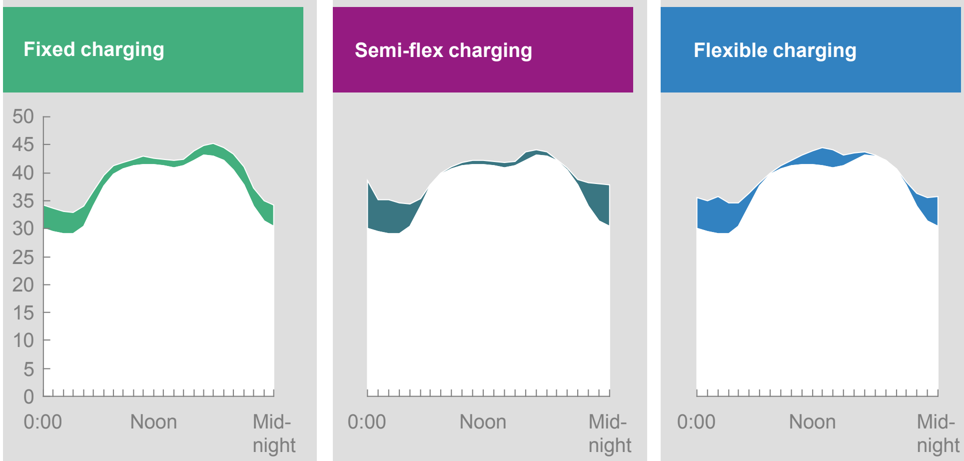
The UK example described in Exhibit 22 shows how EV charging could affect total electricity demand under three charging profiles. The first scenario assumes a fixed charging profile for all EVs in the country, based on current observed EV charging patterns with time-of-use rates in place. This is intended to represent EV charging behavior today. In the second profile, all vehicle charging takes place flexibly at the time of the day when wholesale power prices are the lowest, while still accounting for the time needed to charge. This could minimize the impact on peak demand and improve overall capacity utilization factors. This pattern would also result in much lower CO_2 emissions per electric mile driven, as the lowest wholesale price typically corresponds with high levels of renewable generation by 2030. The third profile is a blend of the two previous profiles, with daytime charging (between 6:00am and 7:00pm) following fixed charging patterns, but with nighttime charging dispatched when wholesale power prices are lowest.

A flexible profile would have the lowest CO_2 emissions, due to rising amounts of solar. In the example above, the weighted average emissions from EV charging in the flexible profile would fall from 253 gCO_2/kWh in 2015 to 76 gCO_2/kWh in 2030. The overall impact is still limited, but would become more pronounced after 2030 as EV penetration rises. Even at modest levels of EV penetration in 2030, EV charging would improve average system utilization and prevent curtailment of renewable generation.

EXHIBIT 22

FLEXIBLE EV CHARGING CAN MAXIMISE POWER SYSTEM BENEFITS

Weekday electricity demand curve
GW



Fixed charging

- Today's daily EV charging patterns remain fixed

Average emissions of EV charging, gCO2/kWh

2015	263
2020	139
2030	86

Semi-flex charging

- During the day, charging follows fixed patterns
- At night, charging at times when wholesale power prices are lowest

Average emissions of EV charging, gCO2/kWh

2015	257
2020	123
2030	86

Flexible charging

- Charging takes place at times whenever wholesale power prices are lowest

Average emissions of EV charging, gCO2/kWh

2015	253
2020	116
2030	76

SOURCE: Bloomberg New Energy Finance

An increase in shared fleets, especially in the context of Seamless Mobility and Clean and Shared, may open up new key accounts for utilities. The future states sketched for 2030 would see a dramatic increase in fleet purchases as ride-hailing, car sharing, and autonomous driving proliferate. Utilities may look to target these groups with specific rate plans as their share of electricity consumption rises. New vehicle leasing structures may emerge that roll jointly negotiated electricity rates into the total lease cost of a vehicle for individuals or mobility operators. Utilities are likely to be highly supportive of the rise of EVs, as they represent a major source new load growth over the coming decades.

Repurposed second-life EV battery volumes will rise dramatically. By the mid-2020s a large quantity of used EV batteries will become available for stationary applications. Early estimates place the cost of repurposing them at around $49/kWh, undercutting the price of new batteries.[42] They will be deployed for grid-scale, commercial, and residential storage applications and will enable higher levels of renewables to be integrated onto the grid. They may also be used to reduce peak demand charges for public fast-charging infrastructure, so improving the business model.

Second-life batteries and tariffs to incentivize off-peak charging will likely have a greater impact on the grid than vehicle-to-grid services until at least the mid-2020s. The latter remain challenging because most vehicles today are not designed to feed power back to the grid. If vehicle-to-grid technology plays a bigger role in the long-term, it will create new opportunities for aggregators. Meanwhile, grid reinforcements would be needed locally: urban areas in particular will require upgrades to local distribution grid infrastructure to support concentrated fast charging of large numbers of delivery vehicles, ride-hailing fleets, and autonomous vehicles.

OIL SECTOR

In previous publications, we outlined how global oil demand from light vehicles may pass its peak in the 2020s due to fuel efficiency and the impact of mobility trends, in particular electrification.[43,44] Nonetheless, a drop in demand from vehicles may catch oil companies unprepared. While OPEC's long-term forecast projects a negligible number of electric vehicles, our modeling suggests, with some metropolitan areas accelerating, electric vehicles may comprise up to 14 percent of the parc.[45] Whether upstream oil and gas players have to adjust to an overall liquid oil demand reduction – potentially including asset write-downs and deferred upstream investments – may depend on the degree of growth in the petrochemical sector, which could offset declining demand from passenger cars.[46]

Downstream oil and gas players should anticipate declines in local fuel demand from light vehicles, the extent of which may vary by city and region. It may fall even faster in metropolitan areas that accelerate to an advanced future state. In places that see a rapid transition towards a Seamless Mobility or Clean and Shared system, local demand for light vehicle fuels may decline by as much as 75 percent between 2015-30, according to our estimates (Exhibit 23).

The combined impact of electric vehicles and ride sharing would not just put downstream fuel sales at risk, but also reduce footfall at companies' convenience store outlets. Downstream players may want to consider a diversified offer on their sites – from charging to convenience retail – and, in the longer term, the ability to provide additional services for people beyond vehicles. In a more advanced autonomous system like Private Autonomy, vehicles may be sent to charge or fuel up on their own, reducing discretional spending on non-energy services at those sites. Retail locations along major highways may retain much of their value by offering products that help pass the time spent in self-driving cars or waiting for a fast recharge. Such services may be complemented by vehicle servicing or cleaning on site, as charge cycles are usually longer than fueling a gasoline car.

An additional value opportunity may exist in energy management services for key accounts. Large fleet

42 Bloomberg New Energy Finance.

43 McKinsey, Is Peak Oil Demand in sight, June 2016.

44 Bloomberg, Here's How Electric Cars will Cause the next Oil Crisis, February 2016.

45 Organization of the Petroleum Exporting Countries, 2015 World Oil Outlook.

46 McKinsey, Is Peak Oil Demand in sight, June 2016.

EXHIBIT 23

FUEL DEMAND FROM LIGHT VEHICLES COULD DROP BY AS MUCH AS 75 PERCENT IN SOME CITIES

Change in fuel consumption from light vehicles

Percent, 2015-2030

SOURCE: McKinsey

operators may possibly undergo a transition during which they operate both ICE and EV vehicles, or still require gasoline for other operations. Oil and gas companies could leverage their existing relationships and capabilities to provide these clients with all their energy needs, including charging infrastructure, optimized use of batteries for vehicle-to-grid applications, wholesale power procurement, and hedging.

AUTOMOTIVE SECTOR

Global light vehicle unit sales will likely continue to grow as a consequence of urbanization and macroeconomic growth, despite a trend towards shared mobility.[47] However, the mix of vehicles sold will shift from today's predominance of ICE vehicles towards a balanced mix of alternative fuel powered and ICE vehicles.

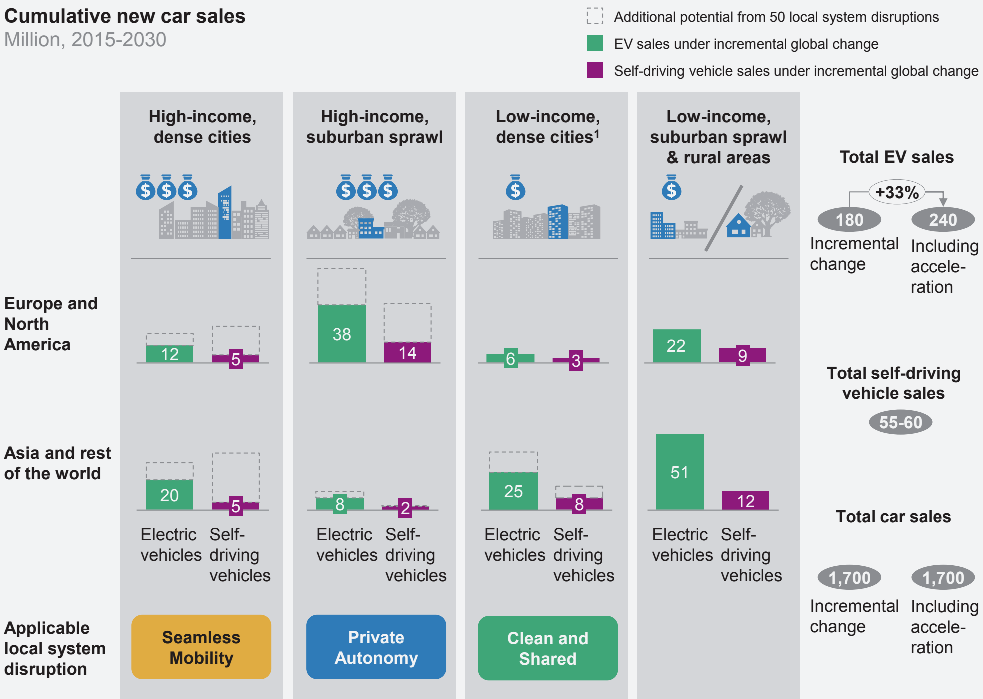
It is important for OEMs to understand which metropolitan areas are the potential early adopters, as these could represent a substantial market for EV and AV sales. If the outlined set of 50 metropolitan areas were to accelerate early, and with the pace and aggressiveness described in this paper, the global electric vehicle market could increase by up to 60 percent, depending on the specific change conditions in these locations (Exhibit 24). The evolution of these cities could impact others across the world. To do so it will be essential to have a thorough process to identify key regions and ramp up accordingly to avoid dealers being left waiting and disappointed customers moving to alternatives. Delays are common in this new EV market and might become a deal breaker where there is fast-paced EV deployment. Auto OEMs could also further prepare for the EV deployment of specific cities by finding the right public or private partnerships and may have a role in ensuring sufficient charging infrastructure is available.

This is in contrast to an outlook in which the rest of the world follows a more incremental pathway, whereby the cumulative market size for EVs for 2015–30 would rise to 180 million vehicles, out of 1,700 million total light vehicles sales. If local systems accelerate rapidly, global 2015–30 EV sales may reach around 240 million.

47 McKinsey, Automotive revolution – perspective towards 2030, January 2016.

EXHIBIT 24

CITIES WILL DETERMINE THE PACE OF EV AND AV UPTAKE GLOBALLY



1 Asia figures include the impact of a few Chinese cities in this archetype expected to achieve Seamless Mobility
SOURCE: IHS baseline data; Automotive perspective 2030; Future of Mobility Model

The market size for self-driving vehicles (L4) could reach 55-60 million units. However, if cities accelerate, this number can be significantly higher. The share of highly autonomous vehicles (L3 and L4) could be ~50 percent of passenger vehicles sold in 2030.

Connectivity has the potential to shift market share between OEMs; changing industry dynamics will also allow new players from other sectors such as hi-tech and media to enter this market. Consumers already indicate a high willingness to pay for connected car services and to change manufacturers for unique car features with respect to applications, data, and media: 20 percent of new-car buyers would switch car brands for better connectivity.[48] The automotive revenue pool will grow and diversify as a result of these new services, potentially becoming a $1.5 trillion market in 2030. Of this, more than $100 billion of recurring revenues is to be gained from data connectivity services, including apps, navigation, entertainment, remote services, and software updates.[49] These markets may emerge first in sprawl areas accelerating to a Private Autonomy state, where connected and autonomous cars are adapted at high pace.

Meanwhile, various fundamental shifts within the automotive sector may force organizations to rethink how they are organized and change their skills sets. The innovation focus and corresponding capex distribution for OEMs looks set to shift from hardware focused to software focused. As a result, OEMs and suppliers would need to switch to new recruiting strategies to tap into talent in software engineering, cloud technology, sensor data collection, and big-data analytics. Currently, automotive OEMs – with their 11:1 ratio of hardware to software engineers versus a 1:2 ratio at tech companies – face a major software and artificial intelligence talent gap (Exhibit 25). The requirement to push updates to autonomous vehicles "over the air" will need automotive R&D functions to adapt to feature-based development, in order to accommodate development of features at different speeds, and also to be decoupled from the traditional vehicle start of production date where features were fixed for the life of the vehicle.[50]

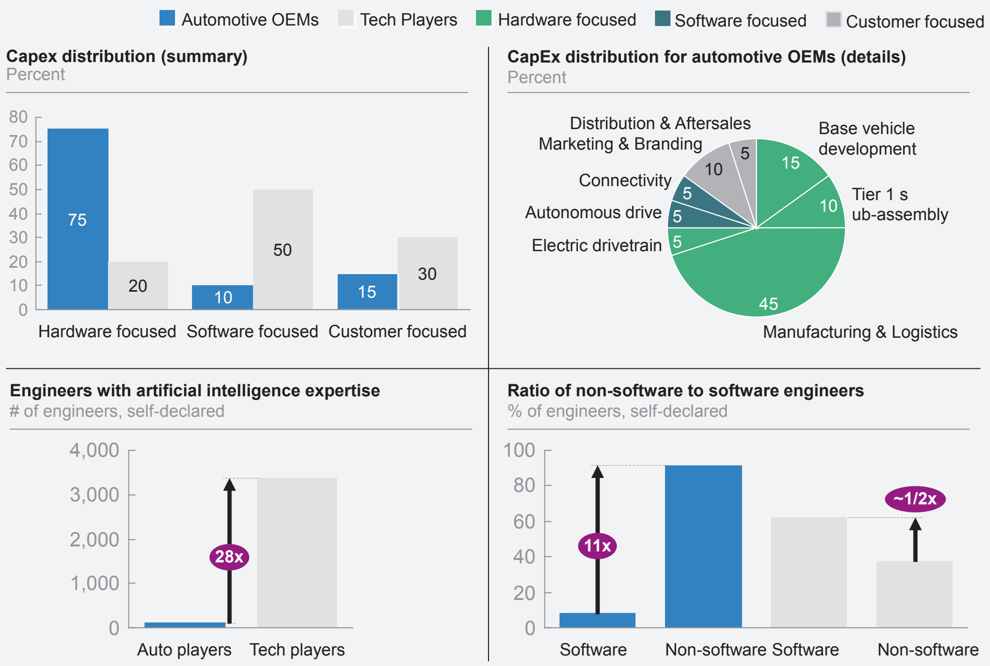
48 McKinsey Connected Car Consumer Survey, 2014.

49 McKinsey, Automotive Revolution – perspective towards 2030, January 2016.

50 McKinsey, The feature revolution, July 2016.

EXHIBIT 25

OEMs FOCUSE ON HARDWARE DEVELOPMENT AND MANUFACTURING, WHILE TECH PLAYERS FOCUS ON SOFTWARE



SOURCE: Expert interviews; Annual reports; LinkedIn; Glassdoor

PUBLIC SECTOR

Metropolitan areas compete for talent, prestige, and businesses in a struggle that ultimately determines the economic dynamism of regions and countries. Addressing mobility concerns can be a key pillar of competitiveness for metropolitan areas. Enhancing mobility in major urban centers can unlock citizen access to better housing further away from the core, improve the city's air quality and use of urban space, improve public safety, and free up valuable commuting time for more productive uses.

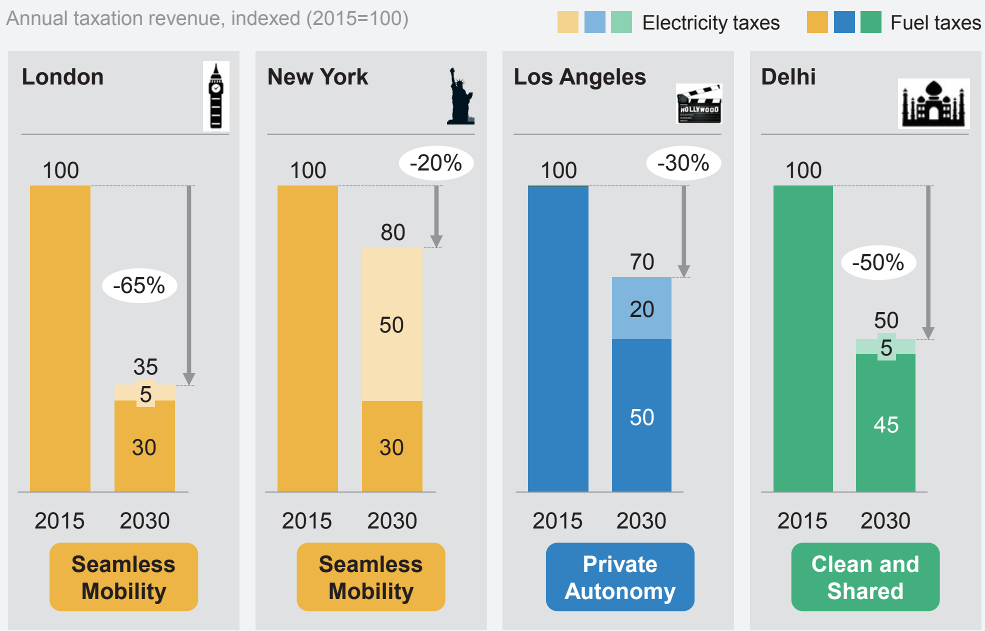
However, there are a number of aspects of the transition that governments would need to address to maximize the benefits and create a stable mobility system. For example, disruptive change to mobility systems may threaten current revenue and taxation models but may equally present new revenue opportunities. Following high levels of electrification in Seamless Mobility or Clean and Shared, and depending on the relative level of fuel and electricity tax, local disruptions may reduce tax revenues from vehicles by 20–65 percent if taxation systems remain unchanged (Exhibit 26). In addition, the increasing role of software and connectivity in all three future states may open up new taxation models based around infrastructure use and time of use. If privacy concerns can be addressed, this taxation model would be admirably simple and might also mitigate the potentially adverse impact from zero-occupancy journeys by self-driving vehicles.

Governments may also need to consider the future role of public transit, especially in light of the increasing penetration of shared mobility. In all three future states, consumers could opt for low-cost, on-demand shared mobility instead of slow or infrequent public transit, especially buses, for the first and last mile. While mass public transit will remain essential to avoid untenable congestion, from an economic standpoint, it may be most sensible to discontinue underperforming public transit routes and subsidize privately operated shared mobility instead. In the longer term, with self-driving vehicles coming into play, governments – particularly in systems heading towards Seamless Mobility – may want to consider whether a fleet of self-driving shared taxis should be privately owned or owned by a new or existing public transit operator.

With the rise of sharing and self-driving vehicles, urban planners have the opportunity to put parking space to more productive use – in many sprawling metropolitan areas this takes up to 15 percent of public space. The

EXHIBIT 26

ELECTRIFICATION MAY REDUCE ENERGY TAX REVENUES BY 20-65 PERCENT



SOURCE: McKinsey analysis based on Gov.uk, IEA, DMV, nyc.gov, delhi.gov

corollary, however, is that customers seeking their shared vehicles or citizens summoning their self-driving vehicle will bring new design requirements, such as drop-off zones, to avoid reductions in the efficient use of public space and deterioration in traffic flows.

Metropolitan areas may be able to access the benefits of mobility changes through adjustments to existing road infrastructure and using less costly demand-side levers. As, on average, new roads become congested within seven years, the increases in mobility projected by this paper would struggle to be met by conventional supply-side road building alone. The use of demand-side levers – such as dynamic road pricing and dedicated lanes – are crucial for unlocking additional capacity within road networks. Already, we see advances towards autonomous-only lanes that have the potential to significantly increase lane capacity and higher speeds through "platooning" even at low penetration rates of autonomous vehicles.[51]

TECHNOLOGY SECTOR

Connectivity is a given for today's consumers: they increasingly expect an end-to-end connected experience while they travel. At the same time, software companies are playing a significant role in developing automobiles and mobility platforms. The Internet of Things continues to grow in influence and promises also to affect the mobility sector.

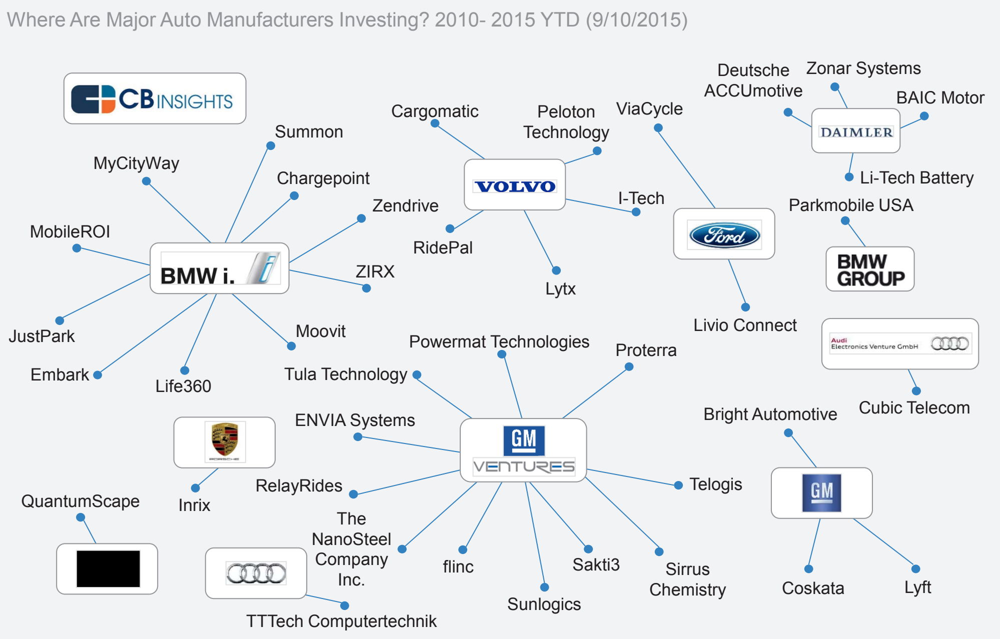
With the growing number of autonomous cars in future, more and more sensors will come into play and, with them, the data streamed through them. There is a real opportunity for high-tech players to own the data, deploy data analytics, and come up with meaningful insights. As the number of sensors and need for management of external data by the car increases, this also boosts demand for faster on-board computers with larger memory. At the same time, it will stimulate the sector to acquire knowledge and new capabilities around machine learning, big data analytics, and predictive analytics at a much faster pace.

51 Platooning involves two or more vehicles connected with vehicle-to-vehicle communication, enabling them to operate as a single unit by driving closely together.

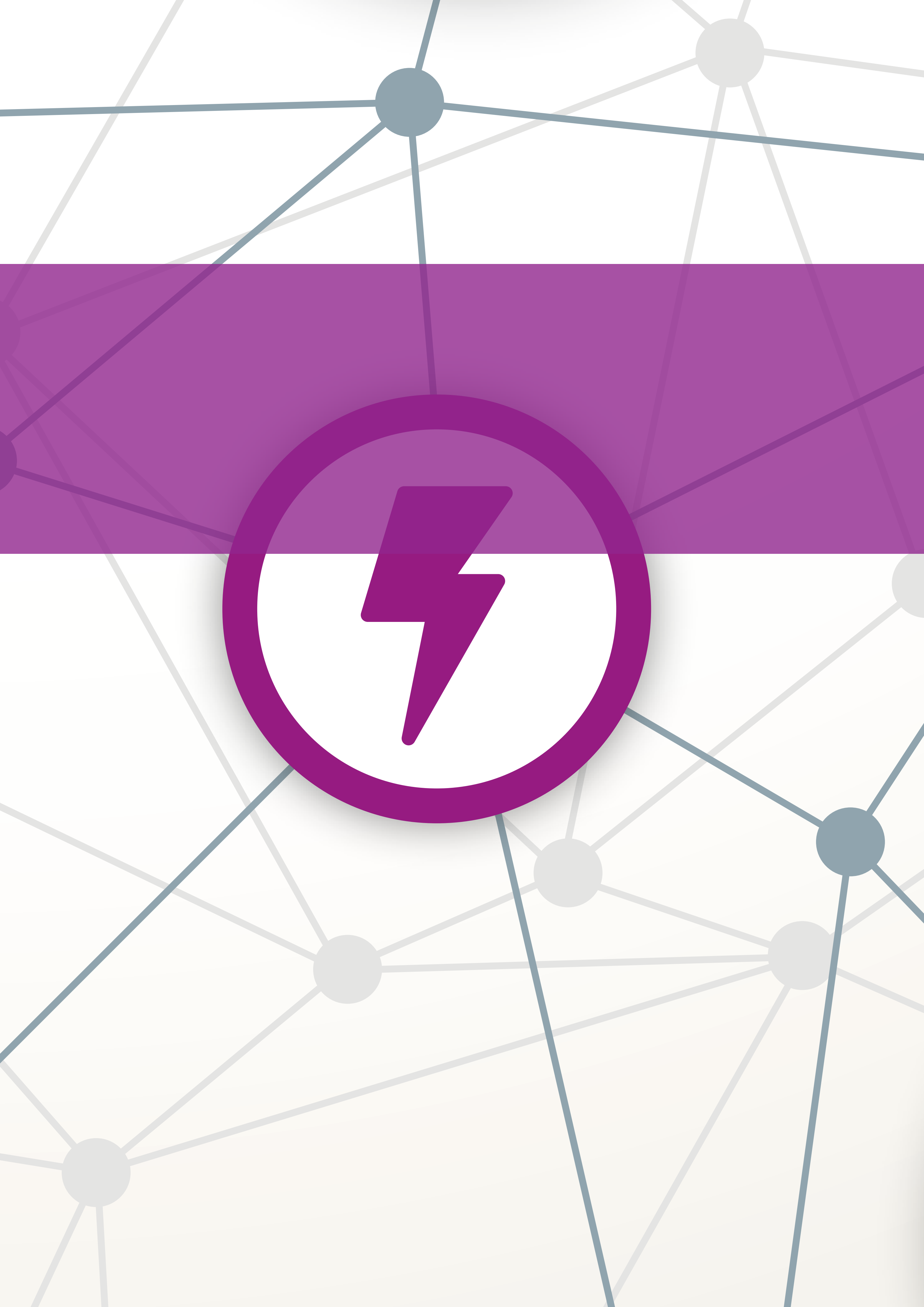
Meanwhile, software companies can play the crucial integrator role of developing technology platforms that support increased connectivity between vehicles, infrastructure, and people. Automotive companies have been investing in technology start-ups to boost their knowledge and understanding of this space (Exhibit 27). There is a wide range of potential applications, from traffic flow management, to mobility-as-a-service, to location-based retail services.

EXHIBIT 27

ESTABLISHED AUTOMOTIVE OEMs ARE INVESTING IN A VARIETY OF TECHNOLOGY START-UPS FOCUSED ON THE DISRUPTIVE TECHNOLOGY TRENDS



SOURCE: CB Insights



CONCLUSIONS – LOOKING AHEAD

The future systems described in this paper are very different from the mobility systems of today. Some local systems may accelerate towards this future in a short time frame; others may take longer – but in many systems change is already under way. These changes will allow people to travel more efficiently, more cheaply and more often, and in different ways. However, these benefits are not guaranteed; issues such as congestion and air pollution could worsen if the transition is not carefully managed.

Individual consumers will remain at the center of this evolution, in terms of their openness to adopt electric and autonomous technologies and to share vehicles and rides. Nonetheless, it is important to understand that, although individual consumers can afford to wait and embrace change when it comes, public and private sector actors have roles to play to prepare for this future:

- **Companies and governments should take an integrated perspective,** rather than looking at each emerging mobility trend in isolation. Appreciating the interdependencies and reinforcing effects between trends is crucial to understanding the potential pace and impact of change, to analyze the trade-offs, and to lay out a clear path forward that balances the upside with potential adverse effects.
- **Governments and regulators could capture societal benefits by addressing bottlenecks to adoption of advanced mobility.** In this context, government could craft regulation that is in sync with technology development and ahead of consumers: this includes support for self-driving vehicle pilot programs and incentives to stimulate uptake of electric vehicles, particularly in urban areas. Public investments in charging infrastructure and dedicated lanes for self-driving vehicles could stimulate uptake of electric and autonomous technologies. Incentives to steer autonomous vehicles toward shared rather than private use will help curb demand increases from zero-occupancy rides and maximize the social returns from this innovation. Regulators should also consider preempting the potentially adverse effects of increased mobility and loss of fuel tax revenue, for example by using connectivity to facilitate infrastructure pricing or introduction of ultra-low zones.
- **Ecosystem players – public and private – will need strong partnerships to succeed.** Basic mobility needs in a system could be provided by a blend of public transit and shared mobility business models. Cities and transit operators should leverage, for instance, the benefits of ridesharing and the potential of autonomous vehicles for first- and last-mile services.

Private sector players should consider partnerships that cut across traditional sector boundaries, many of which have already started to blur. Consumers will judge vehicles by how they are integrated with the services they provide – from in-car entertainment to on-demand rental platforms. Those industry players that manage to unlock new partnerships between technology and service providers will stand the best chance of avoiding being marginalized.

- **Global private sector players should pay attention to changes at a local level and adapt strategic options accordingly.** We are expecting future auto markets to be significantly different to today's geographical markets, making it essential to be prepared for success in new networks and ecosystems. National or regional strategies will likely not recognize the disparity that will emerge between metropolitan systems; applying a local lens helps to understand which metropolitan regions might change most rapidly. This view also allows global players to understand when and where their business is at risk, and where additional opportunities may first emerge. Such insights would enable them to contribute to the creation of improved mobility systems and remain responsive enough to adapt successfully from sudden changes.

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