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The Impact of Autonomous Vehicles on Cities: A Review

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ABSTRACT

Autonomous vehicles (AVs) are starting to hit our roads. It is only a matter of time until the technological challenges still facing full AV implementation are solved, and legal, social, and transport issues related to AVs become part of the public discussion. AVs have the potential to become a major catalyst for urban transformation. To explore some of these transformations, first, we discuss the possibility of decoupling the many functions of urban vehicles from the form factor (without drivers, do cars need to look like they look today?). Second, we question whether AVs will lead to more or fewer cars on the roads, highlighting the synergies between AVs and ride-sharing schemes. Third, with AVs as part of multimodal and sharing-mobility systems, millions of square kilometers currently used for parking spaces might be liberated, or even change the way we design road space. Fourth, freed from the fatigue related to traffic, we question whether AVs would make people search for home locations farther from cities, increasing urban sprawl, or would rather attract more residents to city centers, also freed from congestion and pollution. Fifth, depending on responses to the previous questions and innovative traffic algorithms, we ask whether AVs will demand more or less road infrastructure. We conclude by suggesting that AVs offer the first opportunity to rethink urban life and city design since cars replaced horse-powered traffic and changed the design of cities for a hundred years.

KEYWORDS
Autonomous vehicles; urban design; vehicle form; urban infrastructure

Introduction

In 1909, the First National Conference on City Planning, in Washington DC, was canceled after it became evident that city planners could not solve the traffic and health problems related to the then current transport modes. Big cities, such as New York, relied heavily on horse-powered vehicles, despite the fact that they were imposing a massive burden on the urban population.

However, around the same time, another mode was starting to take over the streets, and less than two decades later, the problems related to horse-powered transport were completely solved without any active participation of planners or designers: internal-combustion vehicles (once called horseless carriages) freed the cities from animal traffic, odors, and carcasses—thousands were left behind yearly in the streets of New York alone once the "engine" of horse-powered vehicles died on duty (Tarr and Mcshane, 2008).

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Soon urbanists understood how powerful internal-combustion vehicles would be in AQ3 transforming the way cities functioned and people moved. In *The City of To-Morrow and Its Planning*, Le Corbusier proposed that cars would overturn "all our old ideas of town planning." Long, wide, and multiple-lane roads would have been its new armature: "a machine for traffic, an apparatus for its circulation" (Le Corbusier, 1987: 123).

Today, one century after cars transformed several aspects of urban life, a new technology can once again become a force in how we think, plan, and design cities. Although in an experimental phase, AVs are starting to hit our roads, and it has already become a consensus among transport planners and urban designers that they might redefine urban mobility in the near future. However, the way in which this will happen is far from decided—and is the focus of this discussion paper.

One should say that the dream of AVs is not new. In the 1920s, radio-controlled Phantom-Autos were showcased in a few American cities, pretending that "there was an invisible driver at the wheel" (cited in Stayton, 2015: 13). In the 1950s, in another utopian phase of the history of AVs, a General Motors ad showed a family enjoying a ride on a landscaped highway, while chatting and playing dominoes in a lounge-like car. In this case, the automation was embedded in the tracks along the roads, not in the car; but the imagery of freeing your time while driving was the same.

It was only in recent years that AVs started becoming a reality. In 2003, the Defense Advanced Research Projects Agency (DARPA) changed the game when they announced a competition to develop AVs capable of driving on desert trails and roads. In March 2004, during the first DARPA Grand Challenge, no vehicle was able to complete the challenge, with the Sandstorm AV going the farthest. A year later, five AVs completed the 244 km race in approximately seven hours. The following year, teams faced a new challenge: drive 97 km in an urban environment in California. In the first phase, 89 teams presented papers demonstrating their technological capabilities. Fifty-three were selected to follow short-test phases, and finally 11 qualified for the Urban Challenge Final (Buehler et al., 2009).

At that point, the belief that AVs were something out of a science-fiction movie was over. Evidence can be found in the increasing number of articles that began to appear in both general media and scholarly journals. For example, *The New York Times* wrote the first article about driverless cars in 2007. Five years later, the newspaper published seven articles, and in 2016, 96 *Times* articles were published on the subject. In scientific publications, the interest in AVs spans a longer period, but the number of articles is also growing. The Institute of Electrical and Electronics Engineers (IEEE) has published 1,929 conference papers and 274 papers in its affiliated journals through 2016. Figure 1 shows the increase in IEEE conference papers published, reflecting the growing interest in AVs.

Indeed, cars have always been blind, deaf, and anosmic (incapable of smelling). AVs, on the other hand, rely on extremely accurate senses. Laser scanning, shape-detection, and computer vision techniques have made AVs able to measure relative distances, avoid obstacles, and keep AVs on track. Even though some researchers see algorithms capable of performing as well as humans in situations with low visibility, such as snow and rain as "unrealistic" (Cord and Gimonet, 2014, p. 50), others see AVs as a "sentient" plat- AQ4 form—to use the title of Mark Shepard's 2011 book—sensing the surroundings and making decisions to conform with general traffic. Combining sensing and communication

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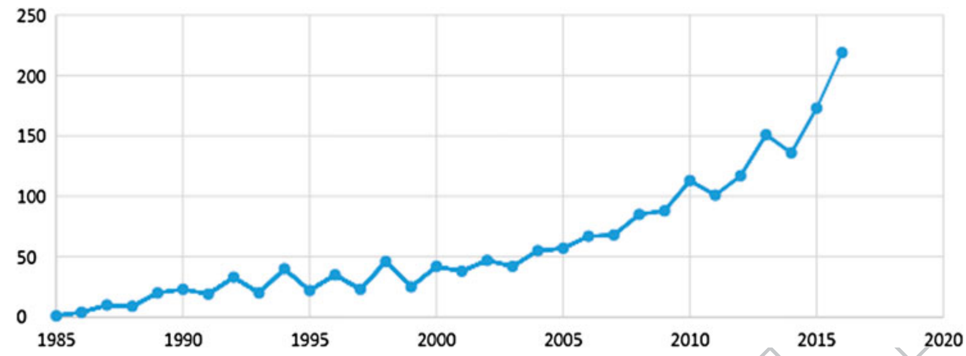

AQ30 AQ16 **Figure 1.** IEEE Conference Papers on Autonomous Vehicles. Source: IEEE <http://ieeexplore.ieee.org/xpl/opaccnf.jsp>Accessed .

features enhances AV's understanding of space, by requesting and accessing information from other cars and static infrastructures, from a 3D-point cloud data to the detection of people and objects that are obstructed by other elements (Kumar et al., 2012).

AVs have to sense the surroundings and communicate with other AVs, mobile devices, and infrastructures, in order to better perform. As Massaro et al. (2017) demonstrated, by collecting data from a 900 in-vehicle car controller area network (CAN), one can understand individual driver's behavior (in a regular car) and the spatial and temporal data from the surrounding environment through which AVs drive.

In 2013, the US Department of Transportation's National Highway Traffic Safety Administration (NHTSA) defined five different levels of autonomous driving: *zero*, when drivers have full control of the car; *one*, when specific functions, such as steering or accelerating, can be performed automatically; *two*, when some functions respond using information about the driving environment, but the driver must be ready to take control; *three*, when cars are fully autonomous under certain traffic conditions; *four*, when cars also perform all safety-critical driving functions within a certain number of driving scenarios; and *five*, when vehicles are fully autonomous, capable of operating in any driving scenario (SAE International, 2016). In fact, the automotive industry has been continuously incorporating parts of the algorithms and devices required by AVs into regular vehicles, including the four performance categories: (1) steering, acceleration, and deceleration, (2) monitoring of driving environment, (3) fallback performance of dynamic driving task, and (4) system capability (driving modes).

When fully autonomous vehicles take the roads, they will pass unnoticed—but their consequences to urban mobility and city designs could be major. Still, reviewing the summary proposed by Stanford (2015) of 50 papers dealing with AVs at the 2015 Transportation Research Board conference, the physical transformation of cities linked to AVs is mentioned only tangentially in one of the 21 categories he proposes. These were summarized by Van Arem (2015), and include residential, employment, and recreational locations, and road, parking, and bicycle and pedestrian infrastructure. In addition, as other authors (Townsend 2014; Ratti and Biderman, 2017) argue, the increasing use of AVs in car-sharing programs also changes car-user habits—although sometimes with contradictory outcomes. For example, these programs could either increase driving, since people could move to suburbs even farther away once they are free from the burden of driving, or reduce driving, giving room to more pedestrian-friendly central business districts (CBD) which, consequently, would attract new residents.

Currently, the cost of the technology required to make a vehicle autonomous varies from $8,000 to $250,000 depending on whom you consult (LeVine, 2017). If autonomy is added in pieces, it goes from $5,500 to add an autopilot and $2,000 for automated parking up to $50,000 for the 64-beam Lidar currently used on Google's self-driving cars (Davies, 2015). If accidents virtually disappear, insurance costs will become lower; however, if an accident happens, all liability might be on the manufacturer, who will somehow incorporate this financial risk in the price of the vehicle. As it happens with the introduction of new technologies, factual or data-based analysis are restrained by the lack of enough facts or data, and when it is done, the risk is to rely on specific cases that are more anecdotal. For example, the accident with an AV Uber in Temple, Arizona (no one injured), the long investigation on a fatal crash involving a driverless Tesla in autopilot mode (federal auto-safety regulators found no defects in the car's system), a Florida district opposing investments on public transport since AV would make it obsolete (Morris, 2014), or even the more than three million kilometers already driven by Google's AV, which although impressive, is residual in the face of the billions of kilometers Americans drive annually.[1]

We are probably on the brink of major transformations in urban mobility, and many changes in urban dynamics and city form could be triggered by AVs. In this paper, we discuss how autonomous vehicles will reshape the way we live and design cities around five questions:

(1) Will AVs look like cars as we know them? Underlying all the possible changes AVs can bring to the cities is that the current form of vehicles might change. Without the need of a driver, why do delivery trucks need to look like ambulances or buses? Freeing AVs from the current form factor that is ultimately linked to a technological constraint (the need of a driver), AVs could be used for other tasks, especially if the form factor changes (working, sleeping, etc.). In summary, by challenging the form factor of current vehicles, AVs could open possibilities to rethink the way cities are spatially organized.
(2) Will AVs lead to more or fewer cars on the roads? Freed from the burden of driving, more people might be willing to move using private cars, including a population currently forbidden to drive, such as under-age youth and elderly people; but on the other hand, AVs can create a mobility web, where the same car is used by different family members or even strangers throughout the day. Combining AVs and car-sharing schemes, the number of cars on the streets can be dramatically reduced.
(3) With AVs creating a mobility web, will we need more or less parking? If more people decide to move using cars, one might argue that more parking spaces will be necessary —but this assumption is based on the fact that cars are idle 95 percent of the time. If AVs are used more frequently, not linked to ownership but forming a mobility web, fewer cars and, therefore, fewer parking spaces, will be necessary, so most likely we will recover much of the land now devoted to urban parking. And this might influence how we design cities.
(4) Will AVs lead to more or less sprawl? Some argue that freed from the burden of driving, and also with AVs coordinating traffic among themselves (consequently

with less congestion and less commuting times), people might decide to move even farther from cities. Consequently, urban sprawl would increase, with the environmental consequences it brings. On the other hand, AVs will decrease the number of casualties in the urban environment, and will be programmed to be conscious of pedestrians, speed limits, and other traffic regulations, making cities more livable—therefore, attracting more residents to denser urban areas, which have more economic, cultural, and social options.

(5) Will AVs require more or less road infrastructure? Part of the answer is tied to the previous questions: if urban sprawl increases and more people move using cars, we'll need more roads. However, since AVs drive more efficiently than human-manned cars, and AVs will exchange data with urban infrastructure, we might need less road infrastructure to carry the same number of people.

Will AVs Look Like Cars as We Know Them?

So far, all discussions about the changes AVs will bring to transportation, urban life, and city form follow a logic of substitution: AVs replacing cars as they are conceived, designed, and used today. But what if we think of AVs as driverless platforms, detached from the form cars have today?

William Mitchell, Christopher Borroni-Bird, and Lawrence Burns (2010) propose a comprehensive study on how cars could be redesigned and, by that, redesign the roads. Their proposed CityCar would weigh one third of a Toyota Prius, and, when folded, occupy 40 percent less space than a Smart Car. In their proposal, cars could have different wheel and door configurations based on the number of passengers. Envisioning some autonomous technologies and a widespread network of electric charging points, their work is a benchmark for the possibilities of cars in contemporary cities. Still, in virtually all cases presented in the book, two pieces are constant: the driver and parking spaces.

What if we disassemble the car in its multiple uses? Currently cars are a "chaperoning" platform. Drivers "chaperone" other passengers, goods, garbage, and law enforcement. Think of the daily commute for a family with two children: one parent chaperones the kids to school and heads to work. During part of the trip, only one seat is occupied, and the trunk has no function. When the parent arrives at the workplace, the car is parked for hours. Now think of this parent stopping at a supermarket on his way home; groceries would probably not completely fill the trunk, and four seats would be empty. Finally, let's imagine the driver ran a red light and was stopped by a police car—in which case at least two seats and the trunk are not used. In the first case, we need to move people; in the second, goods; and in the third, law enforcement. Applying such uses to the same form factor restricts the possibilities of rethinking AVs.

AVs open up the possibility of decoupling the uses of a moving platform from the established shape of a car. AV platforms to transport groceries could be the size of a trunk, or even smaller (in length or width). The British company Just Eat is delivering takeout orders using AVs that look like "large insulated picnic basket[s]" (Johnson, 2017). For delivering goods to a single household, one platform would be used; however, multiple platforms could create a train-like platform and travel together if the trip-planner algorithm indicates this platform will save fuel and avoid traffic.

Likewise, pods moving one person would require only a small pod (rather than a four-seat vehicle), that could either be stretched or combined with other pods to form larger platforms of platoons. Such demand-responsive schemes still need to overcome the challenge of having users accepting sharing vehicles or, at least, combining vehicles. Based on recent data about ridesharing, whose penetration is forecasted to go from 18 percent in 2018 to 23 percent in 2022,[2] it is fair to assume that demand-responsive schemes have market potential.

Although it is not clear how AVs will look like in the future, it seems clear that the form of current cars is a constraint for realizing the full potential AVs have to reshape how we live and design cities. As the examples discussed above point out, for both people and freight transport, and for urban services, decoupling AVs from the general shape of current vehicles (all with driver's and passengers' seats even when all we want from the vehicle is to police the streets), might open up new options to vehicle design.

More or Fewer Cars on the Road?

The car fleet in the world has been growing rapidly, and in tandem with economic growth. The single solution to decreasing the number of cars on the roads has been investing in massive public transport. Indeed, despite all technological breakthroughs, there is no point in thinking of AVs as a substitute for public transport. Even though combining car trips or coordinating fleets could increase throughput by up to 20 times, car platoons would hardly compete with the average capacity of a subway, or even buses. As Stanford (2015) shows, this has been the battle between individual and collective modes since the introduction of cars in the early Twentieth Century. Regardless of how smoothly AVs can negotiate traffic without risks of collision and frequent stops at intersections, the fleet of AVs required to replace a simple subway train would clog urban roads.

However, despite the arguments from public transport advocates and even in cities with large investments in transit, the point-to-point mobility offered by cars continues to be attractive. As Robert Cervero (2017: 7) points out, "[t]he marriage of self-driving cars and car sharing could be America's true mobility game changer." Therefore, AVs benefit to cities and urban mobility will depend on synergies with other innovative technologies and urban design strategies—such as Transit Oriented Development (TOD), as explored by Lu et al. (2017). TOD privileges higher population densities near stations and corridors as a way of both providing transit alternatives to more people and to secure enough passengers to the transit systems. AVs could be used as a feeder mode, bringing passengers from the surrounding areas to TOD stations and corridors, mainly in situations where there is not enough demand for the implementation of a bus-feeder system.

Still, some demographic changes indicate that personal mobility will still increase. On one hand, young people have started driving later than in previous generations and many chose not to get a driver's license, but on the other hand they have less strict working hours and jobs not tied to specific locations, thus increasing mobility, as daily life becomes more hectic (Alessandrini et al., 2015). This population requires more and diverse mobility, freed from the temporal and spatial constraints of public transport, with its fixed routes and schedules.

In addition to this already increasingly mobile population, AVs might attract other demographic segments that currently either remain mostly immobile or rely on public transport or other private modes to move around, such as the elderly and children. Most discussions around AVs have been done keeping some driving regulations from the human-manned-cars point of view. In the current human-manned driving regulations, impaired elderly people and under-driving-age youth are not allowed to drive. With liability burdens removed from drivers, and the comfort of point-to-point mobility maintained, these populations might opt to use AVs—which would increase the number of cars on the roads.

On the other hand, we could argue that AVs can help to reduce the number of cars in cities. In parallel to the AVs development, another mobility transformation has been gaining favor in the transport mix: ride sharing. Sharing a personal car with someone unknown seemed inconceivable a few years ago. However, ride-sharing apps have boomed in many countries, consequently reducing the number of cars on the roads. In its current version, scholars estimate that for each shared vehicle, 9 to 13 cars are removed from the streets (Ratti and Biderman, 2017). In Singapore, only 30 percent of the fleet could meet the personal mobility needs using sharing-mobility solutions (Spieser et al., 2014). Based on more than 150 million taxi trips in New York City, Santi et al. (2014) demonstrate that if passengers were to wait five minutes, more than 60 percent of the trips could be shared, representing over 20 percent of travel time saved daily. Based on three million taxi trips in New York, Alonso-Mora et al. (2017) found that, using fleets of vehicles with varying passenger capacities, 98 percent of the trips had a mean waiting time of about three minutes.

AVs could improve sharing mobility dramatically. Using an agent-based model for shared autonomous vehicles (SAVs), Fagnant and Kockelman (2014) showed unused SAVs relocating themselves in order to shorten wait times for the next riders. Although this increased 10 percent the total distance travelled when compared with non-SAV trips, it required far fewer vehicles to perform the same number of trips. Based on a simulation in Austin, Fagnant and Kockelman (2016) found that each SAV operating in a pooling-like system (3.02 passengers per trip, and waiting times at peak hours below 5 minutes) could replace 10 conventional vehicles. Indeed, with AVs Wendell Cox (2016) argues that the point is not sharing rides, but sharing cars in both short- and long-term leases, with companies dispatching AVs on demand, which, instead of being stored in a central garage, would use existing private garages as intermediate parking spots. AVs could also service the last mile between key transit stations and many more destinations than regular bus feeder services —which could attract more passenger to mass transit. Thus, AVs could leverage transit by combining private and public modes in a seamless moving web.

In fact, the increasing number of ride-sharing users shows how social aspects play an important role in the adoption of new transport modes. The main driver of the household and residents living in households with more than one vehicle (mainly in low-density areas) are less likely to use ride-sharing schemes, whereas residents living in city centers, people with graduate degrees, and frequent users are more likely to adopt ride-sharing schemes (Prieto et al., 2017; Dias et al., 2017). Shen et al. (2016) have proposed ways to incorporate AVs and ride-sharing systems, based on an information center, a fleet of AVs, and self-interested passengers who opt-in and out of the system dynamically.

Therefore, the answer of whether AVs will bring more or fewer cars to the roads is far from straightforward. It will certainly depend on social aspects, which sometimes seem to be moving in opposite directions: on the one hand, sprawling continues to occur and could be fostered by the use of AVs and friction-less traffic, but on the other hand, ride-sharing apps received worldwide acceptance, proving that the trade-off between paying less for fuel and avoiding the trouble of finding parking spots in exchange for sharing the trip with strangers is worthwhile.

However, as shown above, data-driven research on the combination of AVs and ride-sharing apps show the potential AVs have to promote more rational use of personal vehicles and thereby reduce the number of cars on the roads.

More or Fewer Parking Spaces?

"The contemporary car is not a driving machine but a parking machine" (Hawken, 2017: 185). Cars are idle 96 percent of their life span, and AVs could have a utilization rate AQ5 higher than 75 percent ("If Autonomous Vehicles Rule the World," 2015). Martinez (2015) used agent-based algorithms to calculate that traffic in Lisbon could decrease by 90 percent if people used shared taxis and public transport; however, the optimization of driving times of cars would increase mileage traveled, and consequently, pollutant emissions.

One of the positive effects of driverless cars could be decreasing the demand for parking spaces in cities. Limitless fluidity implies less demand for parking. In the United States, where 94.5 percent of the population commutes by car, parking spots cover 4,400 square kilometers—or 75 times the area of Manhattan (Ben-Joseph, 2012). Parking spots in Melbourne cover an area equivalent to 76 percent of downtown (Lipson and Kurman, 2016), and in Los Angeles, the 110,000 on-street parking spots cover an area of 331 hectares, equivalent to 81 percent of the downtown area. Considering the sharing potential presented by Tachet et al. (2017), and considering that AVs can be constantly moving, tens of thousands of parking spots could be converted in nobler uses.

In Donald Shoup's (2006: 128) words, "Everyone parks free at everyone else's expense." Garage buildings create monstrous and unappealing urban structures in downtown areas, and on-street parking spots eat up sidewalk space as well as an additional traffic lane, which negatively affects both pedestrians and drivers. Parking spots externalize the parking costs to everyone, and Shoup (2006) argues that charging for parking could result in more people using different commuter transportation. Considering AVs could serve multiple users during the day and therefore remain parked much less than regular cars, or AVs could move back home or to cheaper parking areas designated by the city as less impactful to the overall traffic, increasing parking costs could induce people to use AVs.

However, John Jakle and Keith Sculle (2004) note that parking, as a "necessary evil," is an extension of the driving experience, and the car has gained prominence in defining the personal identity of its owner. Still, the growing and fast adoption of ride-sharing schemes have showed that the personal attachment to cars might be changing. In a more radical scenario, AVs would be in use most of the time, reducing the need for parking, or, at least, reducing the need for parking space in premium areas, such as downtown areas or CBDs. When not operating, or when the time between trips exceeds a certain threshold, AVs will be in parking mode. The system will calculate the cost of parking as the product of expected parking time and the hourly parking price, as well as the travel distance. Using this logic, Wenwen Zhang and Subhrajit Guhathakurta (2017) simulated the AV parking algorithms in Atlanta, Georgia, and found that each AV could remove up to 20 parking spaces, when in combination with 5 percent of vehicle ownership reduction and vehicle occupancy improvement.

The impact of parking optimization using AVs can be even greater in downtown areas. Garage buildings currently located in premium areas could be converted to other uses, including retail, leading to more dynamic downtown areas. The elimination of on-street parking spaces could spark the creation of public areas, such as the 51 "parklets" created in San Francisco since 2010, and dozens of them worldwide, from Mexico City to Auckland. Also, the elimination of on-street parking spaces could reduce the number of required lanes, making cities denser, helping to reduce the energy consumption per capita tied to private cars as well as the total private and public expenditures on passenger transport (Bruun and Givoni, 2015).

If we combine these arguments with the fact that AVs will be freed from the car form-factor, and instead will likely be thought of as AV platforms with multiple and combinatorial functions, the consequences for parking are even more radical. Freight-transport AV platforms can be stored together, following more of a "container" logic, which would optimize the use of space both horizontally and vertically. Passenger AV platforms could be assembled and decoupled according to the necessity and availability of parking spaces, which cities could manage according to specific events. AVs, if thought of as moving platforms, not cars, can trigger novel road and urban designs.

More or Less Urban Sprawl?

Freed from the burden of driving, with AVs coordinating traffic among themselves (producing less congestion and reducing travel times) and allowing passengers to do non-driving activities and not be attentive to traffic, commuting might stop being cumbersome.

Freed from the current form factor, AVs will not only allow us to play chess or have a picnic while travelling, but AVs could be used for other productive and pleasant tasks, decreasing the value of travel time—and such users do not put much weight on travel time, since other activities can be performed while traveling (Berg and Verhoef, 2016). Reducing the stress related to commuting, and turning the wasted time of driving into a productive or pleasant time, the distance between home and work becomes a minor factor when deciding where to live. Actually, 10 percent of AV market penetration can reduce traffic up to 15 percent, and a 90 percent market penetration could lead to 60 percent reduction in freeway congestion—which would represent savings of about 2,700 million hours but an increase of 9 percent in vehicle-miles traveled (VMT) (Fagnant and Kockelman, 2015). The immediate consequence of all this might be a further increase in urban sprawl.

Indeed, in spite of all the buzz around revitalization of city centers, sprawling continues to grow in the United States, although results are uneven across regions. Los Angeles became more compact between 2000 to 2010, due to infill development, whereas Charlotte, North Carolina has one of the fastest sprawling areas in the country—the conversion of rural areas into urban areas, and the use of private cars are constant factors among sprawling regions (Hamidi and Ewing, 2014).

Therefore, AVs could make people decide to move even farther from cities, based on the long-lasting American ideal of living near natural spaces in single houses with backyards. Even environmentally-conscious people might justify their option with the fact that AVs will probably be electric. Other technological advancements also back an increasing sprawling. Currently, one of the consequences of urban sprawl is that it is significantly associated with fatal car crashes (Ewing, Hamidi, and Grace, 2016). Since AVs might virtually eliminate all car crashes, this negative effect of sprawling will disappear.

Online shopping has been growing steadily—the US National Retail Federation estimated that e-commerce would grow 8 to 12 percent in 2017, three times higher than the overall retail segment (BI Intelligence, 2017); likewise, online courses, from free courses to college degrees, are also growing fast with the support of large and important universities—from 2014 to 2015 the number of higher-education students taking at least one course online has grown 4 percent (Allen and Seaman, 2016); and online entertainment has already disrupted sectors such as music and news, and is on its way to disrupting the literary and movie industries. Within this scenario, AVs will merely foster a growing tendency of decoupling traditional urban and social functions from their respective spatial and temporal constraints.

What is not clear yet are the broader environmental consequences of more sprawl. Sprawling requires the expansion of the road system as well as other physical infrastructures, such as water supply and waste removal—in general, sprawling tends to have negative environmental effects—increasing energy use and decreasing water and air quality (Wilson and Chakraborty, 2013).

On the flip side, since AVs virtually eliminate the number of casualties in urban areas and will be programmed to be conscious of pedestrians, speed limits, and other traffic regulations, cities will likely become safer and more livable. Cities still promote something that developments in communication technologies have not been capable of doing yet: fostering social interactions. In different scales, from a city to university campus, physical proximity boosts casual encounters, which promote novel ideas and social diversity (Florida, Mellander, and Adler, 2015), and plays a major role in scientific innovation (Claudel, Massaro, Santi, Murray and Ratti, 2017). Thus, the promise of a safer urban environment, with fewer accidents, and reduced noise and air pollution, might attract more people to city centers. It is also likely that dense urban areas will attract more shared autonomous vehicles (SAVs), with shorter waiting times. Because commuting time is an important factor in the decision about home location, with more SAVs cities might become more attractive than suburbs or exurban areas.

The tradeoffs between AVs and the built fabric of cities are still unclear, and changes in land use is a slow process, and takes several years before being observed. In any event, the way we design cities will probably change when multipurpose AVs take the road.

More or Less Road Infrastructure?

When cars became the main transport mode, cities were reshaped to accommodate the newcomer. Streets became wider, longer, and straighter to allow for cars' optimal performance. Now, AVs may also require changes in the road infrastructure. Some solutions seem futuristic, such as Elon Musk's underground roadway system for driverless cars, which would allow cars to escape ground traffic through high-speed tunnels, after being "sucked" down in skate-like platforms.[3] Looking closely, you don't see any pedestrian or public transportation. Instead there is a maze of highways and typical four-seat cars. A glossy diversion to the fact that this would imply, again, massive public investments in gargantuan road infrastructures favoring cars—exactly the problem bad planning AQ6 brought to cities throughout the Twentieth Century. Or, as Alissa Walker (2017:) says, "detrimental to those hard at work solving real problems." Moreover, such solutions feel old: in order to accommodate cars in the early Twentieth Century, city planners gave up city-centered and multimodal approaches and adopted highway-centered and single-mode urban freeways (Brown, Morris, and Taylor, 2009).

However appealing these solutions might be from a traffic-engineering standpoint, vibrant cities still rely on the frantic and stimulating traffic of bicycles and pedestrians. The decision, from an urban design point of view, is whether we subjugate to traffic fluidity, adapt to it, or explore it as an opportunity. Examples of subjugation abound in all flyovers across the world. Often pedestrians have to walk hundreds of meters more to cross a single 20-meter wide urban road for the sake of traffic fluidity. Hong Kong's passageways between commercial buildings are examples of adaptation. In parts of the city, the street level is negated to pedestrians, but as most activities happen in commercial centers, passageways are part of the architecture. Still, flyovers and passageways are reactive urban design solutions. Putting aside flashy solutions by merely balancing speed levels when negotiating with other vehicles, AVs could save at least 10 percent in fuel consumption when forming trains, or platoons, travelling bumper to bumper on highways (Waldrop, 2015), or could double the existing average road infrastructure capacity, and freight AVs, always on the move, could reduce the necessity of large urban areas dedicated to warehouses (Flämig, 2016).

Design breakthroughs come when AVs are thought of as a technology integrated and AQ7 exchanging data with other urban infrastructures. Take traffic lights as an example. Some 150 years ago, traffic lights were conceived to negotiate conflicting traffic at intersections. We could argue now that traffic lights could be eliminated with the implementation of distributed systems of traffic data exchange—such as discussed by Tachet et al. (2016). The authors propose a slot-based solution at intersections, where cars, by exchanging data about location, speed, and directionality, could coordinate the right of way among themselves, eliminating the need for a century-old communication device. The throughput of slot-based intersections could be twice as high, in a given amount of time as one with traffic lights. Another research, combining data from millions of drivers' mobile AQ8 phones, proposes traffic optimization schemes (Olmos et al. 2016) that would be even more efficient when combined with AVs frictionless technologies. As Claudel and Ratti (2015: 91) put it, "the world's mobility challenges will increasingly be met with silicon rather than asphalt."

Although these solutions will require substantial investments (and who will pay for such infrastructural changes is still an open question) the social benefits are arguably high. A macro-economic analysis that takes into account the public health costs infringed by road accidents, pollution, and energy consumption (all likely to decrease with AVs) is needed to assess the costs and savings of AVs to urban infrastructure budgets. Still, if AVs help to reduce road fatalities by 99 percent (Hayes, 2011); reduce congestion, saving $60

AQ9 billion to the American economy (Fagnant and Kockelman, 2013); and improve mobility for part of the population currently not well served by public transportation, for example, AQ10 disabled and elderly people ~~(RAND, 2014);~~ the costs of adapting urban infrastructures to accommodate AVs will be largely offset by such positive externalities. What still needs to be seen is how users will react to AVs when they are pedestrians and users (Bonnefon et al., 2016). Although the number of accidents with AVs will presumably be much lower than current numbers, they will inevitably happen. Facing the decision between swerving and sacrificing a passerby in order to avoid running into many pedestrians, or sacrificing its own passengers to save one or more pedestrians, Bonnefon et al. (2016) found that the utilitarian logic prevails among potential users, by which people would minimize the number of casualties on the road; however, when the same people are riding AVs, their choice would be to protect them at all costs. Thus, beyond the technological and planning aspects regarding the adoption of AVs, we all, as a society, will need to face social and moral dilemmas.

Conclusion

A century ago, cars became an unexpected solution for cities engulfed in traffic from horse-powered vehicles and animal detritus. Taken by surprise, most city planners responded reactively, with a few visionary urban designers, such as Le Corbusier, taking cars as a driving force of future cities. On his trail, cities around the world bulldozed city centers and created a maze of urban highways. Soon cars presented a new range of problems—mostly due to bad planning and urban design approaches.

Today, with the emergence of AVs, we have another opportunity to rethink urban life and city design. Instead of thinking reactively, we argue that urban designers should embrace AVs as a catalyst of urban transformation. As with any technological innovation, there are potential pitfalls ahead. They include an increase in urban sprawl, once drivers are freed from the burden of driving. More urban sprawl means more time traveling, increased energy consumption, and more emissions of pollutants. Sprawling also means fewer active city centers, social interactions, and investments in public transportation, which depend on density to be economically feasible.

The introduction of AVs into cities represents a unique opportunity to reimagine the way we think and design road space. In this paper, we began by decoupling AVs from the car form-factor. Once we no longer need a driver to control the vehicle, we can think of AVs as moving platforms—some transporting people, others delivering goods, enforcing the law, and performing other public services. AVs as a communication platform, exchanging data with other urban infrastructures, will promote infrastructural changes in cities. However, unlike the massive infrastructures proposed in the early Twentieth Century, some contemporary solutions actually remove some infrastructures, such as traffic lights, which become unnecessary when AVs communicate with each other and negotiate their right of way.

Combining AVs with shared mobility also presents great opportunities in urban design. For one, it could free huge areas currently dedicated to parking lots. If cars currently spend 96 percent of their lifespan parked, AVs, when combined with car-sharing schemes, will be circulating at a much higher rate. In constant communication and exchanging data between them and urban infrastructures, machine learning techniques already allow

AVs to circulate, when unused, to optimize wait times of predicted next trips. Freeing cities from parking lots might help city planners propose nobler uses, from parks to social housing and mixed-use areas.

We are experiencing a transition to new ways of living in cities—and AVs will be a major driving force here. It is up to us, city planners, policymakers, urban designers, and engineers to use this major technological transformation to our advantage, combining efficient mobility while promoting a safer and more pleasant urban experience.

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Notes

1. **AQ11** Two major studies comparing crashes between manned and unmanned vehicles present different results. A study done at the University of Michigan (~~Schoettle and Sivak~~) concluded that there is an average of 9.1 crashes involving self-driving vehicles per million miles traveled, whereas another study at Virginia Tech (commissioned by Google) found driverless cars were involved in 3.2 crashes per million miles—as a comparison, the NHTSA reports 4.1 crashes per one million miles involving conventional vehicles (and NHTSA believes 64 percent of crashes are not reported).
2. See Statistica recent data at<https://www.statista.com/outlook/368/109/ride-sharing/united-states> Accessed . **AQ12**
3. **AQ13** See demo video at<https://www.youtube.com/watch?v=u5V_VzRrSBI> Accessed .

Disclosure Statement

AQ14 No potential conflict of interest was reported by the authors.

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AQ15

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