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Autonomous Vehicles and Public Transportation

Veículos Autónomos e Transporte Público

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ABSTRACT
Full automation Autonomous Vehicle technology (AV), is announced as possible, and safe, in the future. Widespread deployment would deliver sharp reductions in accidents and parking needs, two boons for society, particularly in cities. AV's role in total travel, hence congestion, energy and emissions is ambiguous, possibly negative. Relieving drivers from driving, better serving those unable to drive, will strain the system. Unless shared AVs reduce vehicle ownership (difficult, uncertain), increase sharing and do not tempt people away from Public Transportation – calling for planning, taxing and subsidizing. Otherwise, less cost, more convenience might double traffic.
Keywords: Autonomous Vehicles; carpooling; ecosystem; public transportation.

JEL Classification: L91; L92; L98; R41

RESUMO
A tecnologia de Veículos Autónomos (AV) é anunciada como possível e segura no futuro. A implantação generalizada proporcionaria reduções drásticas nos acidentes e nas necessidades de estacionamento, duas vantagens para a sociedade, principalmente nas cidades. O papel do AV no total que é viajado e, portanto, no congestionamento, energia e emissões é ambíguo, podendo ser negativo. Livrar os motoristas da guiar, servir (melhor) os que não guiam, vai sobrecarregar o sistema. A menos que os AVs partilhados reduzam a taxa de motorização (difícil, incerto), aumentem a partilha e não afastem as pessoas do transporte público – o que requer planeamento, tributação e subsídios. Caso contrário, com menos custo e mais conveniência, o tráfego pode duplicar.
Palavras-chave: Veículos autónomos; Mobilidade partilhada; Ecosistema de transporte; Transporte Público.

1. Introduction

Land based passenger transportation under 500 kms (a bit over 300 miles) is dominated today by the personal car. Vehicle registration was still growing in 2014 (Davis et al., 2016), and Vehicle Miles Travelled (VMT), in U.S., were also rising as recently as 2016.[1] That includes cities, where only in the biggest does Public Transportation (PT) enjoy any relevance, and even there as a clear non-leader (Button, 2014).[2]

However, the biggest players in technology and the cyberspace, Alphabet, Facebook, Amazon, and in the transport industry, Uber and most car manufacturers, envision a future with driverless vehicles. Amazon and other competitors in the commerce and distribution business hope to automate all road based freight transportation, which currently comprises all city freight traffic, and sizably leads from trains in intercity traffic land based transport.

AV technology, if widely adopted, promises to be disruptive in four ways: (a) dramatically reducing car crashes, avoiding most of the 1,25 Million traffic deaths each year,[3] associated morbidity (injuries and disabilities), and economic toll; (b) vastly improving car use efficiency, promoting less car ownership in favor of 'transport as a service', possibly doing away with 90 per cent of cars; (c) consequently, reducing parking needs; and (d) displacing a lot of jobs, from professional drivers to the 'crash economy',[4] along with those related to producing and servicing a much smaller number of vehicles.

This paper aims to analyze the broad opportunities and challenges for welfare from this seismic change, focusing on internal contradictions that may undermine progress.

The perspective will be one borrowing from Industrial Organization (consumers, markets, supply and regulation), Public Economics (welfare, externalities, fiscal instruments, health issues accidents and emissions), Urban Economics (land use and commuting patterns), and Transport Economics.

A number of broad assumptions will be put forward to frame the analysis:

(a) full AVs will only be allowed when they are safe; with safety being defined as better than the average human driver under all road, traffic and weather conditions;

(b) the ubiquity of the internet, web-enabled smartphones and cloud-based services will expand; the smartphone will continue to rival the personal car as a position good;

(c) online shopping will continue to rise, at the expense of the traditional, face-to-face sort; according to the 'Economist' magazine,[5] "Over the past decade global e-commerce has been expanding at an average rate of 20% ... its share of total retail trade, at 8.5% worldwide, was still modest…";

(d) people who walk, cycle or use PT, instead of the car, will not rise from secondary relevance or less, to any dominant role or share;

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[1] Source: Federal Highway Administration; US Department of Transportation, retrieved at 'https://www.statista.com/statistics/185579/us-vehicle-miles-in-transit-since-1960/'.

[2] Chapter 2, section 2.3, pages 30-32.

[3] Source: World Health Organization, in 'http://www.who.int/gho/road_safety/mortality/en/'.

[4] Set of firms, organizations that profit/exercise activity in dealing with the human/material consequences of accidents, broadly in the Health, Auto and Insurance sectors.

[5] Oct 26th, 2017, 'E-commerce takes off', special report, print edition.

(e) new forms of transportation, if they are to partially replace the current leader – the car – will have to provide not only clear added value in either time, convenience or cost, but also to do so in most, if not all circumstances – carrying kids, shopping, luggage, leisure, non-urban, longer range travel, bad wheather, among other things.

(f) demographically, the best that can be predicted is for current trends to continue, with very low, low or lowering fertility rates in all continents bar Africa, and an ageing society, through better health care and nutrition, and declining smoking habits; and

(g) economically, stagnant real median incomes, across rich economies, should continue, due to the forces of job automation/replacement dampening workers' negotiating power.

The structure will work out as follows: section two is a review of literature; section three, a perspective of where transportation and society are now and where they would be in the next quarter century, if AV technology does not 'take over' – the baseline scenario; in the fourth, the nature of the possible, alternative AV paradigm is described, the players, management of and regulatory framework. A fifth section concludes.

This paper will seek to review the literature and contribute to the ongoing economic debate on the future of transportation, by (a) reflecting on an AV scenario for all of road based transportation, not only urban, and including freight, at least for the scale of a country; and (b) addressing the central tension between the need for a dynamic ride sharing (DRS) – essentially a taxi with multiple sharing clients – system to succeed in delivering better value to lure people out of car ownership, and not to steal too many people from mass transportation (PT), otherwise congestion persists.

2. **Literature Review**

Given than AV technology, is certain to be costly and, since it is not yet deployed, demand for it will have to start from zero, and be large enough for huge economies of scale to bring costs down, it is thought to have to rely mainly shared vehicles. Otherwise, the cost with be bearable only to the very rich, whose valuation of time and safety would demand such an upgrade (the personal AV). Since the current promise of AVs is quite recent, the first articles reviewed focus not on AV, but on car sharing and pooling. Literature uses the word 'sharing' in the usual sense, but the expression 'Car Sharing' usually means a client, individual or a family, hiring a car for a period, during which it is its sole user; the car is 'shared' in the sense that it serves several customers, but one at a time. 'Pooling', refers to a practice where participants take turns, each bringing his vehicle to serve him and the group (pool). Both Pooling and modern DRS (explained above) expect a car to serve several users at the same time.

Correia and Viegas (2011) ran a Web-based survey to assess personal disposition to Carpool, around the Lisbon Metropolitan Area (4 Million people live in and around Portugal's capital city, Lisbon). Carpooling has been associated with employer-based initiatives, especially during the 2nd World war, and after the Oil shocks in the 70s', but has tailed off to insignificance, with the return to normal, affordable fuel prices. The results found respondents were, in general, not keen to join a car pooling club; those with children not at all; money savings, including in parking, were the main reason in favor, so poorer people declined less; sharing with both colleagues or strangers was found negative.

Chan and Shaheen (2012)'s work goes through past, present and future of ridesharing in the U.S., stressing very low market share: schemes lacked of critical mass (enough users) or profitability (private ones) Only the more stable patterned commuters afford the loss of flexibility. Safety and privacy concerns are important, so closed systems inside companies or campuses have met less resistance Large employers, public or private, can succeed.

Vij et al. (2013)'s paper uses a survey to estimate latent modal preferences. Cluster analysis reveals three portraits of users: the 'auto-male', mostly uses his car, is employed and is available only for short walking distances; the 'time-sensitive multi-modals', frequently female, not always employed, probably take lifts from partner/husband, but use other modes if sufficiently convenient; 'time-insensitive multi-modals', are employed and buy a [PT] monthly pass. The article dwells on the relation between everyday behavior and long-term choices like owning a car, regularly buying a pass, stressing the potential for better targeting of public incentives.

Jorge and Correia (2013)'s work reviews literature on car sharing systems, also reporting very low market share. Up-takers are mostly young, urban people, cost and/or environmentally conscious. The logistical and economic problems from managing stocks from the different locations, with the minimum fleet to provide good service (available car), and the minimum human resources to move (empty) cars around, are taxing. Availability is further linked in a two-way relation with the number of rides (demand), leaving a vicious cycle all too probable, if critical mass isn't achieved. Authors raise an important issue, carpooling has severe sociological barriers, to do with strangers, safety and security, and a crucial question: regarding its role for the environment [emissions, efficiency, energy use], does car sharing steal from car owners or PT?

Green et al. (2017)'s article peeks at younger generations' minds about cars, by interviewing 16- to 21-year individuals from small towns in Britain. Their PT system offers poor quality, in comfort, frequency and depth of destinations. But the car is expensive to acquire and keep; accidents do happen and hurt, enduringly; car licenses are expensive, hard to obtain and can be lost, through the point-based system. Sharing is sometimes obligatory, or a way to cut costs. It is a generation less enthralled with the car and driving per se.

The rest of the review deals with AV proper.

Thierer and Hagemann (2014)'s paper focuses on Intelligent vehicles and Driverless Cars, to argue for innovation to be let to flourish unhindered, for the potential huge benefits to come to fruition. They rank less accidents and congestion, more fuel economy, fewer parking needs, mobility to non-drivers and greater convenience and productivity from time freed up from driving as the main 'promises'. But warn about the risk that widespread adoption might not be achieved, if regulation, too restrictive, too fragmented or contradictory stands in the way. They present NHTSA five level categorization of vehicle control automation:[6] 0, is for no automation, 1 is for function-specific automation, one or several non-combined tasks, 2 is combined-function, when at least two primary control functions are jointly automated, e.g. adaptive cruise control and lane centering; 3 is for limited self-driving, where

[6] U.S. Department of Transportation Releases Policy on Automated Vehicle Development, NATIONAL HIGHWAY TRAFFIC SAFETY ADMIN. (May 30th, 2013), URL: www.nhtsa.gov/About+NHTSA/Press+Releases /U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development.

full control may be surrendered, but return to driving is both optional and required in less than normal situations, 4 full self-driving automation dispenses with all driving controls.

Anderson et al. (2016)'s groundbreaking book, first published in 2014, covers AVs' promises and perils. Crashes are 90% human-related. Mobility for those unable/unwilling to drive, poorly served by mass transit PT, taxing relatives/friends, or paratransit agencies for incapacitated, inefficient in their inherent lack of scale. Land use, both by longer commutes becoming acceptable without driving, and vast savings on parking, which they cite as taking up to 31% of Central Business District's space. Effects on energy and emissions, from smoother riding, reducing distance, platooning,[7] less crashing, search for parking. Lighter vehicles if safety features are allowed to become less stringent (again, because of rarer accidents). On the other hand, VMT can increase, from the discussed gains in in-vehicle time, empty travel repositioning of shared/pooled vehicles, and extra travel from those unserved segments, also including too young or old or ill to drive. VMT can further increase for those finding AVs (shared or pooled) cheaper or more convenient than current forms of car use, and/or affordable enough relative to PT. More VMT aggravates congestion. While finding, on balance, that benefits can outweigh costs, the authors call for more research on both, and on how they're distributed between individual user/operator and society.

The need to avert more VMT and the existential threats to PT are central this article.

Burns et al. (2012)'s work sets out to generate synthetic trips for three distinct scenarios: a mid-sized American city, a low-density suburb, and Manhattan, NY. The vehicles are shared, centrally dispatched, but with no carpooling (DRS); personal cars remain. They obtain less costs for mile in all cities, lowest in the first; also, significant reduction in the number of vehicles, higher in the first two. Smaller, purpose built, shared AVs are even cheaper to run. Manhattan's simulation kept mass PT.

Similarly, Fagnant and Kockelman (2014)'s article models how a fleet of Shared AVs (SAVs) would perform in Austin, Texas. Again, no DRS is planned. Following a service (including pick-up), AVs would reposition in places that balanced low parking costs and faster availability. They model just a 3,5% replacement of current trips by conventional cars, resulting in each SAV replacing 12 cars, serving 31-41 persons a day, with an average wait of 20 seconds (more cars could be replaced, but with higher waiting times). On the other hand, 11% more travelled distance takes place, due to repositioning, albeit still with sizable reductions in emissions. They tie some of the gains to the transport system from lower costs per mile, on them not generating excessive extra travel – again this central topic.

Fagnant and Kockelman (2015) compute numbers on a national (American) scale. It focuses on crashes, and their costs, both narrowly and broadly defined. Citing (Hayes 2011), saying fatality rates (per person-mile) could drop to those of aviation and railways, or 1% of current ones, and FHWA's[8] estimate of 25% of congestion being caused by traffic incidents, half of which from crashes, in Cambridge Systematics 2005's report. Economic costs from accidents in the U.S. are 277 billion USD, double those attributable to congestion. The authors agree with previous research that AVs would drastically reduce parking needs, but

[7] Platooning is an experimental technique that uses technology-enabled high coordination within a convoy of trucks, to have them travel as close as possible to each other, saving fuel with the reduction of drag.

[8] U.S. Federal Highway Administration.

would increase mileage, mainly due to previously excluded users. They calculate the effects from a market penetration 90% of AV enabled vehicles, of which 10% would be shared (not DRS), each displacing ten standard vehicles VMT would go up by 10%. Problems facing (mass) deployment of AVs are discussed: security, real and perceived; the threat of hacking; privacy, since AVs generate comprehensive information. This also brings new opportunities to nudge road use and behavior, charging more in congested hours and routes. The savings for society, from less cars, congestion, parking and accidents are significantly higher than those for the individual. Particularly so if ownership isn't curtailed, and early small-scale adoption doesn't drive costs down by much. Some of the congestion-saving improvements will stem from vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, the first being borne by AV owners.

Spieser et al. (2014)'s paper, take a congested big city-state, Singapore, and design a model to predict the performance of a system of AVs that would substitute all modes of travel currently in use, whilst assuming no DRS. The basic scenario yields a need for just 1/3 of the current number of vehicles. A comparison of total cost of ownership between personal car and AV is included, and estimates for total cost of time. Along with the financial costs (where fuel is just 6%), these form the Total Cost of Mobility (TMC). They conclude the fleet of shared AVs (SAVs) would come much cheaper than personal car travel: costs in time would drop by a third, costs from using/owning the vehicle by two thirds, and global TMC by almost half (-46,4%). VMT would increase, mainly because of empty travel.

Luis Martinez's report (ITF, 2015) carries out a similar exercise for a mid-sized, mildly congested capital – Lisbon. Drawing on data from surveys and PT operators, they too construct a synthetic model of the city's transport needs, which they proceed to experiment with total discarding of cars, buses and (human operated) taxis. Crucially, they keep the metro PT system in the main scenario. They put forth what they call Autobots, AV taxis called by app., not shared with different users; and Taxibots, with DRS but severely limited on the number of people, waiting time, total additional time (waiting plus travel time) and extra distance. Results are presented according to 24-hour weekday averages or morning peak. They do not attempt to model additional demand that could arise from more convenience or smaller cost. The model, with Taxibots (DRS) and metro, predicts that 90% of the vehicles could be out, while fulfilling the same needs. Those percentages naturally drop with less pooling, less cars' replacement, or if the metro is removed. Travel volume, with these services and the need for empty car repositioning, rises in all scenarios – in the "greener" (no cars, pooling and metro) only 6,4% over a 24h weekday, and 8,8% at the morning peak. These increases point to congestion remaining. Authors conclude this simulation yields vast improvements in vehicle numbers and parking needs, but not in VMT or congestion; they find it crucial for "impacts of additional demand to be mitigated", through fiscal nudging. Borrowing from predictions above on the impact of AVs in accident reduction, their impact on congestion and on the potential for dwindling parking needs freeing space for extra lane capacity, which the authors do not do, it is possible to accept congestion improving or at least not worsening.

A follow up report (ITF, 2017), retains most of the premises – no cars, taxis or buses, no tourists/travelers from afar – and extends the scope of the analysis to the Greater Lisbon (suburban) area. Mass Transit PT here comprises the metro system, coupled now with suburban rail. The AV actors are slightly tweaked there are smaller Shared Taxis and larger Taxi-Bus both accepting DRS Their role of feeding to and from Mass Transit transport systems is hugely expanded, reducing congestion, time and cost, improving convenience and efficiency. The running of the two AV fleets would be done centrally. The main scenario would result, again, in significant reductions to fleet size and parking needs. Here though, it would also increase the use of Mass Transit PT and end congestion, reducing VMT in the roads/streets, with superior performance, in terms of time and cost. Plausible paths towards gradual adoption were modeled, starting with car users who either pay for parking or for the monthly pass, along with all bus users and some of the taxi users. Earlier market penetration stages deliver much smaller benefits to the system, but successful demonstration can be key to future willingness to switch. Constraining parking, both supply and maximum allowed time, is a way to nudge users towards leaving the car. Another path would be progressively banning suburban residents from bringing cars to the city (thus discriminating them from city residents); it was shown it could work. SAVs were modelled to accept requests for exclusive rides, which hurts efficiency. Multiple dispatchers were simulated, according to vertical market segmentation, also found to impair on performance. Recognizing the exclusive rides' (taxi) effect on an AV-only system, as similar to that of a personal car, they conclude their role is negative, but manageable if kept expensive and small.

Wadud et al. (2016)'s work, on the travel, energy and emissions' impacts from AVs, assumes they will substitute cars and taxis, increasing their use and, without the driver's role, possibly evolve to new sizes, more in line with actual occupation, in turn becoming more efficient. Migration from the Public Transport towards AVs is not covered, nor is DRS (pooling). Under various scenarios, significant savings in energy and emissions are found to be achievable, with cuts to nearly half of the base case. Partial automation can deliver sizable gains. Full automation, though, is more vulnerable to potential downside risks, namely two that have to do with the valuation of time. If significant traits of the population come to value it highly, they are likely to demand more performance (including average speed) which steeply rises energy consumption and emissions (one would add, greater risks for accidents, and less tolerance for waiting, in Pooling). The other risk, of opposite nature, is how invehicle time is valued in AVs – if, through comfort, entertainment or sleep, it is viewed as less costly, greater distances will become tolerable, leading to longer commuting, again increasing total VMT. Time savings (congestion, parking, accidents) reduce one of the largest components of generalized cost. Pricing can play a part – currently, car owners are faced with a high fixed/low marginal cost that stimulates driving. Future pricing models presenting consumers with a higher marginal cost could prevent growth in VMT. This holds for exclusive rides in SAVs and for personal cars, where demand management must be considered. Authors conclude warning overall effects may be positive or negative, meriting further study, planning and policy.

In another article, Wadud (2017) focuses on the costs in personal transportation and commercial freight transportation – operators, to whom driving is just a constraint (legal limits for professional drivers) and a cost (overall labor costs and those attributable to human error related accidents). From these, factors influencing early adoption of AVs are discussed: the sector with the strongest case for automation is freight; next, they predict the most affluent and/or intensive car users will the first to switch, in line with the previous focus on the valuation of time – both total and in-vehicle. Regarding partial, early adoption, differences are pointed out, between the 'everything somewhere' model whereby, in a limited spatial scale, probably urban, AVs are allowed, but not outside it, which limits freight use to urban small freight, and leaves people having to switch vehicles, probably keeping their non AVs; and the 'something everywhere' model, typically level 3 automation, where driving is surrendered in motorways or in good weather, but not always, everywhere, with no driver redundancy for freight operators , nor for personal transportation, either shared or private. Both developments are likely to precede full AVs, which is relevant for planning.

Krueger et al. (2016)'s paper, explores future preferences for AVs, by conducting a survey on willingness to take part in DRS (pooling) and SAVs. Main factors were found to be travel cost, time and waiting time. Cluster analysis yielded four classes: a quarter was composed of exclusive car users; another also had car users, but available for complementary walks; next were cars users, pliant to walking and to (mass) PT, but not to cycling; the final quarter was evenly split, between car users that used PT, but neither walked nor cycled, and people willing to use the full range of modal choices. In line with research above, the probability of switching to either SAVs or DRS, was found to be higher in current 'multi-modals' and, generally, among younger people.

Litman (2018)'s report could be mistakenly thought of as contrarian to AV technology adoption, but it does deliver a dispassionate, balanced analysis, as well as sobering facts and insightful views on the interests behind the AV 'revolution'. Previous vehicle technologies have taken a long time to adopt, not only because reliability had to be achieved and cost had to drop, but because cars are replaced slowly, they last long. Typically, they are the most important household purchase, after housing. The parallels made by AV enthusiasts, with the rapid world adherence to smartphones and tablets, ignores they cannot hurt or kill, neither owners nor people around them – cars can and do. The author identifies three main actors with financial interests in the (AV) industry, as being behind most of the optimism: investors in AV technology; candidates to become dispatchers of AVs and suppliers of AV enabling equipment. Litman also points to the likelihood of additional travel being induced, increasing congestion. Relying on public infrastructure, AVs are bound to require costly upgrades, especially to do with communication. Opposing preferences between individuals and society may arise, regarding speed and safety, the latter in terms of own safety vs fellow citizens', urging public choices. While the AV experience can reduce stress, improve mobility and, thus, productivity, there are several caveats: to shared vehicles, cleaning and vandalism costs will exist; minimizing them will involve sacrificing comfort in favor of "hardened" interiors, or privacy by using cameras, or both; sharing also carries security fears and risks; the success of sharing may reduce support and funding to PT, which may result both in less options and social exclusion, since PT is typically the cheapest mode. So long as human-driven vehicles coexist with SAVs, benefits such as HOV lanes will present a loss to the non-AVs. The ease with which people relax and work in trains cannot be taken for granted in urban transit, where stop-go-turn is more frequent than not – when the novelty expires, the experience may be seen as "more like an elevator than a spaceship". There are potential harms to people not using the technology: if faster and travelling closer together, AVs can leave less room for pedestrians and cyclists; if slower, for more smoothness or to deal with intensive or trickier situations, they can slow traffic as a whole. Costs for purchase and maintenance of these sophisticated platforms, are bound to be high, dampening deployment, but for the most affluent. Ownership has several motives, including prestige, convenience, particularly in less than optimal conditions, comfort (not sharing, leaving your objects, including work-related), that have made sharing a limited option, both in range and appeal. Taxis, buses and freight are heavily weighted down by driver costs, thus being likelier early adopters. Policies will be central, requiring fairness and acceptability, to guide AV deployment. A compromise will have to be struck between being cheap and convenient enough to win a weighty part of car users, to lower costs through scale, and not hurting PT. In turn, PT will require funding in order to stay cheap (or to become cheaper). Delivering superior performance, through higher speeds, raises accident risks, energy consumption, and emissions.

3. Baseline Scenario (no AV)

Starting with freight, since it is less complex: medium to long range inter-city road-based freight is central in Europe and Asia, while very important and increasingly so in the U.S. It uses more energy and emits more per ton. than rail; it adds to congestion directly, by the amount of space it takes, but also indirectly, because trucks move more slowly and clumsily, and disrupt more whenever they are involved in accidents. They will continue to grow with the economy, despite the European Union's efforts to promote more rail; and the competitive threat in some (longer) distances, weights and volumes (smaller) from air freight Assumptions 7 and 8, on low fertility, ageing society and stagnant real incomes point towards feeble GDP growth, so road freight's growth will likely be moderate. Short-haul, city freight transportation is important now, contributes to congestion, albeit less than personal transportation, because it is more evenly distributed across the day, and some can be rescheduled to off-hours (the same holds for road-carried freight, but there, its impact is larger on the roads). Its growth, present and into the future, is fueled by three converging trends:

> Humanity is moving to cities, now host to more than half, more so in the developed world, and since they provide better jobs, income, and quality of life, the trend will continue;
> Online shopping creates billions of parcels to deliver, and expands total commerce;
> Affluence and social networking spread 'fads' and the consumer society will keep consuming ever more, both online and through classic channels.

Looking into a future without AV, one can see freight as weighing (down) more on the transport system's performance in urban traffic. Roads, nonetheless, are strained by trucks, forcing people to commute ever earlier.

In personal transportation, the car leads everywhere, for every function, on the road. For leisure, air travel is important. In regional/rural settings, PT has either withered, under the downward spiral of less demand, less frequency, less comfort, or ceased altogether. Some coaches remain relevant connecting cities using motorways, as do trains, but mostly appealing to the minorities that use PT regularly (also in the cities). Society, some say, has reached an era of "peak car" use, perhaps by over-estimating the numbers of the environmentally conscious, but certainly helped by the convergence of two trends:

> Society's ageing means people move less; some are unable/unwilling to drive; most tend to have more fears, which makes 'mixing in' in PT more daunting; their vulnerabilities outside the home are both real and perceived as such;
> Younger people, almost always online, are going out less; stagnant incomes, and persistent unemployment, particularly in Europe, reinforce savings to be had by staying in, thus reducing transport needs.

The lure of the car is much diminished for younger generations (see Green et al., 2017), who see it as expensive, dangerous, ineffective in dense/congested metropolis with good Public Transportation. So, the car may have reached a (very high) plateau in market share, from which it may not grow, or may gentle descend. It still enjoys a clear leadership, solidly founded on a host of strengths that make it the best 'all-rounder', leaving alternatives "very good for sunny days and… other people".

Public transportation will continue to be relevant, the bigger the cities and either the wealthier or the more congested. The first two because they can host a better PT system, having the scale to have a dense (convenient) network, and the wealth to build it. In congested cities, because Public Transport becomes the smart option, having always been the cheapest (although congestion is a sign of intense car use). Especially where housing is expensive (relative to incomes), a large number of people find they can't afford a premium mode.

Taxis, and sharing stand, in vertical differentiation terms, between car ownership and PT, will continue to enjoy some growth, since the internet, and apps. make them easier to book, organize and plan. Uber's and its rivals' foray into Taxi's market power will carry on delivering lower prices, bringing some additional demand. Sharing schemes, although more intelligent, and 'real time', will struggle to evolve from their (current) irrelevance, because comfort, privacy, and security will still favor the default option – the car.

Walking and cycling will keep their constructive role on an efficient transport system, alleviating congestion, emissions, energy and land use on the shortest distances, as feeders to PT, and complements to the car. Some people's view on their fitness, quality of life, health, 'carbon footprint'/sustainability, or even on saving money, will continue to exist. But because congestion and pollution are externalities (no direct link between individual choice and outcome), and time, safety and convenience, including in bad (weather and other) conditions, favor personal transportation, their number will continue a minority.

4. **Towards an Autonomous Vehicle Ecosystem**

Much of what has been presented and commented in the literature review, and on the baseline scenario, suggests what an AV enabled transport system should look like. To discuss and help plan for AVs, a leap into the future is necessary, with all the fragilities and uncertainties thereof. The essence of an AV ecosystem is the deep interconnectedness of all modes, and their performance, both to their customers and the system. Like in the previous section, in trying to work from the simple to the complex, first, freight will be addressed.

4.1. Freight

Freight companies, either dedicated or those having substantial volumes to carry, like Amazon and its Asian competitors, Walmart and its rivals, face huge pressure to deliver unprecedented amounts of freight, and number of parcels, at the lowest cost, and the shortest time. Several 'offer' free delivery and can't charge much for 'premium'/'express' delivery. Therefore, they are placing high hopes on two technologies: AVs and drones. Both dispense with drivers. Freight companies and those related to big commerce, will surely be early adopters of AV technology, several having announced it, and currently spending to that effect. Their path will interact with the rest of the system in four ways:

Spreading more of the work around the day, cutting accidents, they'll contribute somewhat to de-congestion;
Oiling the growth of online shopping (that includes delivery), they'll reduce people's transport needs, and a major reason to own a car (shopping);
By achieving sizable economies of scale, and scope, they'll help drive down the cost of delivery to a point where personal transport as a service, SAVs or DRS, will offer, cheaply, the extra of luggage, shopping and even work related tools, to be handled separately by freight companies, arriving 'just in time'; Litman (2018) cited this point (work related tools) as an important reason for people to cling to the car;
They need AV technology to spread, to be deployed massively, to make a mark in the (bigger) market for personal transportation, to drive down the technology's costs.

Common to both freight and personal transportation is the objection of AVs, being driverless, leaving people bereft of help in and out (very young or old, disabled, etc.), and cargo loading and unloading. But during all journeys, the helping/loading isn't taking place. It can only be vastly more efficient to have people at one or both ends of journeys, performing those tasks. The problem is real, the solution just doesn't have to travel inside the vehicle.

4.2. Passenger transportation

Most authors agree AV's highest hurdle is for a strong demand to emerge for services as yet nonexistent, enabling, through scale, the costs of a complex, developing technology to come down, and become competitive. Beyond freight, which also needs this to happen, there are the richest of citizens, who may want a driverless car, whatever the costs. Uber and its competitors will want to switch to AV because it's cheaper. This article argues these three segments, 'masters of freight', 'plutocrats', 'modern-day' Taxis will not bring enough scale for AV to deliver its full promise – better, safer and cheaper.

Widespread adoption of AVs promises two valuable boons to the transport system:

Sharply reduce accidents, because 90% of them are caused by human-related mishaps, and all reckless, unlawful behavior will be programmed away;
Reduce parking needs, either on shared fleets or private cars – both AVs can find their ways to efficient, cheaper places to park and fleets can be either too busy to need much parking, or can find it worthwhile to cruise while waiting for the next service.

Both these outputs contribute to de-congestion: the first was estimated to cause a quarter of it; the second, would make traffic flow smoother and free urban space for possible extra lanes. But for the technology to take off, it must reduce own-car use – they are the leaders, the majority of vehicles, and run with an average of 1,2 people for their (usual) five seats; while not increasing VMT, since that would aggravate congestion, energy demands, and emissions.

ITF's reports (ITF, 2015) and (ITF, 2017), show what an AV ecosystem must have to be successful: a SAV and DRS supply that wins over most of car users (car ownership, even in an AV era, must be presumed to continue, at least for the wealthiest); a mass PT that continues to de-congest, is fed by SAVs and DRS, and is not unduly encroached by their convenience and cost.

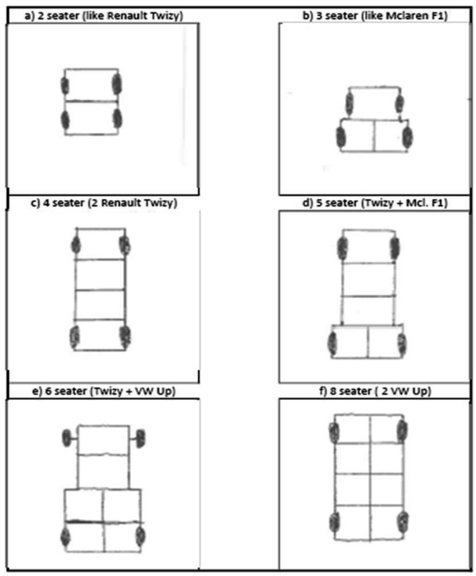
The key to commercial success for any public transport company is summed up in the phrase "keep them packed and busy" – using the fleets as intensively as possible, and with the highest occupancy rate.[9] In scheduled transport, that increases frequency, lowering waiting and total time. Private car sharing and pooling schemes have floundered because of insufficient demand, as has Public Transportation in regional/rural settings.

Dynamic ride sharing, or pooling, as modelled in the ITF reports, where one or two people call for a vehicle, that then stops at one or two extra locations, to pick up two or three additional passengers, and drives them to their final locations, without the stress of driving or parking (and the latter's cost) has crucial strengths. It discourages car ownership and de-congests traffic, as long as it doesn't empty PT. But car users don't want to share or pool. They feel good and familiar with a lot of features their car provides. So, next is a sketch of the desirable features for a good, promising DRS service, to be followed by how those would meet car owners' demands.

A driverless public vehicle, will have four wheels, probably with independent electric or fuel-cell-powered drivetrains and, thus, all visible space will be for passengers; that will allow between one to four rows of seats. Besides enjoying a discount/rebate for allowing the vehicle itself to be shared, raising somewhat waiting time, journey length and total time (within boundaries), the norm will be to have one seat per row/door; and all the layouts with two seater rows are to attend people who are together – if empty, they can take a solo passenger. This way, strangers don't share the same row, ever (comfort/safety). Also, it's safer to exit on the right, so with a single seat-row, no one is forced to step outside (rain, wind, cold?), for the person on their left to exit. Figure 1, illustrates possible seat configurations, under the above restrictions, and placing single seat rows first, since they spoil less of the view.

[9] On occupancy, taxis are an exception, since in their classical pricing model, extra passengers don't pay more.

Figure 1: Six possibly more popular layouts



Darwinian experimentation, with real demand, will determine which of the above, or other, configurations will prove most in demand. As far as low waiting time, few detours and extra miles (all with compensation), vertically differentiation, should dictate the menus the market will accommodate. Never sharing a seat row with strangers addresses multiple objections car users usually pose: security, not mixing with annoying or violent passengers; taking kids, seen as incompatible with pooling; bad weather situations. Naturally, the more pooling, miles and minutes one tolerates, the less one is charged. The most stringent of customers (no sharing), do not de-congest. Hence, they must be priced so as not to become the norm. Freight companies will complement all but the lightest and smallest of shopping/luggage with cheap, on time, delivery. So, how can a such a DRS centered and differentiated scheme measure up to personal (car) transportation?

Personal cars, being the incumbent leader, are the default option. It serves all kinds of travel (making assignment of costs to each kind beyond the effort of most users); its high fixed cost is often not questioned (assignment, again), and the manageably low marginal cost spurs intensive use; of the less immediate or visible motives, the pleasure, and power and privacy around driving are bolted into one's life experience; it is a back-up instrument for emergencies, such as hospital/maternity, or evacuation from natural or other disasters. Contrary to ITF's simulations and (Spieser et al., 2014)'s in Singapore, and others,[10]

[10] All studies project the demise of the personal car as an exercise on the effects to congestion, and the gains from an AV alternative, not as a prediction.

personal cars needn't be totally removed from the system; non shared/pooled public AVs, running empty miles during repositioning, can be just as congesting, and the wealthiest will continue to own AVs. They will, however, pay their way: in parking, both at home and at work, for ownership, at purchase and regularly, and for the use, more if at congested hours or routes. The bulk of the (less affluent) car users, though, ought to be tempted by personal transportation as a service propositions, for regular, practical journeys, as long as it is clearly cheaper, more convenient.

It is being assumed that AVs can go anywhere, not being confined to cities, even if not from the outset. Otherwise, a changeover, somewhere, would be needed a losing proposition, in replacing the car. Also, at some point of their successful deployment, human driving will be barred from public roads (most authors agree), since they will come to be seen as posing unwarranted risks to others; when AVs are safe at all times, deaths and injuries from human error become unacceptable. As far as driving pleasure, there are two kinds to consider:

> The one from a sightseeing journey, where not driving allows all occupants to fully appreciate the scenery and interact;
> The one from sports driving, with all the extra risks, more serious to others,[11] is already forbidden, but currently takes place (in hiding from law enforcement); several entities profit – sports car are costlier, consume more fuel, and governments tax both; AVs force society to face there's no room for sports driving in public roads; at the same time, they open up a large opportunity for a market to provide tracks of all kinds.

So, the main actors, freight companies or those handling a lot of freight, AV enabling suppliers, tech giants vying for the dispatching role, fleet owning companies, possibly in alliance or owned by car manufacturers, will push for AV to succeed, and that will have to come at some expense of the personal car. Car companies may worry about simulations where 90% of all vehicles become useless, but there are countervailing factors:

> AVs will be more complex to produce and service, so can be more profitable;
> Some personal car ownership will remain, with infinite scope for vertical differentiation, including amenities;
> The continuum of vertical differentiation inside sharing and DRS will, in the upper segments, dent the savings on vehicle numbers, because bigger fleets are necessary to cater for demanding customers (less tolerant of waiting, sharing or mid-stops);
> Shared, DRS vehicles will be used so intensively, they will be serviced and replaced more frequently, helping various revenue streams;
> All the extra convenience, and lower cost, that will be put into ensuring the success of the SAV, DRS model will generate extra demand, adding to that of previously non-served or poorly served publics – young, old, disabled, etc.

[11] Both because they are 'innocent' to the cause, and don't share the pleasure.

4.3. Pricing and externalities

The challenge to attract as much demand as possible for a new service, by sophisticated, profit-maximizing companies has best and most recently been seen in telecoms and all the new services, generations of devices and protocols (3G, 4G, etc.). Those markets present companies with direct competition and very powerful lock-in, network effects, that grant market power if a loyal customer base to your company grows to become large. It is clear management of the AV traffic and dispatch of SAVs will have to be centrally run by a sole company or agency, at least in the scale of a relevant market – it may be smaller than a whole country, but not as small as any small city. The private company or companies offering transport as a service are to be expected, in trying to win over as many costumers as possible, and having them use the system intensively, to offer 'all you can eat menus' –subscription type pay-structures – or, in PT terms, a kind of monthly pass. It has happened in telecoms, with voice calls, SMS, and internet traffic, and it has worked, in expanding the various markets from non-existence.

This practice is particularly well suited to counter personal transportation, because a subscription puts the customer facing zero marginal cost, spurring consumption. Car owners, who have to be won over, also face low marginal costs to travel. But there are two, connected perils surrounding this possible development that merit continuing evaluation, and possible counter-acting intervention:

> Overusing transport services aggravates negative externalities in emissions and congestion, unlike in telecoms, where (over)consumption, the number of hours spent on the phone, tablet, etc. does not clog traffic, or leave a higher carbon footprint.[12]

Threatening PT – efforts put into making a foray into personal transportation, time, privacy, convenience and cost, risk tempting people away from public transportation; this is a major problem with AV mass deployment, most authors agree; the problem is not one of nostalgia or pity for a suffering PT – it is that mass transit PT de-congests, whilst cars, AV or not, do not, unless in the most efficient, tolerant of pooling, segments.

Time is one of the top elements on modal choice and evaluation – this positive/negative externality ties AVs to PT inextricably – if SAVs and personally owned AVs steal too much custom from PT, two effects are clear: VMT rises substantially, worsening congestion, hence part of the promised improvement; and PT loses critical mass, hurting frequency (thus convenience) and profitability, possibly survival – it has happened in regional traffic.

What can be done? It depends on the scale of the transport system, and on how many layers it has: in a village, there may not exist any PT, so competition from DRS to personal AVs is welcome, bringing more efficiency to the system. Possibly, configurations of vehicles emerge with room for luggage, work-related tools, even shopping, if it is not economical for freight companies to serve such markets. Overconsumption should only be dealt with (taxing, managing demand), if and when the whole country chooses to. The principle is

[12] Although the server farms, that power the net and the 'clouds', are becoming ever more energy demanding.

VMT reduction should cost/hurt everyone the same, everywhere, unless too much congestion makes it urgent.

In a small town, there won't be metro, but there could be buses, and/or rail connecting to a bigger city. For buses to remain attractive, at least in the main routes which offer more frequency, two complementary approaches must be in place:

- Keeping PT cheap, maintain pricing structures ranging from single tickets, quantity discount for multiple tickets, various discounts for identifiable publics, and monthly passes, in essence, the flexibility to cater for as many transport needs as possible, while ensuring a significant discount over the price from SAV options; if the marginal price in SAVs is zero, through subscription, zero may have to be the cost in PT (Germany has recently pondered such a move, in dealing with crippling congestion and pollution);[13] since cars and car use (including fuels and parking) have always been taxed, there is scope for cross-subsidization;
- Monitoring, regulating, at times curtailing, the aggressiveness of SAV companies' drive for extra custom; subscription-based models usually include a caveat that consuming beyond a threshold costs more; regulators can intervene on these boundaries, to force people to face marginal social cost pricing, so as to manage demand and over-consumption.

The commuting PT, though typically only alleviating congestion in the bigger city it connects to, should likewise be fiscally protected, with SAVs acting as feeders to commuting PT, and seamless changeover.

In a large city, with all the possible layers, from personally owned AVs, SAVs with segmented DRS, buses, metro, pedestrians and cyclists, SAVs continuing experimentation with how much people accept, in pooling (waits, detours, extra time), vehicle configurations, in terms of capacity, may endanger buses. Or leave just a fraction of successful lines – it has happened when metro systems are introduced.[14] But the central tension and 'battleground' is between the Metro and SAVs, with the implications referred above. Huge, valuable, scarce space will be freed by significantly reduced parking needs from a SAV-dominated, public street using system. Multiple candidates for that space uses exist: extra lanes, if congestion persists, cyclist lanes, wider sidewalks; for outdoor parking lots, public parks; or anything else, including sale, for in-door parks. Some AV private cars will remain, but will have to arrange for parking, both at residence and work. Street parking (as opposed to stopping for drop-offs) may disappear. Private cars will be confined to the very rich few, so upmarket malls may offer parking, to cater for these lucrative customers. For large, cultural or sports events, metro and buses are the most efficient candidates. If the latter are no longer around, SAV companies will use the maximum capacity vehicles they have. Tourists and other infrequent visitors to the city (on business, for example), probably skip mass transit PT systems, with their fixed routes and timetables, but use SAVs. Group organized tourism, will be able to

[13] The Guardian, February ,14th, 2018, URL: www.theguardian.com/world/2018/feb/14/german-cities-to--trial-free-public-transport-to-cut-pollution.

[14] Oporto, Portugal's second city, has a recent Metro system that led the supply of Buses to contract.

save considerably, by planning with SAV companies, the most efficient set of vehicles, routes and hours that set of predictable, shared journeys need.

4.4. Policy implications

Widespread deployment of AVs will come about through piecemeal erosion of personal car use, in favor of DRS alternatives. A set of policies to nudge people in that direction include:

- Creating a standard measure of transport inefficiency, such as the number of hours lost to congestion,[15] to breed consciousness on the problem and support for policies to improve; that index should be publicly visible and object of debate; then, goals could be set in performance gains from alleviating congestion, quantifying how change from less cars, more people in each car, DRS, PT, walking and cycling – would achieve; similarly, an index on road mortality and morbidity could help in winning acceptance for limits on human driving;
- Giving steep discounts, or temporary gratuities in public transportation to youngsters/students, inviting them to try out the PT experience and away from car culture; giving away some money's worth of PT or SAV travel, to all household members, whenever their fleet is reduced (a one-off); giving away a free trial in PT, for anyone with a car, for example, one month once every two years;
- Parking should be made gradually more expensive, for everyone, including residents and workers; rebates should be worked out based on two cumulative criteria: wealth/ability to pay; modal choice/availability of alternatives;
- Expand HOV lanes and explore with high occupancy tolls (discounts), thus increasing the money gains from sharing;
- Police wrong driving behavior, including substance abuse; enforce points-based licenses; together, these policies remove relevant part of offenders that cause more than their share of accidents, possibly making them captive to PT or SAVs.

4.5. Economics and market structure in an AV ecosystem

Being public transport systems, fleets of SAVs should be private, local or regional monopolies, granted by competitive tender contracts, unless a way is found for competition not to interfere with fleet efficiency They would deal directly with customers, with relationships ranging from the one-off tourist, through the more or less casual user, to the intensive, committed client. In offering transport as a service, they will handle fueling, servicing, parking, and overall management of the fleets, in their various sizes (seat range). SAVs will be able to leave their city or region, possibly paying their way as they do, because they must be able to accept, and perform, any service, as long as it starts in their 'domain'. Separate from SAV companies, there will be public or private dispatchers, in local or regional monopoly, to act

[15] Much as the federal debt clock in the U.S. or the PM.I. indexes.

as flight controllers do presently for air flight: gathering, and processing V2I information, managing the dispatch of SAVs to achieve the maximum of efficiency. They will validate, and manage privately owned AVs' journeys. These companies/agencies, much as the fleet companies, will require oversight, and regulation. Their algorithms must be transparent, as well as their pricing behavior. Taxation will have very fine-grained information, from which to base its incidence: miles travelled, times of day, routes taken (more or less congested), and vehicle occupancy.

Vertical differentiation will naturally take place both in privately owned AVs (size and luxury) and SAVs (waiting, sharing, detours, extra time), and the taxman can intervene, in order for demand to be managed, keeping PT's role in de-congesting streets and roads, and promoting DRS, as long as all pay their way (in proportion to what each takes in parking and public road space, energy, and emissions).

5. Conclusion

Widespread deployment of AV technology, for full automation, will deliver sharp reductions in accidents and parking needs, two boons for society at large and cities in particular. AV paradigm's role in Vehicle Miles Travelled, hence congestion, energy and emissions in comparison with today is ambiguous, which means it can be negative. The cornerstone of AVs improving on the status quo rests on sharing taking center stage, offering privacy (not sharing rows with strangers) and heavy discounts on flexibility (how much bother you tolerate for sharing). To lower the costs for AV, through scale, the personal car's leading position must be conquered. Also, shared AV's (SAVs) convenience must not endanger Public Transportation, at least in cities, where they are needed to decongest. To ensure that survival, PT will need continued support, and SAVs companies may need taxation or regulation to moderate/manage their quest for custom, namely curtailing the aggressiveness of 'all you can eat' menus.

Further research in this developing and prospective field include consumers' tastes and choices and technological developments on safe deployment of full automation and policy implications for SAVs.

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