VEHICLES THAT DRIVE THEMSELVES: WHAT TO EXPECT WITH AUTONOMOUS VEHICLES

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Background

Humans are headed into a mobility revolution, thanks to the emergence of self-driving vehicles. Tesla's "Autopilot" feature has been used by many consumers in freeway conditions, and testing of fully automated or "autonomous" vehicles (AVs) have become rather common in many settings, like the City of San Francisco, Phoenix metro area, and Detroit region. Technological improvements and investments by vehicle manufacturers and technology companies suggest that AVs will be publicly accessible in many locations within 10 years, although design, production, and licensing challenges remain.

AV technologies may radically change several aspects of personal trip-making and freight mobility, including crash counts and congestion, energy use and emissions, and land use decisions. For certain impact areas, one may be confident that benefits will outweigh costs – such as in safety and vehicle efficiency per mile driven. In the case of other impact areas, it is not clear whether automation of vehicles ultimately will be viewed as beneficial, since making "driving" easier adds demand to already congested roadways and can support further regional sprawl. Predicting AVs' direct and indirect effects is a daunting task, given the uncertainties inherent in AV technology development, public attitudes, policymaking, and safety standards. Nevertheless, it is valuable at this early stage to try understanding all potential implications in order to move toward more sustainable/less unsustainable travel choices and urban systems.

This paper provides an overview of such topics by surveying recent research results and publicly available reports. After a discussion of AV adoption forecasts, we examine travel choice, traffic and congestion impacts, shared vehicle systems and shared rides. We conclude with a discussion on potential impacts for freight movement. Readers are referred to many references throughout these sections, including a section on "Further Reading" for more details.

AV Adoption

There has been much news hype regarding release of AVs to the public, driven in part by competition within the manufacturing space, for investment and returns. Machine learning algorithms have advanced quickly, while sensor prices have fallen, but "corner cases" in design remain daunting (unusual situations that could bring to wrong detection) and LiDAR remains expensive. Some of the most detailed work in household-fleet forecasting, recognizing the long lifetime (17 years on average) of existing household vehicles, includes that by Bansal and Kockelman (2017) and Quarles et al. (2019), who surveyed thousands of Americans regarding their vehicle holding choices and simulated, year by year, U.S. household fleet evolution. Those predictions do not suggest 80% adoption until year 2050 or later, without public policy interventions (like AV-only requirements in sales and/or use at certain points in time). Using a Bass diffusion model, with parameters based on adoption of other technologies in the U.S., Lavasani et al. (2016) suspect that technology cost will play little role. Clements and Kockelman (2018) estimate the value-of-time and crash-avoidance benefits to be so valuable to most travelers in developed countries (with high wages) that the choice may be easy (saving drivers effectively 100+ hours of time or almost $2,000 in time-cost every year, with similar property and injury benefits), once vehicles become available in showrooms. But experience can be critical, and manufacturers do not want to release vehicles that are not yet ready for prime-time success. As to the potential initial customers of AVs, they will likely be young, more educated, and more frequent travelers (Haboucha et al., 2017). The major determinants behind their adoption are consumer perceptions of their improved usefulness and trustworthiness (Choi & Ji, 2015.)

People's opinions can and do change, based on what they and their colleagues', friends, family members and neighbors are experiencing (like being served by a shared AV while on business travel). So preferences will evolve alongside AV cost reductions and policymaking, presumably shifting those survey-data-based adoption curves to higher ownership and use rates. In addition, most or nearly all early AV releases may be to professional fleet managers (like existing car-rental companies and ride-hailing companies), who sign lengthy contracts agreeing to restricted use cases (like specific corridors and weather contexts, under specific lighting situations) and special maintenance provisions (like daily equipment reboots, algorithm checks, and sensor cleaning). So household AV adoption may not be nearly as important as shared AV (SAV) release and adoption, raising roadways' AV vehicle-miles traveled quickly. Attitudinal and lifestyle factors, such as a person's tech-savviness and past use of ride-hailing services, together with safety concerns and expectations of driving automation, will play important roles in AV and SAV adoption (Lavieri et al., 2017; Nazari, 2018; Bansal et al. 2017). Quarels et al.'s (2019) extensive U.S. survey work and household simulation over time suggest that one-third of US personal ground travel in year 2050 may be by SAVs (with about one-third of that in true ride-sharing - with a stranger) and that 60 percent or more of vehicle-miles travelled (VMT) should be in self-driving mode.

Travel Behavior Impacts

Vehicle automation is widely agreed to affect travelers' travel cost and experiences – both monetary and perceived. The fixed costs of owning an AV will be high (at least in the early, adoption phase) to accommodate expensive equipment, including computers and cameras, radar and presumably LiDAR, automated controls and wireless communications for safe, accurate, and rapid navigation. Initial prices are expected to be $20,000 or more above base comparable vehicles (Fagnant and Kockelman 2016, Litman, 2019). Maintenance costs may rise as well, thanks to the added vehicle complexity, specialized sensor maintenance, and more expensive equipment replacement (Litman, 2019). On the other hand, AV operating costs should fall, thanks to sizable reductions in collision-insurance costs (Fagnant and Kockelman, 2014; Bosch et al., 2018) and per-mile fuel savings of 5% to 20%, depending on driving environment and user preferences, thanks to speed synchronization, inter-vehicle coordination, and eco-driving (Stephens et al., 2016; Lee and Kockelman 2018). Parking search and use costs may also fall, as travelers rely on SAVs for many trips to high-parking-cost locations (like central business districts) and/or if AVs are permitted to park away from where they drop off their owners/users (Litman, 2019) and/or at least better anticipate available spaces (Shoup, 2006).

There is not yet strong agreement on the value of travel time (VOTT) effects of using AVs. Most experts expect significant VOTT reductions since AVs allow former drivers (though not former passengers, presumably) to suddenly engage in leisure and work activities (see, e.g., van den Berg and Verhoef, 2016; Zhao and Kockelman, 2017; Bansal and Kockelman, 2017; Auld et al., 2017) and to reduce driving stress (Singleton, 2018). Of course, being stuck in a vehicle is still limiting, so VOTTs are not expected to fall more, say, 50% for drivers (Cyganski et al., 2015, Lenz et al., 2016, Yap et al., 2016). Given the importance of VOTT assumptions in travel demand modeling and network performance predictions, further research involving revealed preference data (rather than stated preference surveys) is needed.

A key outcome of lower VOTTs is higher VMT. This addition to VMT comes alongside empty driving by SAVs, better "driving" access for those with disabilities (Harper et al., 2016) and lowered monetary costs of "driving" that translates in higher frequencies and longer distance traveled to the detriment of public transit and active modes competitiveness (Loeb and Kockelman, 2018; Simoni et al., 2019). All together, these behavioral changes portend a potentially dramatic rise in VMT demand and thus very serious congestion issues. Different simulation-based studies anticipate overall VMT increases between 10 and 50 percent from the adoption of (privately owned) AVs, depending on their cost and competition with other modes (Kim et al., 2015; Auld et al., 2017; Zhang et al., 2018). Significant increases are also evident in SAV-focused studies (Childress, 2015; Liu et al., 2017; Fagnant and Kockelman 2016; Loeb and Kockelman 2018), due to about 5% to 25% extra VMT from empty driving between passengers. Finally, AVs may dramatically affect long-distance travel choices (modes and destinations), by reducing air and rail travel by passengers and freight, while increasing highway travel between regions (Perrine et al., 2017; Huang et al., 2019b).

In order to limit the externalities related to the increase of motorized trips, different travel demand management strategies could be adopted. Lamotte (2017) propose a reservation-based strategy to manage automated vehicles' departures in Vickrey's bottleneck model. Simoni et al. (2019) assess alternative congestion pricing schemes to curb AV and SAV demand in alternative future scenarios. Tscharaktschiew and Evangelinos (2019) evaluate tolls to affect travelers' decision to switch between autonomous and manual driving and limit congestion. Conversely, Lee & Kockelman (2019) suggest that traffic flow benefits from AV adoption might obviate the need of congestion pricing schemes.

Traffic Impacts

Connected and automated driving systems (CADS) may increase traffic flow along lanes and through intersections and other points of conflicts by improving reaction maneuvers and inter-vehicle coordination decisions, reducing headways and crashes, and facilitating merging and mini-platoons. Benefits over time ultimately depend on manufacturers' design decisions, government regulations, and consumer adoption rates.

Thanks to having information on more vehicles around them, along with shorter reaction times, highly automated vehicles can reduce headways and increase road capacity (Tientrakool et al., 2011; Van Arem, 2006; Hoogendoorn et al., 2014). For example, Shladover et al.'s (2012) simulations suggest basic-freeway link capacity increases up to 80%, simply thanks to full adoption and application of cooperative adaptive cruise control (CACC). Most existing studies anticipate considerable flow improvements only at high adoption rates (e.g., above 50%), but Jerath and Brennan (2012) and Kesting et al. (2008) anticipate benefits at lower rates (e.g., above 30%). Talebour and Mahmassani (2016) by means of microsimulation identify automation as the main factor behind the capacity improvement (thanks to a significant increase of traffic stability) especially in comparison to communication technologies implemented alone. However, the highest benefits will be mostly likely achieved by the possibility of quickly sharing traffic information among vehicles, processing it by means of advanced algorithms, and identifying efficient solutions without involving humans.

Some recent theoretical traffic-flow work emphasizes general formulations for feasible lane policies (Chen et al., 2017) and adaptations of existing models (Levin and Boyles, 2016) to try and reproduce mixed-flow behaviors involving both, conventionally driven and fully automated vehicles. By investigating the influence of different factors (e.g., minimum inter-vehicle spacing, headway options, and market penetration, researchers like Bujanovic et al. (2018) developed analytical models for predicting platoons' traffic effects based on platoon lengths and CADS penetration rates.

Other studies have focused on achieving better road network use via innovative control strategies using advanced automation and communication technologies. For example, Dresner and Stone (2008) proposed and then micro-simulated autonomous intersection management (AIM), where vehicles approaching an intersection can coordinate arrivals and movements via reservation, greatly reducing travel delays. Sharon et al. (2017) developed link-based "micro-tolls" across a downtown network that dynamically vary to reflect and thus lower congestion costs from AVs' routing choices. Several (CACC)-based strategies have been developed to stabilize traffic flows and thereby help avoid triggering certain types of congestion (Naus et al. 2010; Milanes and Shladover, 2014; Wang et al. 2014). The estimated capacity gain from CACC-equipped vehicles can almost correspond to 90% of the original throughput for low headways (e.g. below 1s) and high penetration rates (above 90%). Zhou et al. (2017) proposed an AV-based strategy to maximize highway on-ramps' efficiency by smoothening traffic oscillations with halved speed dispersion rates for 25% AV penetration rates. Stern et al. (2018) show how a single AV can be effectively used to dampen stop-and-go waves (with 10-15% throughput increases for a single AV controlling the flow of 20 "traditional" vehicles). Wu et al. (2018) obtained similar results using artificial intelligence-based control techniques for AV flows. It is worth mentioning that in these studies, only vehicular flows are investigated and conflicts with other modes such as pedestrians and cyclists are not considered.

Finally, CADS are expected to significantly reduce crashes rates (Li and Kockelman, 2018), since over 90% of public-roadway crashes involve human error (NHTSA, 2008). Since such crashes currently account for about 25% of roadway delay costs in the U.S. and presumably elsewhere (FHWA, 2017), AVs may reduce congestion costs by that much in the long run (assuming very high market penetration rates, which may come with regulations, much like seat belts and electronic stability control requirements on all new vehicles being sold in most developed countries). It should also be noted that reduction in non-recurring congestion from crashes and from reduced congestion overall should improve reliability of the entire transportation system (by reducing uncertainty or variability in door-to-door travel times). This does require that AV technologies plus variable road pricing strategies, for example, are able to avoid the added congestion and potential gridlock that many expect from having too many AVs and other vehicles on the road). Moreover, improved safety and congestion delay reductions often involve a trade-off: in order to reduce crash likelihood, larger spacings between vehicles and lower speeds are often desired. Finally, long-term testing and programming will still be needed before this technology can guarantee zero (or close) risk of failure.

Shared Mobility: SAVs + DRS

High initial costs for vehicle automation, special maintenance needs, and use restrictions on early AVs will favor deployment of heavily used shared fleets of AVs or "SAVs". Since automation can significantly reduce operating costs for taxi and ride-hailing fleet owners or managers, transportation network companies (like Lyft, Uber, and Didi) are running AV tests (Kang, 2016a; Hawkings, 2017), investing considerable resources (Buhr, 2017) and developing strategic collaborations with automakers and governments (Russell, 2017) for future, large-scale SAV deployments. Automakers like Ford, GM, Fiat Chrysler, BMW, Daimler and

Volvo are also considering the possibility of serving as SAV providers (Stocker and Shaheen, 2017). Even cities and local transportation authorities are considering SAVs as potential development for the future mobility services. For example, in 2016, Switzerland's largest bus company (PostBus) launched an AV shuttle service trial in the city of Sion to serve less accessible areas (Lavars, 2016). That same year, a local transit operator tested a similar service in Lyon, France (Pultarova, 2016). Since then, several cities worldwide have been launching similar pilot tests (e.g., Paris, Helsinki, and London in Europe, Ann Arbor and Las Vegas in the US) in order to provide innovative "first-/last-mile" solutions (linking local vehicles with longer-distance, existing, fixed-rail investments, for example). Waymo, a Google-initiated program of SAVs, has been serving households around the Phoenix, Arizona region as well, using plug-in hybrid-electric minivans (DeBord, 2018).

From a sustainability perspective, self-driving, on-demand mobility can offer an attractive alternative to privately owned and, often, less fuel-efficient vehicles while ideally enabling efficient integration with existing transit system investments. Nevertheless, SAVs also often act in direct competition to existing public transport services, and can generate new VMT. In order to steer the development of SAV services in less unsustainable directions, it is important to better understand SAVs users' perceptions, along with likely operations, performance metrics, passenger-mile costs, and other SAV-fleet implications for mobility and the natural environment.

A few studies have explicitly explored SAV use tendencies, using stated preference surveys. Bansal et al.'s survey (2016) found that Austin, Texas respondents more inclined to state a willingness to use SAVs are males, full-time workers, tech-savvy individuals and those living in densely populated urban areas. Similarly, Krueger et al. (2016) identified relatively young males as the most interested demographic for use of SAVs, via a survey across several major Australian cities. Meaningfully, a distinction between car drivers and car passengers emerged from this survey, with the latter more inclined to make use of SAVs with dynamic ride-sharing (DRS). Using paired comparisons of current and future travel modes in Germany, Pakusch et al (2018) anticipated a growth of car sharing thanks to automation, and mainly at the expense of public transit. Although such studies can provide useful indications of trends and key factors at play in SAV adoption, reliance on stated preferences is always tricky. Other studies use existing parameters and estimates of VOTT changes to anticipate adoption rates largely via existing parameters and mode-cost estimates in transport planning models (Davidson and Spinoulas, 2016; Lavieri et al., 2017; Zhao and Kockelman 2018, Huang and Kockelman 2019).

Fleet performance metrics are also crucial in anticipating SAV competitiveness and sustainability. Using simulation of vehicles and travelers, Fagnant et al. (2015) demonstrated how SAVs may be able to replace up to 10 conventional vehicles in a small region or town while reducing carbon monoxide and various other emissions, at the expense of a 10 to 20% increase in VMT. Chen and Kockelman (2016) then explored the influence of different SAV-use pricing strategies with a fleet of range-constrained all-electric SAVs and highlighted trade-offs between fleet performance (including response times and empty VMT), fares, and overall demand for SAV services. In the case of all-electric SAVs, charging infrastructure investments and battery size/vehicle range can be crucial to the fleet's competitive performance (Chen et al. 2017; Loeb et al., 2018). Furthermore, sophisticated customer assignment strategies (involving reassignment of travel requests among different vehicles) can be developed to improve fleet performance by lowering response times during the most congested hours (Hyland and Mahmassani, 2018).

Of course, dynamic/real-time matching of overlapping rides for distinct travelers via DRS should also reduce SAVs' congestion impacts and environmental footprint. A few studies, mainly based on simulation, have explicitly explored the issue of DRS for SAVs and examined the propensity to share rides based on fares and levels-of-service (e.g., Fagnant and Kockelman 2016; Farhan and Chen, 2018; and Loeb and Kockelman, 2018 & 2019). Recently, Gurmurthy et al. (2019) found that pricing strategies reflecting overall levels of congestion and fleet usage can be particularly useful in incentivizing users to adopt DRS and thereby reduce SAVs' VMT.

Freight Transportation

Automation will affect freight transport via use of platooned trucks relying on CACC technologies, self-driving trucks, drone deliveries, and ground-based robots. AV research in freight transport has focused on long-distance trucking applications and drone-based delivery systems.

Assisted highway trucking may be one of the first AV applications in public use, thanks to high trucking costs (for labor and vehicles) and long-distance use, making the economic case for AV investment clear and rather immediate. Using a random-utility-based multi-regional input-output (RUBMRIO) mode of production and trade across the US, Huang and Kockelman (2019) estimate a long-term shift away from conventional trucks and railroad to automated heavy trucks for routes over 500 miles. Smart, safe, truck-driving and vehicle-following algorithms can improve safety, give operators needed rest for longer drives, and decrease fuel consumption by about 10%, when platooned (Tsugawa et al., 2011; Bergenhem et al., 2012; Alam et al., 2015). Operators may take control for the shortest and most complex sections of long journeys while dealing with other tasks and supervising the cruise during the long legs of the trip. Although truck platooning has been successfully tested worldwide in the last few years (Tsugawa et al., 2016) several safety issues (e.g., V2V communication failures, hijacking, infrastructure constraints) and regulations (e.g., platoon size limits, road prohibitions, liability rules) will need to be addressed before implementation (Janssen et al., 2015).

Smaller, autonomous or semiautonomous ground vans and single-unit trucks may also be employed for delivery, with a person on board to perform loading/unloading tasks and/or with different compartments that can be unlocked by customers at destinations (DHL, 2014). Drones or Unmanned Aerial Vehicles (UAVs) may soon improve supply chains and freight operations by delivering very small (weighting less than 3 kilograms) packages over the "last mile" of urban trips and/or by performing deliveries in less accessible areas. UAV use offers several advantages over conventional vehicles. For example, drones can typically perform quicker deliveries than trucks since they are not as constrained by street networks (although they might be mandated to fly over public right of ways in cities) and hindered by congestion. They also can more easily deliver light-weight packages in rural areas with low demand and in difficult terrains. Various supply chain businesses (like Amazon, DHL, and Google) have been testing drone-based solutions in an effort to reduce last-leg distribution costs (Hern, 2014). In 2019, UPS started the first commercial drone-delivery service in order to deliver medical supplies in North Carolina (Stradling, 2019). Several recent studies have explored the profitability of drones and their integration in current delivery systems using optimization and business approaches (see Otto et al. (2018) for a comprehensive review). Depending on the speed, flight range, carrying capacity, and deployment strategy drones can yield up to 30% savings (over the traditional TSP) in total delivery time (Murray and Chu, 2015; Agatz et al., 2018). However, drones will probably be employed for only a small share of total delivery volumes because of fly-height and battery-range restrictions. Public safety concerns can also slow their adoption.

Another automotive innovation with potential applications in the area of last-mile freight distribution is delivery robots. Several companies are exploring the possibility of delivering groceries and parcels via robots operating on sidewalks (Starship, Dispatch, Marble) and roads (Nuro). Similarly to drones, robots could be employed in combination with larger delivery trucks that can not so easily penetrate neighborhoods or park in front of delivery addresses. Before large-scale implementation, however, issues related to their operations in crowded areas and regulations will need to be addressed (Hoffmann and Prause, 2018).

Conclusion

AVs are expected to transform the passenger and freight mobility landscapes in several ways. This chapter discusses their expected impacts on travel choices, traffic flows, shared mobility, and freight distribution, by reviewing various research findings. Several decades may pass before AVs' large-scale impacts become visible in most locations, due the technological challenges, costs, and other complex issues that surround AV use - including public perceptions, demonstrated safety statistics, liability (for manufacturers as well as policy makers), market trends, and specific deployment decisions and settings. Nevertheless, it is important to gain a better understanding of AVs' many potential effects at this early stage, in order to foster more sustainable travel choices and smarter transport-system investments.

While autonomous and connected driving has great potential to ultimately improve traffic efficiency, its extent will strongly depend on demand decisions, public policy, and user trust, in addition to technical challenges from algorithm and sensor development. As discussed here, travel costs for persons and freight are expected to fall thanks to once-drivers being able to perform other activities en route and travel longer distances without driver fatigue and sleep requirements. One downside of lower VOTTs, however, is a rise in trip-making, motorized vehicle use, travel distances, and suddenly empty-vehicle travel. If empty VMT is not limited by law or pricing policies and local-intersection operational overhauls, congestion can become much worse in urban areas. Stated preference surveys and extensions of existing travel models offer meaningful indications of potential vehicle-choice, travel-choice and network-condition changes, but additional research based on real observations will be needed in the future to better anticipate long-term shifts while developing more appropriate policies.

While added VMT may swamp any traffic benefits from AVs and SAVs, in the near term, highway and major arterial's streets' traffic performance may eventually benefit from the possibility of shorter headways and improved coordination at intersections. Within this context, advanced cellular and radio-based communication technologies will presumably play a key role in enabling effective coordination among vehicles and hopefully with pedestrians and cyclists. Moreover, shared mobility options may greatly facilitate inter-modal trips, higher-occupancy (shared-ride) vehicle use, and a regular reliance on battery-only vehicles without range anxiety for users. Of course, automation via drones and robots may also considerably change freight-delivery landscapes, in terms of last-mile distribution.

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