Chapter 7

Multimodal relationships:

Shared and autonomous vehicles and high-capacity public transit

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Today's urban transportation system does not function adequately for most of its users. Those who take transit are frequently beset by infrequent service, crowded trains, delayed buses, and inadequate coverage. Those who drive or are driven are stuck in traffic, contributing to climate change, and subject to the ever-present possibility of committing vehicular carnage. Those who walk or bike are confined to poorly maintained, often discontinuous, dangerous, and circuitous routes. Few receive the transportation services that adequately meet their needs, and some are excluded from the transportation system altogether due to their inability to pay, their age, or their physical abilities.

Part of the problem is that no mode, by itself, provides the capacity necessary to carry all people over all the necessary distances and with reasonable directness, which requires serving the full array of origins and destinations. Transportation network companies (TNCs), for example, offer direct door-to-door services but have limited capacity to carry large numbers of passengers; typical public transportation options, on the other hand, are high capacity but not direct. The introduction of autonomous vehicle (AV) technology, which we expect to be largely an extension of today's private automobile and TNC system, will not by itself alter this dichotomous relationship. In Figure 7.1, we compare several of the key advantages of AVs and public transit. A transportation system that is made up primarily of these two modes would offer options that are demand responsive and offer economies of scale, respectively—but not both at the same time.

In this chapter, we consider the potential for a more integrated transportation system that merges access to services offered across modes in order to effectively bridge the gap between the three demands of capacity, directness, and distance, and that combines the respective advantages of AVs and transit as enumerated in Figure 7.1. Our examination specifically considers whether the advent of AV technology—particularly shared autonomous vehicles (SAVs)—can be used as a lever to enhance

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transit systems, not only by improving their efficiency, but also by filling the major gap that has limited transit's success in attracting riders, especially in the United States: directness. Thus the fundamental motivation for our text is an effort to understand whether and how the transportation system can maintain the capacity benefits of transit (and thus its congestion-relieving and sustainable characteristics), while improving services to more people.

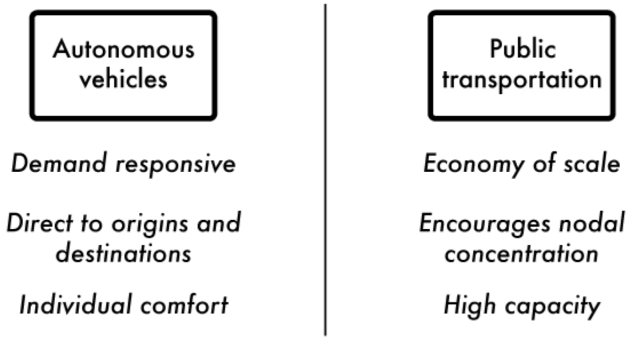

Figure 7.1 The key advantages of autonomous vehicles versus public transportation

Our contribution is premised on the assumption that AV technology will have a major influence on the workings of the transportation system, but that its influence can be shaped. Simply layered on top of today's options, it will have both positive and negative consequences. It promises to improve certain aspects of the ground transportation system, potentially expanding options in underserved neighborhoods, offering new connections for historically excluded populations, and reducing transportation-related externalities, such as casualties and pollution. An AV system can theoretically respond to changes in system demand more quickly and with fewer implementation obstacles than a human-driven one. On the other hand, AVs may reinforce the negative attributes of the current network, encouraging more vehicle use, congestion, and pollution. Evidence from TNCs thus far, as we shall show, suggest that these impacts are not to be dismissed—and that neither TNCs nor AVs will replace the high-capacity benefits of transit.

In this chapter, we emphasize that public transportation is, and will continue to be, an important element of the ground-transportation system, but that its role, too, can and should be altered in the context of AVs for an improved urban transportation future that serves more people more effectively. We begin by parsing out how transit interacts with shared vehicles operated by TNCs today, examining how their markets intersect and their effects on one another. We review recent scholarship to demonstrate that the manner in which TNCs have been rolled out has largely been in competition, rather than complementary, with transit. Second, we consider the potential for integration between these two modes in the context of autonomy, a technological change that will ultimately affect TNCs, transit systems, and privately owned cars (though we do not focus on the latter in this chapter). Third, we point to ways in which AV technology offers the opportunity to expand transit's reach by allowing the provision of smaller vehicles in more places and encouraging intermodal links. By taking advantage of autonomous technology to allow real-time, fleet-based decisions about the network, we show how an integrated system can advance a transportation system that responds best to the constrained urban right-of-way. And finally, we consider several key questions related to a potential integrated system, such as what behavioural and regulatory norms would have to be upended to make such integration possible.

7.1 Current relationship between TNCs and public transit

In this section, we describe the existing relationships between public transit systems and TNC services, with a focus on North America. We investigate the modal characteristics of each, highlighting the range of services both provide and their strengths and weaknesses in addressing mobility needs. We then investigate how their passenger markets and operational patterns interact.

7.1.1. Modal characteristics

We begin by defining transit: the provision of fixed-route services using vehicles (usually buses or trains) that have the capacity to carry many people at once (see Reference [1] for more detail on alternative definitions of transit). Over 95 percent of all transit vehicle miles in the United States, as defined by the Federal Transit Administration [2], are operated in such a fashion, and about 99 percent of riders use transit in this way. Most transit services in developed countries are planned by public sector organizations, which subsidize them using funds generated from other sources. Many services are operated by public-sector agencies, though this was historically not the case, and is not always the case today. Transit typically serves two primary purposes, which sometimes intersect. First, it offers transportation in dense areas with high travel demand, for which frequent transit vehicles provide the highest-capacity and most cost-efficient option available to a wide range of riders (sometimes referred to as “mass transit”); and second, it offers a minimum level of service with infrequent, circuitous routes for people and neighborhoods with limited alternative options (“social transit”) [3].

Non-transit shared vehicles, on the other hand, typically provide point-to-point services without a fixed route. Carpooling is a traditional way of accomplishing this; passengers headed to the same destination, such as school or work, share a trip. But its use in the U.S. has fallen from about 20 percent of commuting trips in 1980 to less than 10 percent today, a consequence of increased affordability of and access to private automobiles [4,5]. Even so, online carpooling services such as BlaBlaCar, operating on a peer-to-peer transaction model, have increased in popularity recently [6,7,8].

For the remainder of this section, we focus on the market of services provided by third parties at a cost through taxis or TNCs (such as Lyft and Uber), which typically occurs through mobile phone-based applications (“ride-hailing” or “ridesourcing”). Unlike transit, these services are offered in four-door automobiles, minivans, and sport-utility vehicles; they are not planned, subsidized, or provided by the public sector; and vehicles are generally owned by drivers, not as a fleet. TNC companies allow users to select from an array of services, some mimicking taxis in that only a single passenger or a group of passengers who know one another share a trip, or departing from the taxi precedent by allowing individuals unknown to one another to share trips.

This latter service, sometimes referred to as “pooled” rides, can be operated in at least two ways. The most common approach, offered through services such as Lyft Line and UberPool, is to connect multiple passengers whose origins and destinations may not be exactly shared, but which are “on the way” of one another. A traveller going from point 1 to point 3 may pass near or through point 2; in the process, a driver may be able to pick up a passenger going from point 2 to point 4, a trip which may pass near or through point 3. This system may cause some inconvenience depending on just how overlapping the two routes are with one another, and the willingness of passengers to share space. Another approach has been piloted by ride-hailing services such as Via and involves customers walking to a nearby pickup location before being picked up on an “optimized” route that reduces detours to pick up shared rides [9,10].

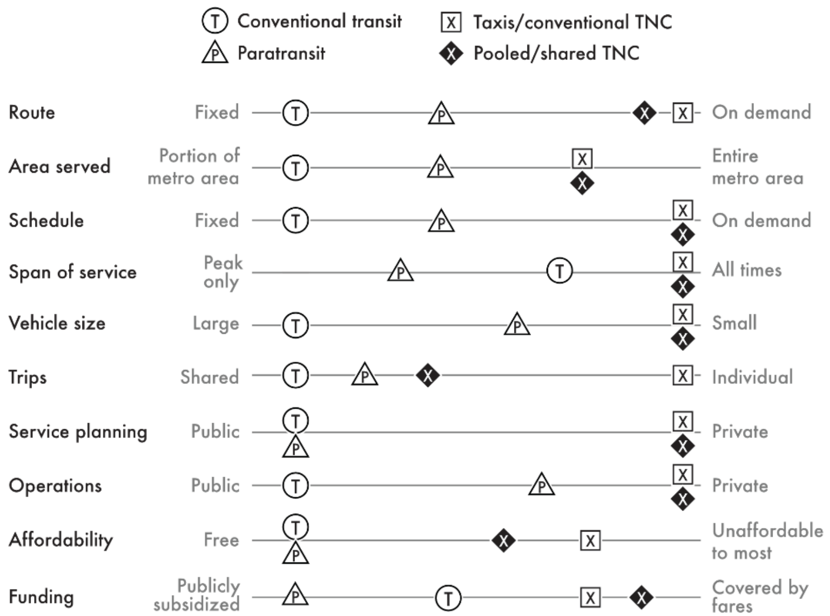

Figure 7.2 Spectrum of ground transportation services, across an array of characteristics

Figure 7.2 maps out the spectrum of transportation services, noting how conventional transit differs from paratransit (optimized-route services operated or funded by transit agencies, typically serving disabled riders), conventional TNC service, and pooled TNC service across ten characteristics: route, area served, schedule, span of service, vehicle size, trip sharing, service planning, operations, affordability, and funding. This figure provides a view of the differences between these modes, but this should be seen as illustrative, since the reality is that transportation services are location-specific and in flux. Key to Figure 7.2 are the differing norms by which passengers interact with each mode. Passengers using transit understand that they will be in a shared environment, receiving scheduled service on pre-determined routes; people using taxis (or their privately-owned vehicles) expect isolation and on-demand, door-to-door service. Given these differing norms, an integrated AV-transit system, in which people move between services in different-size vehicles would undoubtedly require the cultivation of a new norm among passengers.

Transit is designed to encourage road-space and vehicular efficiency (its specific characteristics depend on mode and location). Its fixed routes, schedules, service only at certain times of the day, low costs, and large vehicles are in theory meant to move the largest number of people while consuming the smallest possible footprint in the transportation network (not that transit always achieves this goal). Transit services attempt to achieve these objectives by typically being planned, subsidized, and operated by public-sector entities. TNCs, on the other hand, are operated to encourage operational flexibility. On-demand routes, schedules, high costs, and small vehicles respond to individual needs. This is typically done through private decision-making related to service planning and funding, and public involvement is limited to regulations over issues such as medallions or driver qualifications. In most metropolitan areas, transit and TNC operations reflect these opposing goals, and are largely separated. Few people take multimodal trips incorporating TNC and transit links. The dual advantages of transit efficiency and operational flexibility, referenced in Figure 7.1, thus largely have yet to be combined. Figure 7.2, for example, illustrates that current options fail to offer on-demand, affordable, publicly planned services that meet the transportation needs of an entire metropolitan area.

Even so, the availability of shared ride-hailing services demonstrates that the dichotomous view of transportation services—taxi (individuals riding alone or with known others from their chosen origins to their chosen destinations) versus transit (groups of people who do not know one another riding between fixed stops)—is evolving into something that begins to fill the gaps in the spectrum presented above. This is perhaps made most evident by certain demand-responsive offerings used to provide transportation either for people unable to use the conventional transit system or for “last-mile” connections intended to extend its reach. Transit agencies such as the Massachusetts Bay Transportation Authority [11], for example, have contracted with TNCs to provide such services that are sometimes as affordable for passengers as conventional transit. In the case of Altamonte Springs, Florida [12], these offerings have replaced the transit system.

Moreover, transit is increasingly being contracted out; the share of services directly operated by public agencies in the United States declined from 81 percent in 2002 to 70 percent in 2018 [13]. Similarly, the rise of public subsidies for TNCs plus the decision of some cities to impose specific taxes and regulations on TNCs (such as New York’s limitation on the number of ride-hailed vehicles. Wodinsky [14] suggests that these services are increasingly within the purview of public decision making. From a passenger perspective, the incorporation of transit and TNC information on the same application, an approach being piloted in several cities, means that many may experience them as part of the same transportation “ecosystem.”

The deployment of AV technology will make TNC services even less clearly differentiable from the transit system, and vice-versa, blurring the spectrum. For example, rather than a difference between transit and TNCs being whether their routes are fixed, an integrated system could incorporate both types of routes. This blurring of the modal spectrum provides an opportunity for the transportation system to become more integrated among the services available and thus achieve higher levels of capacity, directness, and distance.

7.1.2. Passenger markets interactions

We so far lack adequate information about how, exactly, AVs will impact the public transportation system; it remains to be seen whether they will be rolled out as TNCs (with separate fares and no public-sector planning), like the private automobile system (individual car ownership), or as part of the transit system (such as with larger vehicles). Nevertheless, the rise of TNCs over the past decade provides evidence for what we might expect from the perspective of interactions with both passenger markets, which we describe here, and transportation operations, which we describe in the next section. TNCs have addressed some of the problems with transit networks, offering new, low-wait-time options for underserved areas at an arguably higher comfort level; in this way, they may be seen as providing a net benefit for the urban transport network. At the same time, we show that most scholarship indicates that TNCs have competed with transit, reducing ridership, and in the process increased congestion, particularly in dense neighborhoods. If operated similarly, AVs would likely produce similar results.

TNCs have become particularly attractive in North American cities for a specific audience. Surveys point to a ride-hailing user base that is disproportionately young, wealthy, and well-educated [15,16,17,18,19]. This is partly a reflection of the fact that such services are typically much pricier than equivalent transit options (more than four times as expensive on average—for pooled rides—in one Chicago study; see [20], and their use requires access to, and competency in, phone-based applications. TNC passenger markets, then, are different from those of most transit systems, whose clientele is on average poorer than the population overall. The gradual transfer of riders from transit to TNCs, which we describe below, has likely widened this difference.

TNC use varies based on location. In the U.S. overall, 70 percent of ridership is in just nine metropolitan areas, generally the country's densest [18]; and use there is concentrated in dense neighborhoods [16] with high levels of local activity in terms of employment or attractions [15]. Transit use, of course, is equally concentrated in dense communities. The environments where the two modes work most effectively, then, are the same, meaning that if there is a limited passenger market, they become competitors (increasing use of one means reduced use of the other). Higher TNC prices become acceptable to many customers because trip times, especially outside of downtown, can be shortened dramatically through ride-hailing—even when shared [20]. Competition between modes is stimulated by the minimal integration between the two. Intermodal trips combining transit and TNC segments are complicated by the lack of a common fare card, the logistical difficulty of planning a trip that includes both, and the reality that arriving at a transit station may involve a long wait for a bus or train.

Demonstrating the competitive nature of the TNC-transit relationship, Jin et al. [21] and Circella and Alemi [16] find that a large share of TNC users previously used transit; Schaller [18] demonstrates that 60 percent of customers would have otherwise ridden transit, walked, biked, or not taken the trip at all without a TNC option. In other words, TNCs act as substitutes for transit service. Graehler et al. [22]

note that this competitive relationship grows over time, with transit (especially bus services) losing an increasing number of passengers after a TNC service is introduced.

If there is a competitive relationship between transit and TNCs *in general*, the two modes can be complementary (reinforcing the use of one another). Though Hall et al. [23] find that TNC service reduces transit ridership among cities with already-high transit use, they find that it increases transit ridership *on average*, and specifically in cities where transit is currently least effective. Nelson and Sadowsky [24] identify a short-term increase in transit ridership after TNC entry. Whether TNCs are competitive or complementary depends on temporal and spatial effects. For example, ride-hailing is frequently used for non-home-work trips [19,21], situations where transit often does not offer convenient frequency. In a neighborhood comparison in Chengdu, China, Kong et al. [25] show that in suburban communities with poor transit coverage, riders used TNCs to fill last-mile gaps rather than replacing transit altogether.

In some cases, TNCs are neither complementary nor competitive with transit. They may be independent (their use having no effect on the other), such as in cases where there is no transit service, either because neighborhoods are too sprawling or because it is too late at night. TNC use may also replace personal automobiles [26], since they allow people not to have to look for, or pay for, parking [18]. These examples suggest avenues for thinking of TNCs—and, in the future, AVs—as a mechanism to broaden urban transportation options, rather than compete with transit.

Are TNCs the cause of the drop in ridership among U.S. transit agencies that has occurred over the past few years? In 2017, per-capita ridership declined to its lowest level since 1997, and buses have suffered most (though in some cities, such as Seattle, transit increased). While buses accounted for 64 percent of U.S. ridership in 2002, they had fallen below rail in use 15 years later [27]. Transit ridership declines produce a vicious cycle, because they reduce revenues, which in turn force transit agencies to either hike fares or worsen service, both of which further dissuade transit use. But TNCs are only one of several potential explanations for ridership decline. Boisjoly et al. [28] point to reductions in transit service offered, and share Manville et al.'s [29] argument that increased access to motor vehicles (particularly among low-income families) has disincentivized transit use.

Even so, the weight of the evidence suggests that transit and TNCs are competitors for at least a portion of the passenger market—that portion concentrated in the densest neighborhoods and the largest cities. In these cases, transit loses ridership where is it most effective. As we describe below, this relationship could worsen in the context of AVs if they are rolled out similarly to TNCs.

7.1.3. Operational impacts

If there is competition between TNCs and transit to attract passengers, there is also competition between the two modes over space. This problem is aggravated in dense urban areas that already have limited room and which consequently are congested. These are the places where transit is most useful, since it is simply more effective from a spatial perspective to travel collectively, and it is possible to move far more people to a single point on trains and buses than in cars, whether personally driven, driven as part of TNC networks, or operated as automobile-sized AVs [1].

TNCs impact transit operations in several ways. First, if they move people out of transit into smaller, less spatially efficient cars, they increase traffic, assuming demand remains constant. Second, if they increase traffic, they slow speeds and reduce road-network reliability, therefore making street-running transit trips take longer, inconveniencing passengers and increasing the cost for transit agencies to provide a certain level of service. And third, if they use curb lanes for pick up and drop off, they may stand in the way of buses attempting to make similar moves.

To consider the net impact of TNCs, we propose an index of road-space usage efficiency: passenger miles traveled (PMT) divided by passenger-car-equivalent vehicle miles traveled (VMT). A higher index is preferable. This index can be written as follows:

$$R_c = \sum P_c / \sum V_c$$

Where Rc is the road-space usage efficiency for a specific corridor c; Pc is the total passenger miles traveled; and Vc is the passenger-car equivalent VMT (for example, a bus might have a road-space occupancy of three times that of a car). If 10 passengers ride one mile on one bus whose footprint is three times that of a car, their index would be 10 / 3 = 3.3. If those passengers all moved to individual TNCs (unshared), their index would be 10 / 10 = 1; if they moved to two-passenger shared TNCs, their index would be 10 / 5 = 2. In order to be useful, the index must include non-revenue miles. We will return to this index later in this chapter, but note that a shift from transit to TNCs not only reduces the index for the transit system (since it is still running, but emptier), but adds new low-index automobiles to the street. [3] We emphasize that this is just one metric among many needed to assess how various services have affected urban transportation; for example, it might be useful for cities to develop a measure of geographical coverage based on different modes.

But this tool for analyzing road-space usage efficiency is particularly important now because evidence suggests that ride-hailing has already been an important contributor to increased VMT—thus reduced efficiency [17]. A New York City study showed TNCs put 2.8 miles on the road for each mile of personal driving removed; even shared TNCs produced more VMT than previously [18]. Another study showed TNCs produced 83.5 percent more VMT than would have occurred otherwise [30], partly a product of the additional driving TNC drivers undertake to pick up passengers and while waiting for dispatch, when they often continue driving in order to avoid paying for parking. In San Francisco, Castiglione et al. [31] show TNCs contributed half of the increase in congestion that occurred between 2010 to 2016—thus increasing vehicle hours of delay and VMT, and reducing average street speeds (employment and population growth accounted for the remainder of the change). Street speeds declined from 24 mph on average to 20.9 mph.

Reductions in street speeds had detrimental impacts on bus service in San Francisco, with average local bus speeds declining by almost eight percent between

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[3] It is also important to emphasize that what matters is *passenger* miles, not total occupancy. If we were applying this index to privately owned cars, a car with a parent driving a child to soccer practice would only count for one passenger, not two. Henao and Marshall [30] find TNC vehicular passenger occupancy of just 0.8 when accounting for deadheading. The average passengers per mile for New York City buses is 7.7 (Federal Transit Administration, Reference 13), producing an index of 2.6, thus more than three times as spatially efficient.

2010 and 2016 [13] . Though scholarship is limited on TNC impacts on bus stops and lanes, anecdotal evidence suggests that this, too, is a cause of transit delay [32]. As a result, operators have to spend more money (in hours) to provide the same service (in miles). Passengers suffer from lengthier commutes. The incentive for many choice riders, then, is to stop using buses. They may shift to TNCs or private automobiles. Either shift worsens bus service.

7.2. Knowns and unknowns, needs and necessities

In the previous section, we show that under the current regulatory regime TNCs are competing with transit for a significant portion of the market and for limited street space. In doing so, TNCs increase traffic. This produces a vicious spiral of reduced surface transit effectiveness that pushes more riders from transit to TNCs, further adding to congestion and pollution. We assume that AVs will take on many of the characteristics of current TNCs, albeit at lower costs. Thus, if submitted to the same regulatory and behavioural norms as today, AVs may exacerbate TNCs' negative effects—though the degree to which these future services are pooled, or SAVs, will influence the magnitude of these impacts. In this section, we summarize scholarship on the interaction between transit and AVs. We argue that though AVs will extend access to urban transportation for many, left unregulated, they will also diminish the effectiveness of the transit system.

7.2.1. Transit automation and AVs

The London Underground Victoria Line has featured automated train control since 1968. Fully driverless operations have been used for fixed-guideway rail systems since the early 1970s, and major cities from Dubai to Vancouver collectively carry millions of passengers every day on such lines, of which there are now more than 1,000 kilometers in operation [33]. Transit automation is not a new phenomenon, though its relevance has grown.

In this article, however, we focus on *autonomous* vehicle (AV) technology. As with automated transit, AV takes the human out of the driver's seat, relying on computers to make decisions about how to navigate and when to accelerate and decelerate. The technology could be applied to vehicles of any size. Yet unlike automated transit, AV allows operation outside of fixed-guideway, grade-separated environments that are typically the domain of high-capacity metro systems. AVs, theoretically, will be able to drive on whatever transportation rights-of-way human-driven cars use today, such as highways or city streets. AVs thus represent a dramatic geographical and service expansion of automation. It also suggests new options for transit service, since it means that routes could be adjusted on the fly.

Autonomous buses are being trialed throughout the world, typically in the form of shuttles that carry about 10 people each, operating in special areas such as largely pedestrianized business districts or touristic zones [34]. As this technology matures, it will be extended to the 40-to-60-foot buses that account for the majority of the American surface-transit rolling stock.

The extension of autonomous technology to buses comes in the context of the development of 2-to-8-passenger automobile-size AVs. If European cities have largely focused on autonomous shuttle trials, U.S. cities and states have been working with companies like General Motors and Waymo to test smaller-vehicle AVs, which could provide services similar to what is available today via TNCs—both ride-hailing pickups for individuals and people they know, and pooled rides combining journeys between strangers.

7.2.2. Economics of AV operations and future impacts on transit

To what degree will autonomous technology alter mobility costs? Public transportation—particularly bus transit—is labour-dependent. In cities like Austin, labour accounts for more than 45 percent of operating expenses [35]. Bus system productivity in the U.S. has expanded slowly, thereby increasing labour costs as a share of expenses over time [36]. The result is a growing difficulty on the part of agencies to maintain cost-effective transit systems, and a need for rising subsidies to support minimum levels of service.

There is limited scholarship on the relative cost-efficiency and mobility benefits of automated versus human-driven transit, though Cohen et al. [37] provide an overview of recent experience with automated trains. They find that automated lines allow for a staffing reduction of 30 to 70 percent, with a smaller reduction in operating expenses (due to automated-system supervisors earning more than drivers they replace). Such systems are more reliable, allow higher train frequency, and carry more passengers per train due to the lack of cabs. This experience is suggestive of changes that could accompany automated transit generally. A move to electrified, autonomous buses could, for example, reduce overall capital and operating expenses by about a third, saving transit systems millions of dollars that could be redistributed elsewhere [35].

Many models used to evaluate automobile-sized AV systems assume a single operator e.g., Wen et al., [38], an assumption that may bias results because it produces greater network efficiency estimates than may actually occur with competitive operators, as is the case with TNCs today. This same assumption, however, highlights one of the key differences between AVs and cheaper human-driven TNC services: With AVs, the entire network can be controlled as an ensemble, allowing much quicker responses to new demands through movement of vehicle location. Human-driven vehicles, on the other hand, require the individual judgement and driver compliance—and their personal interests may not be aligned with the interests of the system as a whole. Thus AVs could improve the level of service offered on the network. Yet an open-market AV system may suffer from considerable overlap between operators, which may mean more-than-optimal VMT and a larger fleet. These models are also limited in that the actual rollout of AVs remains speculative; modelling must advance to incorporate changes such as fleet size elasticity and vehicle repositioning [39].

One major question affecting the cost of AVs is the degree of sharing they engender. First, will be vehicles largely be privately owned, and thus left to sit idly most of the day (as is the case for most privately-owned cars in the U.S. now), or will they mostly be operated by third-party service providers (like TNCs)? The latter option could lower passenger-mile costs below those of traditional automobiles because, even with higher capital costs, operational costs would be much lower than those of today's TNCs because the cost of paying drivers would be eliminated [40]. This reduction in costs would attract significantly more riders [41]. Second, if the vehicles are owned by third parties, will they largely be operated with individuals and known companions riding alone (like taxis), or will they serve multiple unknown people at the same time (like transit or pooled TNCs)? This latter approach, which we refer to as SAVs, could reduce costs even further by maximizing vehicular occupancy.

Models that consider the introduction of SAV systems suggest that it is possible to reduce the automobile fleet's size if linked to vehicle repositioning to serve appropriate trips [42,43]. This, in turn, could reduce the need for parking and allow for urban redevelopment in its place. At the same time, cheaper AV service would increase VMT, specifically if rides are not shared [44], and particularly in urban cores, where parking is now often costly [45]. Empty unshared cars will circulate around, either waiting for their owners to "pick them up" or in pursuit of long-away parking lots [46].

A mode shift toward SAVs at the primary travel mode may be unlikely. Of those surveyed by Cools et al. [47], 60 percent agreed they would prefer owning a private AV, rather than using TNC services exclusively, and only 47 percent agreed they would be willing to share AVs with strangers. Even so, those levels would be an improvement over the 91.5 percent of U.S. households who own at least one vehicle and the 76 percent of commuters who drive alone to work, according to 2017 U.S. Census data.

If regulated in the same manner as TNCs today and not integrated into the larger-vehicle transit system, AVs (whether shared or not) offering cheaper-than-TNC service can be expected to have several impacts on transit. First, an increase in VMT from AVs would slow the road network, therefore slowing surface transit. Second, the ability to avoid paid parking would encourage people to opt out of traditional transit services, since their overall costs would decline. And third, as we detail below, expanded accessibility to travel for the young, the old, the disabled, and others who currently rely on transit, would, in turn, reduce transit ridership. In other words, an AV system that simply replicates the TNC status quo would magnify its deleterious effects on transit.

7.2.3. Equity, accessibility, and environmental sustainability

If unregulated automobile-sized AV service may challenge traditional transit operations, it is nonetheless worth emphasizing the potentially large benefits of AV rollout from the perspective of equity and accessibility. By lowering costs compared to TNCs, SAVs could increase mobility for many low-income people who do not currently have automobile access, easing links to jobs and services for people who live in a society largely built around automobiles and who are currently stuck using inadequate transit [48].

Increased mobility in much of the U.S. is unlikely to be provided anytime soon through traditional transit expansion—though automated technology may make doing so somewhat easier—because of the high cost of moving large vehicles around low-density communities. If two planning goals are efficiently transporting people while serving those who are least able to afford travel, SAVs may fill an important gap [49]. A similar argument can be made for AVs improving access for people who are left out of the automobile-dominated transportation system for other reasons, such as being too old, too young, or physically disabled.

Nevertheless, if automobile-sized AVs are deployed as a continuation of the current privately-owned automobile system or current TNC business models, these equity benefits will be undermined by increasing traffic and continued inequality in access. Low-income individuals who continue riding the bus as AVs clog the streets (because AVs remain unaffordable) will suffer from reduced mobility. Eased long trips for some, moreover, may spur urban sprawl and decrease easy connections to jobs and services, further widening disparities in access.

Finally, the environmental impacts of automobile-sized AVs remain unclear. Though AV technology is frequently discussed in association with transportation-system electrification, most of the automobile-sized AVs currently being tested are powered by fossil fuels. Increased VMT from them could increase particulate emissions while worsening climate change. Here, too, eased access to far-off areas could be deleterious, since low-density development is also associated with higher carbon emissions than neighborhoods designed around pedestrians and transit access.

We thus stand at a crossroads. AVs could benefit people who have been left behind by both the automobile and transit systems. Yet they could also worsen certain aspects of urban life, including congestion, pollution, and inequality. In the next section, we articulate an approach to integrating transit and SAVs that attempts to reconcile the contrasting features of this new technology.

7.3. Opportunities for integration of SAVs with public transit

In this section, we articulate a vision for a future integrated AV and transit network that combines the positive elements of the two modes that we first identified in Figure 7.1. This vision, we believe, offers an opportunity to expand the directness of the transportation network—offering more useful access to more people—while maximizing its capacity. This, of course, is a speculative view, one whose manifestation would require policymakers to develop plans and regulations that orient new technology. But our hope is that, in offering a framework for how such integration can occur, we can best take advantage of AVs, rather than allow their introduction to worsen urban transportation systems.

Ainsalu et al. [34] identify two approaches that can be taken with regards to AV rollout: “pedestrian-friendly” versus “rider-friendly.” The former focuses on building dense, walkable communities in which AVs complement a growing, productive transit system; this requires multimodal local planning. The latter prioritizes individual AV use, and the result would be more sprawl, congestion, and pollution. In some places, transit will thrive, being complemented by AVs; in others, it will struggle, suffering from competition. Even so, we have identified almost universal consensus among leaders of U.S. city transportation and planning departments for integrating the two modes. In a representative survey of more than 120 cities with populations of 100,000 or more, we found 88.4 percent of officials agreed that they should redesign transit in the context of AVs [50].

Here, we return to the index of road-space usage efficiency we described in Section 7.3. In Figure 7.3, we show how optimal road-space efficiency can be achieved using different modes, depending on the number of passengers moved along a corridor. Given constrained street space, different vehicle types fulfill different demands. In this view, it is most efficient to move people by automobile (SAV) if one to four people are sharing a route; by shuttle if five to 10 people are on the same path; and by bus otherwise. This theoretical model, of course, assumes that people are willing to share vehicles and that it is possible to allocate people to the "appropriate" vehicle when necessary. Despite this limitation, this model can help us identify which modes make the most sense in which circumstances.[4]

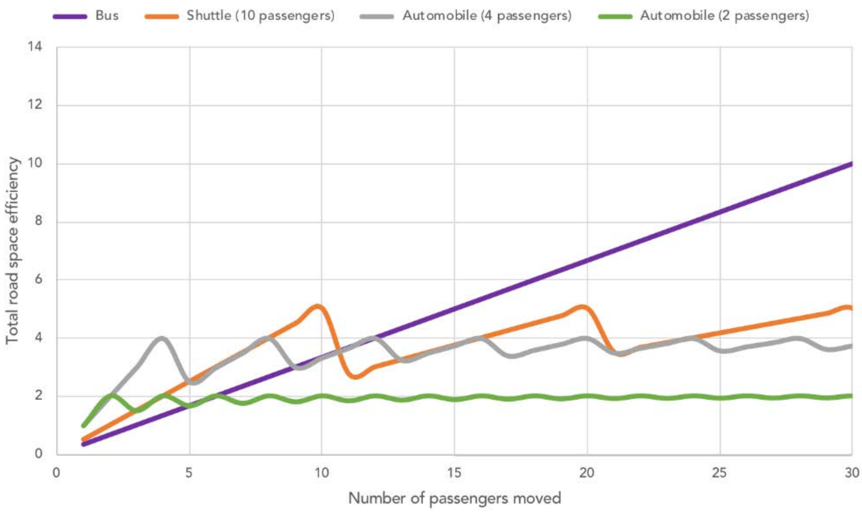

Figure 7.3: Road space efficiency by mode

7.3.1. Synergies involved in integration between SAV and transit

If we come to see automobile-sized AVs and transit as two transportation modes competing for riders and road space, our cities will suffer from increased traffic and transit systems will become increasingly difficult to operate effectively. Yet the advent of AVs offers an alternative: Expanding, rather than decreasing, transit's footprint through a multi-modal travel system incorporating vehicles of many sizes [51,52]. This means shared, automated transportation as a spectrum of services adapted to the needs of travellers in different areas—from sedan-sized cars and minivans to shuttles and buses. To make this spectrum of services useful, integration details matter.

Yan et al. [53] and Shen et al. [54] show that SAVs could replace low-ridership bus routes and provide last-mile access to stations, in so doing reducing wait and travel times, while consuming fewer road resources and using public resources more judiciously. Wen et al. [55] emphasize how SAVs can serve low-density, suburban areas—neighborhoods where transit performs least effectively—and find that doing so could reduce car use and increase transit ridership. An SAV-transit synergy means providing the level of service appropriate for the demand, in terms of vehicle size and frequency, altered based on geography and time. In doing so, the transportation system can meet the needs both of "mass transit"—moving the most people possible

[4] It is worth emphasizing that this simplified model assumes three fixed vehicle sizes. With AVs, however, a wider variety of vehicular options may be available (especially if crash-safety standards are reduced due to fewer crashes); moreover, it is feasible to envision AVs travelling in platoons, which would reduce their relative footprint on the street network.

through limited space—and "social transit"—guaranteeing mobility and accessibility to all.

Even in an optimistic AV rollout scenario [49], many cities will continue to need high-capacity transit to serve the highest-demand areas. Major regions feature routes that carry more than 20,000 people per direction per hour—much more than is possible with automobile-sized SAVs [56]. The capacity limitations of such vehicles are two-fold: First, given limited room and little public support for highway expansion, existing roadways simply do not have the capacity to move an adequate number of vehicles. Second, pedestrian-accessible transit stations served by trains carrying up to 2,000 people each are more capable of responding to demands generated by dense employment zones than streets.[5]

To supplement those high-demand routes, SAVs could offer first- and last-mile connectivity where origins and destinations are not within walkable distance of transit stations, or when temporal conditions merit it—for example, at night. Routes operated by larger autonomous shuttles and buses could be interlined. In the absence of an extensive rail network, fixed-route automated buses operated in high-demand corridors or line-hauls may also improve transit efficiency. With operational-cost savings, transit authorities could deliver more frequent services to a wider suburban geography, reduce passenger waiting and walking times, and improve ridership and fare revenue.

In lower-density areas, lower-capacity services would be most appropriate. Depending on the neighborhood, it might be reasonable to provide service using automated buses on fixed routes, autonomous shuttles, or automobile-sized SAVs. The latter two services could be offered on demand, with routes adjusted based on passenger requests, replacing low-productivity transit routes and add service in areas that currently have none. In the process, transit agencies will need to consider route redesigns, focusing large-vehicle, fixed routes in areas with heavy demand and providing small-vehicle, adjustable routes in areas with light demand. Attracting passengers to these services will require a significant change in norms among residents of such areas, now used to traveling alone. This may be the greatest challenge in the implementation of any integrated system.

Services may also be differentiated by speed and distance. For longer trips requiring faster speeds to maintain reasonable travel times, fixed-guideway, large-vehicle, limited-stop services may be more appropriate than road-based SAVs. This is particularly true in cities with road capacity constraints, where high-speed travel is impossible at peak hours, even on expressways. Identifying appropriate solutions for this sort of operational integration requires further analysis and will surely be location specific.

7.3.2. Details of SAV-transit service integration

Integrating automobile-sized SAVs with autonomous shuttles and an automated

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[5] For example, if we envision an AV service provided by four-person vehicles the size of the Toyota Camry (4.9 meters by 1.8 meters), you would need 500 vehicles, taking up a total of 4,400 square meters (with no space between them) to provide the same capacity as a 2,000-person train. For comparison, a New York City subway train is about 446 square meters in surface area, so it is at minimum 10 times as space efficient.

transit system will require partnerships between modes to avoid overlapping services and congestion, and to promote multimodal trips [57]. We identify four strategies to encourage such partnerships.

First, information about demand, system use, and performance must be integrated between operators. Data is essential to optimize provision of appropriate-scale vehicles along appropriate routes. Information integration allows the system to anticipate, and respond to, demand. The primary goal of information sharing is to guarantee high-quality options throughout a metropolitan area without overwhelming the system with unnecessary service. Today, TNCs and transit offer overlapping services in the same places and at the same times; the result is frequently empty seats and wasted service miles, for which we all pay the price, not only from service inefficiencies but also from the resulting additional congestion and pollution.

From a governance perspective, integrating access to information requires either a centralized control system—all shared transportation services operating under the same roof—or a series of cautious, well-executed contracts between providers. This means real-time, clearly defined data about where passengers are and where services are offered. And it means that operators must share information to one another and to users about services they plan to provide. A multimodal journey planner integrating transit options with access/egress alternatives can help riders make better travel choices by providing estimates for real-time travel and transfer times, cost, carbon footprint, and more.

Such information is closely guarded by TNC operators today, and the consequence is that planners considering whether to upgrade or downgrade transit routes operate on only partial knowledge. The impulse to hide data makes sense in a private sector where competition is the primary motivation. Yet transportation has an important role to play for society as a whole, and the negative externalities of such competition mean that AVs must be approached as a public service with freely shared information.

Second, pricing strategy and policies must be integrated. For riders to feel comfortable moving between multiple services, they need to be confident that their rides will reflect the service provided, no matter which type of vehicle they happen to be riding in. The question of setting fare policy is especially important from the perspective of ensuring equitable access. If automobile-sized SAVs, autonomous shuttles, and automated transit are all made available to low-income people or people in currently transit-inaccessible neighborhoods, for example, they will require subsidies; but those subsidies will only be reasonably allocated if all operators are on the same page about what fares to charge for a certain type of trip.

The pricing strategy of an integrated system will require compromise between affordability to the full spectrum of the public, political acceptance, and ensuring adequate revenues to cover operations costs. Fare policies should encourage achieving the maximum road-usage index, as presented previously. Rider costs must be distributed so as to incentivize vehicle use that minimizes street-network impact, and that sometimes should require providing monetary incentives to transfer to higher-capacity vehicles on high-demand portions of their journeys. As such, a closed-circuit system where operators encourage customers to use just their services (e.g., transit riders stay on transit; Uber riders stay on Uber) is unacceptable.

A fully integrated system that shifts much of the population out of single-occupancy automobiles will produce beneficial knock-on effects, including lower pollution, less congestion, less sprawl, and more equitable access. These externalities will be difficult to incorporate into the network's revenue and subsidy structure, but these broader impacts must be integrated into its financial structure. This will require political initiative to make the link successfully.

Relatedly, all operators in the SAV and transit network must use a single set of ticketing technologies. This means that a passenger using a fare card, a cell phone-based ticket, or anything else accepted on one mode should be able to use that same technology to take a new trip or transfer onto any other mode.

Third, operations must be integrated to allow seamless access to the entire system. This means ensuring that various-sized vehicles are available as necessary at major transit nodes. It would be unreasonable to make changes to bus services that eliminate low-density routes unless users continue to have access (both physically and monetarily) to the new SAVs that replace them. It also means limiting the number of automobile-sized AVs in dense zones where their mass deployment would increase congestion rather than increase mobility.

Integrated operation could also include service coordination and timed transfers. By coordinating with train departure times, SAV itineraries could be optimized to reduce waiting at transfer points (first-mile), and vehicle rebalancing trips can coordinate with train arrivals and among operators to avoid service shortages or congestion due to over-rebalancing (last-mile). Central dispatching and passenger matching of vehicles among multiple SAV providers could further reduce vehicle idle times and VMT. For example, an Uber request could pool with a Lyft rider if the two operators were integrated, but this, again, would require altering the competitive mentality that now dominates among TNC operators.

Similarly, the business models of multiple operators require coordination. This may mean the development of a fully public system, with publicly supported and operated services at all scales, or it might mean a mix of public and private operations. Yet in all cases, all operators must follow policy that supports ensuring adequate transportation service to the whole population. An integrated business model could incorporate shared incentives among different operators. For example, a passenger can be transferred from one SAV to another if this transfer would reduce VMT and both operators have enough incentive to coordinate and execute this transfer.

Fourth, and finally, regulations related to the system must be coordinated, perhaps requiring the development of a separate set of codes specific to this new network. Today, the public sector typically oversees transit planning and operations, determining which routes go where, how much labour is paid, and minimum levels of service. On the other hand, regulations over TNCs are far less explicit; other than in New York, no American city has mandated a minimum take-home pay for drivers. And operations are generally allowed wherever—with no consequences for operators if they provide insufficient service in certain neighborhoods.

In the context of an integrated system, service standards must be treated similarly across the full range of offerings. Similarly, riders' rights, such as their ability to resolve legal concerns or address poor service, must be put on an even playing field. Even with multiple operators, people using the system should be comfortable raising complaints and resolving problems in a uniform fashion.

Together, these strategies offer a framework for integrating transit networks with AVs, offering variously sized vehicles for different needs and opportunities.

These strategies are rooted in a view of the transportation system as a single network. It is unreasonable and untenable, in our view, to continue separating modes into individual services experienced differently by riders and, in the process, furthering the problems of inequality, pollution, and congestion. At the same time, we are aware that such an integrated view is not universally supported, as it would limit potential profits and could reduce certain types of service innovation. Making decisions about specific aspects of these strategies requires a broad debate about what goals we prioritize for the transportation system, which we describe in the next section.

7.4. Transit-oriented versus generic SAV deployment

In this chapter, we make the case for an integrated transportation system that unites traditional transit with future AVs of various sizes. This system would preserve many of the accessibility-expanding benefits of automobile-sized AVs while circumventing many of the negative products of a system that replicates the TNC experience. If AVs are deployed without being integrated with transit, we fear that cities will have unproductive and ineffective fixed-route bus and rail systems relegated to the least well off, congestion in dense neighborhoods, and higher levels of pollution. These are outcomes to be avoided.

The details of an integrated system, however, remain to be formulated. We have not touched on what are likely to be intense disagreements between levels of government about who should be regulating what, for example. Nor do we explore other important aspects of mobility, such as bike sharing or freight. We recognize that planning for AVs is at a preliminary stage. Nevertheless, there is considerable interest among cities to begin planning to take these vehicles into account [58]. We thus end this chapter by asking a series of questions that require further research and debate. We explore how a transit-oriented SAV system—the integrated network we believe cities should promote—differs from what we refer to as “generic” SAV deployment, which would replicate current TNCs. We consider these differences across four levels: The social purpose expected from each, regulations related to and required for each, different agents involved and intrinsic behavioural differences among them, and the algorithmic specifications that pertain to each orientation of AV technology deployment. In order to advance an integrated system, certain norms will need to change: As a society, we will need to reconsider how we use the transportation system, and we will need to think about multiple options as a spectrum of services, not as a series of differentiated modes.

7.4.1. Who are we to serve?

Broadening access to the transportation system is an equity question as much as a mobility one. Generic SAV deployment might mean simply allowing TNCs to offer service wherever makes most sense for their profit margins. SAVs would be accessible throughout metropolitan areas, but at significantly higher costs than transit, especially for longer trips, thereby excluding a portion of the population from their use. They would concentrate in dense neighborhoods, increasing congestion.

An alternative approach—transit-oriented SAV deployment—focuses on ensuring equitable access without worsening service on the existing system. To ensure affordability for everyone, one approach would be to use means testing to determine user fares throughout the transportation system, providing subsidies for certain groups of people, such as low-income families, but doing so would create a daunting bureaucracy. Moreover, what level of subsidy is reasonable? Do we envision transportation costing the average person about as much of their salary as it costs to own and operate a personal car today (about $10,000 a year), or about as much as it costs to subscribe to a monthly unlimited transit pass (about $1,500 a year)? Do we need to also consider peoples' ability to convert monetary means into their real capabilities to access transport, jobs, and other services?

Let us also consider the question of geography. An integrated transit-SAV network, given its breadth, would serve many more people and trips than today's transit. It would connect people living and working in low-density, often unwalkable, suburban neighborhoods whose communities make them inhospitable to trains or buses. Should people in those areas receive equal service, at the same cost, as those in zones where providing collective services is more efficient, neighborhoods that are more walkable and friendlier to higher-capacity transit?

Finally, let us return to the issue of vehicle size. People living in lower-density neighborhoods would also be those receiving service with smaller vehicles, while people in dense neighborhoods ride in higher-capacity shuttles, buses, and trains for many of their trips. Is there a difference in comfort level between these options? Is it unfair to give some people access to a certain type of vehicle, while depriving it from others, just because of where they live?

7.4.2. How do we regulate?

The street transportation system today is largely divided into publicly planned, publicly operated transit systems; TNCs run by multinational corporations; and individuals driving privately owned automobiles. A generic SAV rollout would reinforce this modal disintegration. It could decrease the number of people driving personal automobiles due to lower costs of SAVs, but it would continue to promote competition among both individuals who own automobiles and private corporations providing services. The result would be overlapping services and a less efficient system.

An integrated transit-SAV network eliminates this division by transforming the relationship between public and private actors. First, it suggests treating autonomous, automobile-sized TNCs as the base level of a spectrum of shared transportation services and recommends integrating them in terms of pricing, planning, and operations. Second, it is founded on the principle that a full suite of mobility options will encourage significant mode shift away from private automobiles.

This network requires a growing role for the public sector in planning, coordinating operations, and identifying sources of subsidies. Would this expansion of government's involvement be politically acceptable? Would it be acceptable for some countries, states, and cities to engage in developing a publicly supervised, integrated system, whereas others choose limited, if any, regulations over private AV operators?

7.4.3. How will riders behave?

The deployment of a generic SAV system would use price-discrimination mechanisms to encourage riders to choose shared vehicles, but also continue to allow them to choose to ride in AVs alone, as TNCs do today. It would provide door-to-door rides, doing little to diminish the automobile orientation of most neighborhoods. This would reinforce the experience that pervades in American cities; many people would continue to understand the transportation system as one that is experienced primarily by individuals moving alone or with people they know.

The integrated transit-SAV approach, on the other hand, prioritizes moving many people together and maximizing street capacity. As such, it would minimize levels of solo travel and try to move as many people as possible in shared vehicles of various sizes. It might encourage people to walk a few blocks to get onto an SAV, rather than receive door-to-door service. It would also incentivize multimodality through transfers between modes to maximize system efficiency.

The integrated strategy would attempt to alter the behavioural norms of transportation in the U.S. But to what degree would the average person be willing to support travel on a sharing-heavy network, even if it were cheaper? Would concerns about interacting with people of different social groups and economic classes raise problems? Would people be willing to make walking a key part of their daily routines, or would they be hostile to this change? And would a transfer-based system make transportation inconvenient to many, even if it were faster?

7.4.4. What types of algorithms are needed?

The current TNC system responds to passenger demand in bursts. A major event, for example, may attract hordes of TNCs outside a stadium, waiting to pick people up. The result is ineffectiveness and congestion—the same outcome that would occur in the context of generic SAV rollout. These problems are magnified in the context of competition between operators.

An integrated transit-SAV network would engage an alternative approach, organizing passengers by final destination, perhaps, placing them first in larger vehicles and then having them transfer later in their journeys to smaller shuttles or automobile-sized vehicles. Such coordination may require advanced algorithms for addressing the vehicle routing problem with time windows (VRPTW) in real-time which is known to be computationally expensive [59]. There is a gap in heuristic solution algorithms that can solve VRPTW quickly enough for real-time vehicle dispatching in transit-SAV networks. Such formulations would also apply to first-mile services, when dispatching and routing decisions can be made with information on transit departure times to minimize transfer delays.

In order to account for and reduce the negative footprint of SAVs on the network, such as impacts on traffic, congestion-aware SAV routing approaches will be desired. System Optimal Dynamic Traffic Assignment algorithms can be utilized to optimize SAV paths in order to reduce path-choice externalities [60,61]. Congestion impacts can be considered in SAV dispatching decisions (vehicle-to-passenger assignment and ride-share choices) for a more effective minimization of SAV externalities [62]. SAV rebalancing decisions can also be optimized to reduce network impacts.

In creating these algorithms, transportation providers will have to consider what to prioritize: Access to all or congestion relief? Speedier service or higher efficiencies? Higher-paying customers or the public at large? Developing a clear sense of the public-policy goals that inform how these algorithms should work is a key element of any integrated transit-SAV system.

7.5. Conclusion: Searching for new avenues for integration

In this chapter, we offer a vision for enhancing urban transportation. We show that TNCs have largely competed with, and undermined, transit systems, often to the detriment of city mobility. Left unchecked, AVs will replicate or worsen this experience. But by integrating transit systems with SAVs across a variety of vehicle sizes, cities will be able to respond more effectively to travel demand while improving access to the population. An integrated system will address many of transit's flaws—particularly its limited breadth due to its need to concentrate on the densest neighborhoods—while reducing the negative impacts of TNCs produced by their low capacity, such as increased traffic. But achieving an integrated system will not be easy; it will require real action by public officials and a commitment to developing a new approach to using the automobile. Challenging the norm that suggests that it is acceptable to occupy most of the public right-of-way with single-occupancy automobiles will require altering the behavioural assumption that people have the right to travel alone in virtually all circumstances. It will also require breaking the lock on access to data and decisions about service that many private transportation operators hold today.

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The authors declared no potential conflict of interest with respect to publication of this chapter.

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