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Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles

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Supplementary Note:

Autonomous vehicle (AV) technology development began in 1977 in Japan[1], and subsequently included Germany, Italy, the European Union and the U.S.[1-4]. From 2004 to 2007, the U.S. Defense Advanced Research Projects Agency sponsored Grand Challenge races with large prizes[5]. Carnegie Mellon University[6], Environmental Research Institute of Michigan[7], and SRI International[8] provided a foundation for current activities.

The National Highway Traffic Safety Administration (NHTSA) defined five levels of AV functionality, ranging from no AV features (Level 0) to full automation without the need for a human driver (Level 4)[9]. Levels 1 and 2 include some AV capability, while Level 3 achieves limited automation, defined as enabling "the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions," but expecting the driver "to be available for occasional control" with adequate warning. IHS Automotive expanded these definitions to include Level 5 (full automation without driver controls)[10]. Of interest in this paper are primarily Level 0 (conventionally-driven vehicles or CDVs) and Levels 4 and 5 (full AVs). For a summary, see **Supplementary Table 1**.

As of 2014, four U.S. states and Washington, D.C. allow AV testing on roadways, with thirteen more contemplating similar laws[11]. Nevada is the first state offering "certificates of compliance" for non-testing use of AVs, which may offer a path to commercialization. Among the requirements of the Nevada law are a mechanism to capture and store sensor data for at least 30 seconds before a collision occurs between the AV and another vehicle, object or person (and to store the data for three years afterward), a switch to engage or disengage the autonomous functions of the vehicle, and a driver alert if the AV technology fails[11].

Supplementary Discussion:

GHG emissions

Supplementary Table 2 shows GHG intensity data corresponding in **Figure 1** in the main text to vehicles relative to a conventionally-driven 2014 LDV ICEV with 2014 fuel GHG intensity. The table also includes some additional calculations not shown in the figure.

Right-sizing and ride-sharing

If ride-sharing is combined with right-sized ATs, further energy savings could be obtained. We explored the consequence of shifting 10% of single-occupancy VMT (6.2% of total VMT) to higher-occupancies. If we assumed that all such one-person rides became two-person rides, total VMT would decrease 3.1% and average energy consumption would increase 0.6%, resulting in a net energy decrease of 2.5%. If we further assumed that 10% of two-person rides became three-person rides, 10% of three-person rides became four-person rides, etc., total VMT would decrease 4.2% and average energy consumption would increase 1.1%, resulting in a net energy savings of 3.2%. Using our simple model, results scale linearly with higher fractions shifted: e.g., shifting 50% of single-occupancy rides (30.8% of VMT) would result in fivefold increases in savings for the two cases outlined above.

Ride-sharing has also been shown to decrease vehicle ownership and increase non-vehicle transportation use[12], with further savings in energy and GHG emissions. ATs could enable more ride-sharing, positively reinforcing these trends.

Right-sizing and larger vehicle assumptions

As noted in the main text, people could choose larger-sized ATs to increase comfort. We considered three cases (1-3) where vehicle energy consumption corresponded to occupancies of between one and three levels higher, respectively, than assumed in **Table 1** in the main text. That is, for case 1, a 1-person vehicle would have the reference efficiency assumed for a 2-person vehicle; for case 2, a 1-person vehicle would have the reference efficiency assumed for a 3-person vehicle; and for case 3, a 1-person vehicle would have the reference efficiency assumed for a 4-person vehicle. For the highest-occupancy vehicles, we assumed in case 1 that vehicles with occupancy of 6+ people had an energy consumption corresponding to the square of the reference case value (e.g., $1.345^2 = 1.810$ times LDV average). Similarly for cases 2 and 3, we assumed that vehicles with occupancy of 6+ people had energy consumptions equal to the third and fourth powers, respectively, of the reference case value. Full assumptions and results are shown in **Supplementary Table 5**. In summary, the average increase in energy consumption across all vehicle occupancies for increases of one to three sizes is 26%, 68% and 100%, respectively.

Economics of increased utilization: Detailed results

Supplementary Table 4 through **Supplementary Table 7** summarize the data presented in **Figure 2** in the main text and **Supplementary Figure 1**. Data have been split out separately for passenger cars light trucks. Underlined total costs of ownership indicate minimum cost technology for each annual VMT case.

These data presented results without right-sizing. We have also explored how results change with right-sizing, considering three scenarios for how capital costs scale with energy consumption.

In the simplest case, we assume capital costs scale linearly with energy consumption. Thus, since energy consumption of right-sized ATs is 0.551 times that of average LDVs, capital costs would similarly scale by 0.551. In this case, cost relationships among technology types and VMT are unchanged except for an absolute reduction in costs.

Our second scenario considered a square root dependence of capital cost on energy consumption, so for right-sized ATs, capital costs would scale by $0.551^{0.5} = 0.742$. Results are shown in **Supplementary Figure 2**. We find that the cost relationships among technologies have shifted somewhat, so that for 2014 vehicles, BEVs are no longer the most cost-effective at 70,000 mi./yr (it becomes most cost-effective above 79,000 mi./yr); instead, HEVs are the most cost-effective. However, the cost ordering of the other three technologies (ICEV, HEV, HFCV) remain the same. For 2030, the cost ordering is the same as in the full-sized case at 70,000 mi./yr; thus, BEVs remain the most cost-effective technology.

Our third scenario assumed no dependence of capital cost on energy consumption, so that for right-sized ATs, capital costs were unchanged from their full-sized counterparts. Results are shown in **Supplementary Figure 3**. For 2014 vehicles, HEVs are the most cost-effective technology at 70,000 mi./yr, and costs of ICEVs, HFCVs and BEVs are all about the same; BEVs do not become the most cost-effective technology until 107,000 mi./yr. For 2030, the cost ordering at 70,000 mi./yr is essentially the same as in the full-sized case, with BEVs remaining the most cost-effective technology, HFCV and HEV costs being approximately identical and somewhat higher, and ICEVs being the most costly.

Of these three scenarios, the second (square root dependence) is probably closest to reality, since it is unreasonable to expect vehicle capital costs to either scale linearly or remain fixed with respect to vehicle energy consumption.

Longevity and lifetime VMT

The U.S. Department of Transportation maintains statistics on vehicle ages, accident rates and average annual VMT. We used data from Lu[13] to estimate lifetime VMT of passenger cars and light trucks, and NHTSA[14] and New York Department of Motor Vehicles (NYDMV)[15] to estimate accident rates.

We have laid out a strong case for high utilization of shared ATs, but are such vehicles able to last over the assumed five-year service lifetime and loan repayment agreement? Schaller[16] reports that New York City requires taxis to be retired after five years, but many taxis last longer than this, and “most major cities allow vehicles to be used for 5 to 9 years.” With an average annual VMT of ~65,000 mi., New York City taxis routinely reach 325,000 mi. or more. For Irish taxis and limousines, using data in Goodbody[17], we estimated an average fleet age of 6.6 years and an average lifetime VMT of 231,000 mi.; we also found that 24% of vehicles exceeded 300,000 mi. lifetime VMT, at an average age of 8.4 years.

NHTSA, which periodically publishes VMT estimates for the U.S. vehicle fleet, indicates that average lifetime VMT is currently ~152,000 mi. for passenger cars and ~180,000 mi. for light trucks[13]. These results reflect an average lifetime of ~13-15 years for vehicles with an annual VMT of 12,000 mi. According to the NHTSA data, while less than 3% of passenger cars reach 250,000 mi., more than 22% of light trucks do. Moreover, almost 8% of light trucks reach 300,000 mi., and nearly 3% reach 350,000 mi. There is also much anecdotal evidence supporting the increasing longevity of personal vehicles; a recent New York Times article proclaimed

“200,000 [miles] is [the] new 100,000”[18], and cited several examples of individual vehicles that exceed 300,000 miles.

NHTSA[14] found that 93% of crashes between 2005 and 2007 were human-caused, while NYDMV[15] found a lower human attribution rate (78%). If ATs could eliminate all human causes of crashes, accident rates could fall by ~80-90%. Taking 85% as an average estimate, and using the data from Lu[13], we estimated that passenger cars would last an additional ~7,000 mi. and light trucks ~18,000 mi. if driven autonomously, by assuming that the minimum annual vehicle loss rates estimated in Lu[13]—about 0.5% per 10,000 mi. for passenger cars and 0.9% per 10,000 mi. for light trucks—were reduced by 85%, and this decrease added to the vehicle survival rates in all years. Also, passenger car data were extended to 36 years using assumptions similar to those used for light trucks in Lu[13]. However, these increases would not significantly increase the fraction of vehicles surviving beyond 300,000 mi.

The fact that taxis survive for five years or more at accelerated annual VMT suggests that there is a much higher survival rate per mile when annual VMT is greater, though rates of vehicle crashes may actually be higher. Data from Schaller[16] indicate that 12,779 taxis traveling a total of 811 million miles in 2005 incurred 4,270 crashes, of which 71% resulted in injuries. This translates into an injury rate of 3.7 per million mi., about four times higher than that of ordinary LDVs in New York[15]. Lower seat belt use appears partly to blame for this difference. We assume that the combination of regular maintenance and the overall younger physical age of vehicle components in highly-utilized ATs will allow them to survive for the full five-year duration assumed in our model.

Vehicle range and temporal requirements of battery charging

Most BEVs currently being sold have a battery range of ~80 mi.[19]: the EPA-rated range of 13 current models excepting Tesla varies from 62 to 127 mi., with a median of 83 mi. and an average of 86 mi. Tesla’s vehicle ranges stand out at 208 mi. (60 kWh battery) to 265 mi. (85 kWh battery); Tesla’s own estimates are even higher: 244 and 306 mi., respectively[20], comparable to conventional ICEVs[19]. However these vehicles are far more expensive ($70,000+)[21] than mass-market BEVs (~$12,500-30,000)[22-24].

While an 80-mi. range may be regarded as inadequate for satisfying the normal daily travel needs for some drivers, who are used to a much larger ICEV range, it is based on people’s expectations of driving to a service station only occasionally (e.g., assuming 12,000 mi./yr and a 300 mi. range, the average refueling period would be 9 days). If a vehicle (AT or otherwise) needs to accommodate only single trips at a time, a substantial majority of trips are accommodated with an 80-mi. range. BEVs can be charged at home, work or public charging stations daily or even more frequently, greatly reducing the required range between charging events. FHA[25] indicates that daily VMT is 29 mi. with an average of 3.0 trips/vehicle/day, resulting in an average trip length of ~10 mi., whereas for New York City taxis, the average trip length is 2.6 mi.[26]. While passengers occasionally take much longer trips, Saxena et al.[27] have found that across a realistic range of actual trip distances, an 80-mi. range BEV could satisfy the overwhelming majority (>85%) of trips even in the worst case scenario of charging occurring only at home locations using standard 120V wall outlets.

Auxiliary power use is another important consideration affecting battery range. Battery thermal management, interior climate control (heating and cooling), and other functions (lights, radio, etc.) can draw substantial power, perhaps as much as ~4 kW in a Nissan LEAF at –25°C ambient outdoor temperature, or ~5 kW in a Chevrolet Volt at –4°C[28]. The difference between these two estimates lies in the mainly passive cooling used in the LEAF, leading to lower auxiliary loads at low temperatures. Auxiliary loads at high temperatures (35°C) were found to be less demanding (~1-2 kW)[28]. One recent study that considered both interior heating/cooling as well as battery performance at different ambient temperatures found that annual energy consumption of BEVs was an average of 15% higher in the Upper Midwest and Southwest regions compared to the milder Pacific Coast.[29] As a worst-case scenario, high heating loads could be comparable to average engine power at low speeds, roughly doubling energy consumption. However, it is unlikely that auxiliary loads would be this high throughout the year; in subsequent calculations, we assume an average auxiliary load of 20% of average engine power, reducing an 80 mi. range to ~67 mi.

Assuming that the average passenger trip length remains constant in the future, ATs with a 67 mi. real-world BEV range would be able to provide an average of ~7 typical U.S. trips or ~26 New York City trips to different passengers before requiring recharging. Since passengers would not be involved in the recharging process, it would be invisible to them, as a vehicle with adequate range for the specific trip requested would presumably always be provided. During peak daily travel periods, AT fleets could be managed so that enough fully-charged vehicles are always available. Data from New York City[26] indicate that taxis are dispatched in two daily waves, each of ~6 hours' duration starting at ~9 am and ~6 pm, with a ~3 hour lull in the mid-afternoon (where the number of taxis falls to ~60% of peak), and very low overnight usage (dropping to ~15% of peak around 3 am). Therefore, even with long recharge times (~3.5 hours to recharge the ~21 kWh usable capacity of a 24 kWh Nissan LEAF battery, assuming a 6 kW charge rate; smaller BEVs would charge more quickly), there is ample time (~14 hrs.) throughout the day for ATs to serve customers: assuming 70,000 mi./yr, ATs can cover 192 mi./day with an average speed of ~14 mi./hr (or ~20 mi./hr assuming 30% of time is spent idle). DC fast charging could further reduce recharge time, but it raises concerns about enhanced battery degradation[30]. If necessary, battery-swapping technology[31] could reduce recharge time to a few minutes.

As a result, an even-smaller range BEV could be deployed and still satisfy most trip needs; the optimal-range BEV would depend on local trip demand, which could vary strongly with location. For instance, cities located far from airports might require a dedicated fleet of long-distance ATs to satisfy transport to and from these destinations, whereas locations where passengers make mainly very short trips, such as New York City, could maintain fleets of economical short-distance ATs. Long-distance trips could be satisfied by ATs with greater range (BEV, HFCV or even HEV/ICEV depending on the economic optimum). If a trip length exceeded even the longest-range vehicle available, automatic recharging along the route or hand-off to another fully-charged AT to continue the trip would be possible, with minimal inconvenience to the passenger.

Cost sensitivity to battery degradation

Battery degradation can have a large impact on total cost if the battery must be replaced before the five-year vehicle lifetime is reached, because the battery in a BEV represents a significant portion of total cost. NAS[32] estimates battery cost will fall from $482/kWh in 2010 to

$268/kWh in 2030 (all values in 2012$). Note that these costs may be conservative; a recent analysis indicated costs of "market-leading BEV manufacturers" fell to $300/kWh in 2014, with an expectation that costs could approach $200/kWh "in the near future"[33]. Some analysts believe Tesla has already achieved $274/kWh, and expects improvements to $196/kWh once its battery "Gigafactory" is built[34], while others, including Tesla CEO Elon Musk, predict costs as low as $100/kWh in less than 10 years[35].

Keeping with the NAS values, while an average passenger car has a battery capacity of ~26 kWh, yielding a replacement cost of ~$7,000 in 2030, the battery capacity of an average LDV (a ~56:44 ratio of passenger cars to light trucks) is 32 kWh, translating to a replacement cost of ~$8,500.

Battery degradation is complex and estimates of battery lifetime are varied. Many factors, including calendar lifetime, state of charge, and temperature, affect battery capacity; a study by Wang et al.[36] explored all of these variables and found that degradation was most strongly affected by temperature, with a 15% loss of capacity occurring at ~1,000 cycles at 60°C, ~3,000 cycles at 45°C and >20,000 cycles at 15°C, across a range of discharge cycle times from 1/6 h to 2 h[37]. Depth of discharge was found to be less important than other factors. Capacity loss was found to scale roughly with square root of number of equivalent full cycles (number of cycles × depth of discharge), so further degradation occurs more slowly, though it is also recognized that batteries suffer accelerated degradation after a certain point, probably well beyond 20% capacity loss[37]. Including the effects of auxiliary loads as discussed above, we assume a real-world battery range of 67 mi. when new, thus, ~5,300 cycles corresponds to 350,000 mi., which is the lifetime VMT of an AT assuming 70,000 mi./yr and five-year vehicle life. Depending on average temperature, remaining battery capacity could range from 94% (at 15°C) to 66% (at 60°C).

The Nissan LEAF battery is warranted for 75% of original capacity at 60,000 mi.[24], while others estimate an average of 60-70% of original capacity remains after 100,000 mi.[30]. Assuming the Wang et al. model is correct, such rapid degradation points toward very high (>60°C) average temperatures. We expect better temperature management as well as intrinsically lower battery degradation by 2030, but use current parameters in our below analysis.

Depending on how often the battery is replaced, the total cost of replacement over the BEV lifetime could be prohibitively expensive, e.g., >$5,000/yr assuming a 100,000 mi. replacement interval and 70,000 mi./yr VMT; however, as noted above, if battery costs fall substantially below the NAS estimates assumed here, this issue could become less of a concern. Moreover, recent work by Saxena et al.[38] finds that BEV batteries could continue to meet daily travel needs of drivers well below 80% of original capacity, so that battery replacement should be governed by when batteries are unable to satisfy daily travel needs, rather than a set schedule. In the context of ATs, vehicles with older batteries could be dispatched preferentially for shorter trips, in lieu of replacing the battery, though such ATs would have diminished flexibility.

Finally, when battery replacement is desirable, it is important to recognize that used batteries have considerable residual value, for instance, in stationary electricity storage applications[39]. Therefore, we presume a second-hand battery market that would pay a portion of the initial battery cost. Including this trade-in credit for the original and all replacement batteries used over the lifetime VMT of the BEV makes a critical difference, lowering the additional cost of battery replacement to as little as zero for reasonable assumptions of battery replacement interval and trade-in payment.

Supplementary Figure 4 illustrates the interplay of these factors, showing, as a function of battery replacement lifetime VMT, the estimated battery degradation at 15°C (purple) and 60°C (blue), assuming 20% additional load due to auxiliary power requirements. The green line indicates the necessary trade-in value (as a fraction of initial battery cost) required to offset the annualized cost of battery replacement; the red line indicates this annualized cost, assuming 70,000 mi./yr VMT. The trade-in value is received for all batteries, including the original one included with the new vehicle. The figure shows, for instance, that an assumed 100,000 mi. battery replacement interval would require a trade-in value 71% of the original battery cost in order for the net cost of battery replacement to be zero (including final battery credit upon vehicle retirement). In this case, the total cost of BEV ownership would be the same as modeled in the main analysis, with ~$5,200 annualized cost of replacement, offset by trade-in credits. At higher VMT replacement intervals, trade-in value and annualized cost fall, with both reaching zero at end of vehicle life (350,000 mi. after 5 years, assuming 70,000 mi./yr).

Although a second-hand battery is not worth as much as a new one, due to its diminished capacity and remaining lifetime, so long as the minimum trade-in value lies below the remaining battery capacity (which occurs at 60°C for VMT replacement intervals of ≳50,000 mi., and at 15°C for essentially any VMT replacement interval), purchasers of such batteries could receive substantial value, possibly at a large discount relative to a new battery. For instance, at a battery replacement interval of 200,000 mi., the remaining battery capacity at 60°C is 74%, and the minimum trade-in value is 43%; thus, the purchaser pays 43%/74% = 58% of the new-battery cost.

In fact, the economics could allow for even lower trade-in values while still being more cost-effective than the next best technology, HFCVs, whose total cost is ~$950/yr higher. If we assume that the difference between the annualized battery replacement cost and trade-in credit is less than this incremental cost, a trade-in value of ≥58% of the original battery cost would be sufficient at a 100,000 mi. replacement interval, and the value falls to zero at 240,000 mi.

We conclude that BEVs can be cost effective across a wide range of battery lifetimes. As a consequence, the cost of battery replacement was not included in our main analysis results. Decreases in battery cost or degradation rates would further improve the BEV economics.

Ownership cost sensitivity to fuel prices

Because the total ownership cost in 2030 at 12,000 mi./yr was fairly similar across technologies, we investigated cost sensitivities to changes in oil, hydrogen and electricity prices. Results are shown in **Supplementary Figure 1** for average LDVs. Reference costs are shown as solid bars, with low and high price sensitivities shown as black vertical lines. Additional ICEV technologies from 2014[32] are included for reference, because in the low oil price sensitivity they have lower total annual cost than 2030 ICEVs.

For the reference case, the lowest cost point is an HEV, whereas in the low oil price sensitivity case it is an ICEV that is only slightly more efficient than the 2014 base case (denoted ICEV* in the figure). On the other hand, in the high oil price sensitivity case, ICEVs have higher total cost than the reference HFCVs and BEVs. Clearly, the cost-effectiveness of gasoline-powered vehicle technologies strongly depends on the price of gasoline.

The total cost of ownership for HFCVs is very sensitive to the future price of hydrogen: across a range of \$1.5-4/kg, the total cost of ownership could be lower than or as high as any other vehicle type in the reference case. (DOE projected a range of \$2-4/kg delivered at the pump in 2020[40]. We expanded this range slightly for 2030.) For the low oil price case, the annual cost of HFCVs is higher than any gasoline-based technology, regardless of the projected price of hydrogen, but in the high oil price case, HFCVs have the minimum annual cost of all technologies when hydrogen is toward the lower end of this price range ($\lesssim$\$1.9/kg).

Across all 31 scenarios that EIA[41] considered, the projected future price of electricity varied by 29%, far less than variation in the price of oil or hydrogen, so the cost of BEV technology is mainly driven by capital cost. [Specifically, the lowest price case was 93% (high oil and gas resource scenario) and the highest price case was 122% (GHG \$25/tCO_2 scenario) of the reference case of 10.8 ¢/kWh for transportation-sector electricity in 2030[41]. Regional electricity price variations are also important to consider, but these were not explored here.] At 12,000 mi./yr, the total cost of ownership of BEV technology remains more expensive than other technologies except for 2014 ICEVs under the high oil price sensitivity case.

It should be emphasized that all these cost differences are relatively minor compared to the absolute cost of ownership (from the lowest to highest cost cases in the figure, the difference is <10%), indicating that by 2030, the projected cost of ownership of ICEV, HEV, HFCV and BEV technologies will all be similar at 12,000 mi./yr. By contrast, at VMT levels envisioned for ATs (≥40,000 mi./yr), increased utilization will strongly push ownership economics toward very efficient vehicles (e.g., BEVs) by 2030.

In the case of higher electricity prices that may accompany lower GHG intensities, BEVs at 70,000 mi./yr appear to be cost-optimal up to 17.0 ¢/kWh, and remain lower than HEVs up to 18.8 ¢/kWh—nearly a doubling from the 2014 average electricity price of 10.2 ¢/kWh. Note that these calculations assumed no changes in the prices of hydrogen or gasoline; if either of these increased, BEVs would remain competitive at even higher electricity prices.

Supplementary Table 8 through **Supplementary Table 10** summarize the price sensitivity data presented above for 12,000 mi./yr. Underlined total costs of ownership indicate minimum cost technology for each oil price case.

Vehicle costs per mile

The vehicle cost per mile is dramatically lower in highly-utilized vehicles than in less-utilized ones. As an example, we estimate the cost per mile of private vehicles, shared CDVs (e.g., car-share, rental or fleet vehicles) and ATs. The private vehicles are driven 12,000 mi./yr while the shared CDVs and ATs vary between 40,000 and 70,000 mi./yr. All private vehicles are assumed to be CDVs except for one case (2030 HEV) where AV technology is included, but it is used like a private vehicle, not an AT. The shared CDVs are included to compare the costs of non-AT shared vehicles with those of both private vehicles and ATs.
Results are shown in

Supplementary Table 11. For private vehicles, the cost per mile does not vary much depending on whether it is an ICEV, HEV or BEV; all costs lie between 80.0 and 82.6 ¢/mi. Adding AV technology increases the HEV cost to 90.9 ¢/mi., making it the most expensive option. Note that these are average costs over the first five years of vehicle ownership, but private vehicle lifetimes are much longer. Therefore, in order to compare equivalent five-year costs, we also considered the residual (resale) value after five years, which is approximately 40% of the initial capital value after adjusting for inflation[42,43]. Subtracting this credit from the annual capital cost, the adjusted cost per mile would be ~54 to ~65 ¢/mi.

For shared CDVs, per-mile costs drop to 31.2-48.1 ¢/mi, depending on year, vehicle technology and annual VMT. There is a clear economic benefit to car sharing if a passenger is not interested in outright ownership.

For ATs, the per-mile costs are comparable or slightly lower. Here we compared among BEV options, and found that the cost is 43.9 ¢/mi. for a full-sized BEV at 40,000 mi./yr, dropping to 32.2 ¢/mi. at 70,000 mi./yr. For the case of a small BEV, we had no information about how vehicle cost scaled with physical size, so we considered two extreme assumptions: 1. vehicle cost scaled linearly with relative fuel consumption, or 2. vehicle cost was invariant to relative fuel consumption. We felt both cases were unrealistic, so we opted for a middle ground: vehicle cost scaled with the square root of relative fuel consumption. We calculated the per mile costs in the two extreme cases to explore the sensitivity of this assumption, however, and found that it varied between 27.1 ¢/mi. (linear scaling) and 31.5 ¢/mi. (no scaling); our best estimate of total cost was 29.1 ¢/mi. (square root scaling). AV technology itself contributes 2.8-4.3 ¢/mi. (~9-10%) to the overall cost. The added benefits of small BEV ATs are lower GHG emissions and zero oil consumption.

Studies have estimated that AV technology would provide a number of substantial economic benefits, most importantly a reduction in crashes, but also decreases in insurance, traffic congestion, and parking costs. NHTSA[44] estimated vehicle crashes cost the U.S. economy $277 billion in 2010, or $1,232/yr/vehicle, assuming 224.9 million LDVs in 2010[41], while human error is responsible for ~80-90% of crashes[14,15], implying that AVs, by reducing human-caused crashes, could save on the order of $1,000/yr/vehicle. The Eno Center[45] built upon these estimates, adding the additional savings listed above to arrive at a total benefit of between $2,960 and $3,900/yr/vehicle. Assuming 12,000 mi/yr,[41] these savings would amount to an additional 25-33 ¢/mi., and therefore more than pay for the incremental cost of AV technology.

Vehicle stocks and licensed drivers

EIA[41] provided estimates of LDV vehicle stocks for 2011 through 2040, while current (2013 or 2014) estimates of fleet, rental and taxi vehicle stocks were provided by Auto Rental News[46] and Automotive Fleet[47]. The Transportation Sustainability Research Center[48], BLS[49] and EIA[41] provided estimates of car share member, taxi/limousine and total licensed drivers, respectively.

The vast majority of vehicles today are privately owned—about 96%. Examples of shared ownership include car-share vehicles, rental cars, taxis, and fleet vehicles. Car sharing has been a small but growing trend in recent years, with 2014 U.S. car-sharing membership claiming 0.56% of licensed drivers[41,48], though the number of vehicles used is less. Rental cars have been a more prominent and persistent phenomenon in the U.S., and constitute about 1% of LDV stock[46,47]. Similarly, taxis have long been an available transportation option, particularly in cities; while taxi drivers constitute only 0.106% of U.S. licensed drivers[49] and 0.07% of LDV stock[47], they provide services to 12% of Americans at least once each month[50]. Corporate, government and police fleet vehicles comprise about 2.7% of the LDV fleet[47].

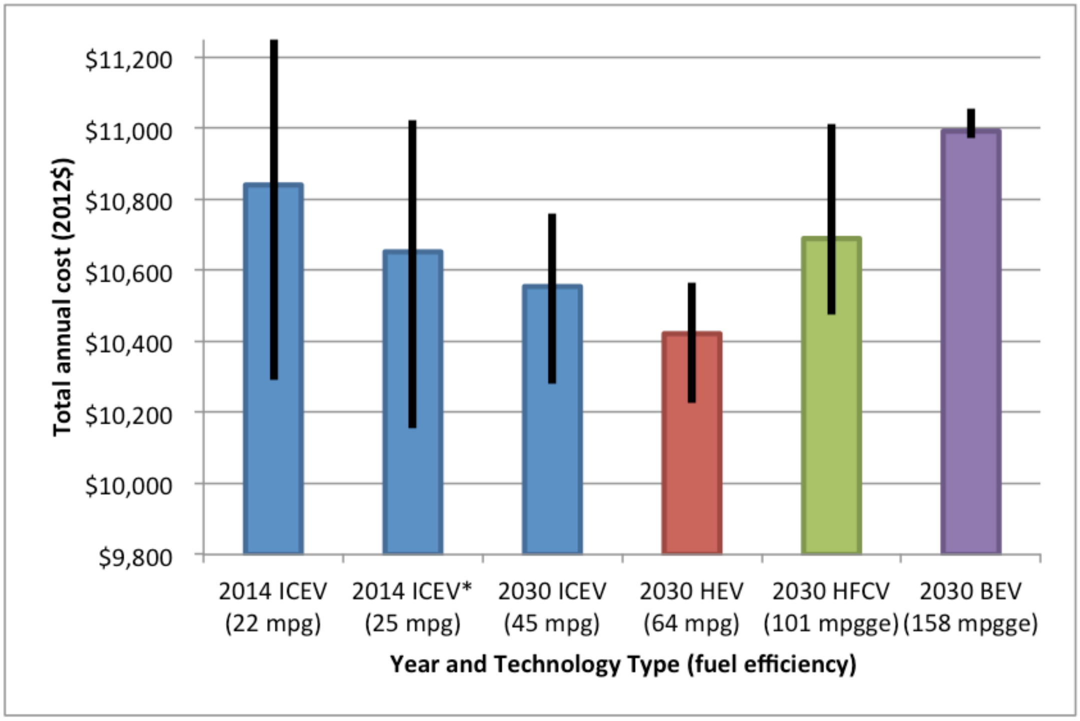
While each of these shared vehicle modes contributes modestly to U.S. passenger transportation today, shared AVs may be strongly adopted due to the ability to deliver vehicles directly to consumers, eliminating a significant adoption barrier, while offering all of the aforementioned benefits of AVs without the up-front cost of vehicle ownership or AV technology. This is because shared vehicles all use “pay as you go” financing structures, spreading the potentially significant capital cost of AVs across several years of use and many members or ratepayers. Indeed, lifetime operating costs may be the same or lower than CDVs, due to the potential for significant fuel savings as well as the elimination of the driver in taxis, which could provide extra capital to pay for more expensive AV technology during the early adoption phase.

The availability of ATs would allow large numbers of users to gain familiarity with AV technology, a prerequisite for customer acceptance, without committing to them. By exposing a large portion of the population to AVs, ATs would help drive down the cost of AV technology and pave the way for wider consumer adoption. Given the attractiveness of ATs, we believe that this transition could happen quickly.

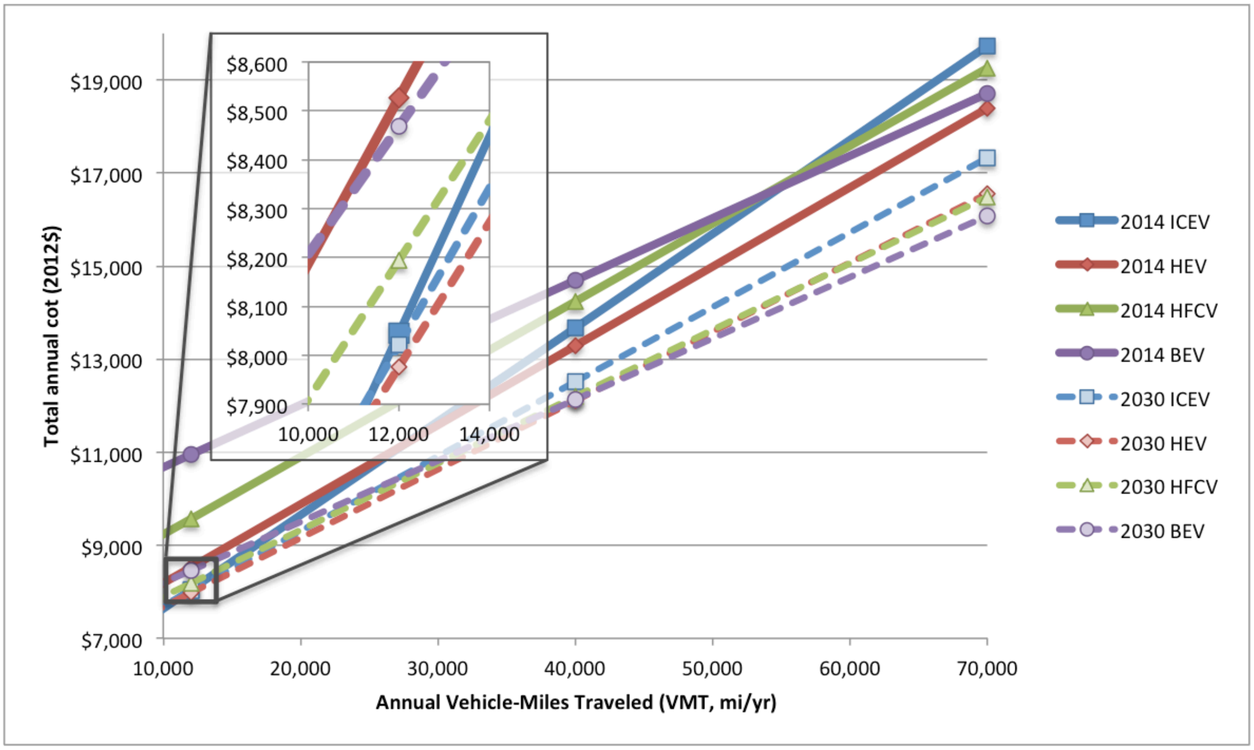
Parking impacts

Several researchers have noted that AVs could considerably decrease our need for parking spaces, particularly in urban environments[11,51,52], with one estimate placing parking at 31% of urban land area[11]. Two potentially important implications of decreased parking are decreases in municipal parking revenues, and increases in VMT as AVs travel additional distances between parking locations and passengers. On the other hand, VMT may decrease due to less time spent by drivers looking for parking[52]. The increased VMT due to parking was included in our estimates of potential VMT increases in the main text.

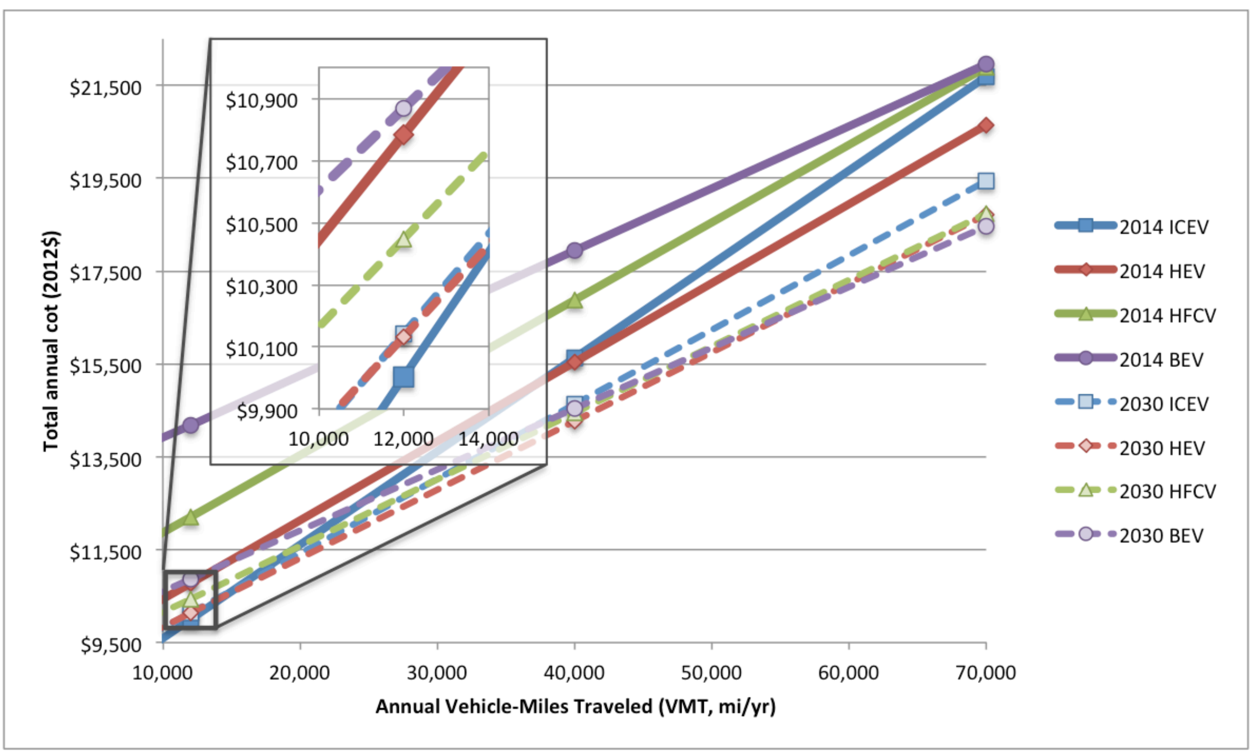
Supplementary Figures:



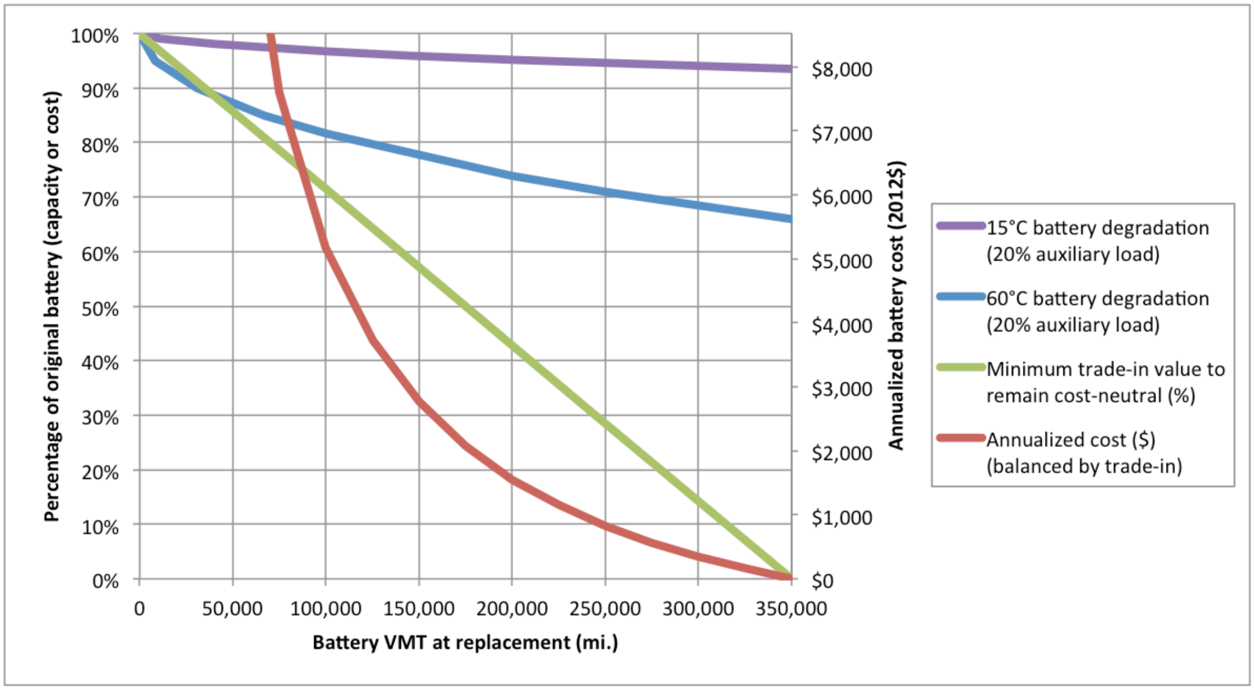
Supplementary Figure 1. Sensitivity of total annual cost of LDVs to oil, hydrogen and electricity prices in 2030 for 12,000 mi./yr. Fuel efficiency shown in parentheses. Color code: ICEV, blue; HEV, red; HFCV, green; BEV, purple. Solid bars indicate reference values from Figure 2; we added "2014 ICEV*"[32], which is somewhat more efficient than the 2014 ICEV reference. Black vertical lines indicate fuel price sensitivities. ICEVs/HEVs use low and high oil prices[41]; HFCVs use low and high future hydrogen prices[40]; BEVs use lowest and highest 2030 electricity prices[41]. Vertical axis is greatly magnified from data shown in Figure 2.



Supplementary Figure 2. Total annual cost versus annual vehicle-miles traveled for right-sized vehicle technologies in 2014 and 2030, assuming capital costs scale with square root of energy consumption.



Supplementary Figure 3. Total annual cost versus annual vehicle-miles traveled for right-sized vehicle technologies in 2014 and 2030, assuming capital costs remain constant with energy consumption.



Supplementary Figure 4. Estimated battery degradation, necessary minimum trade-in value and annualized cost versus battery replacement lifetime VMT for a 2030 BEV at 70,000 mi./yr annual VMT. Battery degradation rates at 15°C (purple line) and 60°C (blue line) from Ref. 36 assuming 20% average additional power draw due to auxiliary loads, and new battery cost from Ref. 32. Green line indicates minimum trade-in value for the net annual cost to be unchanged from data presented in Figure 2 in the main text. Red line indicates the annualized cost of battery replacement, which is assumed to be balanced by battery trade-in.

Supplementary Tables:

Supplementary Table 1. Vehicle automation level definitions

Automation level	Description
Level 0	No automation
Level 1	Autonomy of one primary control function, e.g., adaptive cruise control, self-parking, lane-keep assist or autonomous braking
Level 2	Autonomy of two or more primary control functions “designed to work in unison to relieve the driver of control of those functions”

Level 3	Limited self-driving; driver may "cede full control of all safety-critical functions under certain traffic or environmental conditions," but is "expected to be available for occasional control" with adequate warning
Level 4	Full self-driving; driver "is not expected to be available for control at any time during the trip" (includes unoccupied vehicles)
Level 5	Full self-driving without human controls

Sources: Refs. 9,10

Supplementary Table 2. GHG intensities of vehicles relative to a conventionally-driven 2014 LDV ICEV with 2014 fuel GHG intensity (480 gCO_2/mi.)

			GHG intensity assumption				
Year	**LDV technology**	**VMT (mi./yr)**	**EIA (2014)**	**EIA (2030)**	**EPA (2030)[a]**	**CA (2030)**	**Equivalent mpg**
CDVs							
2014	ICEV	12,000	100.0%	96.2%	N/A	N/A	22.4
	HEV		62.2%	59.9%	N/A	N/A	36.0
	HFCV		34.3%	34.3%	48.4%	31.3%	75.1
	BEV		32.4%	29.6%	22.4%	14.5%	121.8
2030	ICEV min. effic. (low oil[b])		90.3%	86.9%	N/A	N/A	24.8
	LDV EIA[c]		58.0%	55.8%	N/A	N/A	38.6
	ICEV max. effic. (ref. [b])		50.0%	48.1%	N/A	N/A	44.9
	HEV		35.3%	33.9%	N/A	N/A	63.5
	HFCV		25.4%	25.4%	35.8%	23.2%	101.3
	BEV		25.0%	22.9%	17.3%	11.2%	157.5
ATs (right-sized)							
2014	HEV	40,000	34.3%	33.0%	N/A	N/A	65.5
	HFCV	40,000	18.9%	18.9%	26.6%	17.2%	136.4
	BEV	70,000	17.8%	16.3%	12.3%	8.0%	221.2
2030	BEV	40,000+	13.8%	12.6%	9.5%	6.2%	286.1

[a] EPA[56] assumption applies to the electricity sector only; therefore, only BEV GHG intensities are listed; gasoline-based vehicle GHG intensities (ICEV, LDV EIA and HEV) are assumed to be the same as in EIA[41].

[b] "Low oil" corresponds to minimum total LDV ICEV cost in low oil price case (see sensitivity discussion), whereas "ref." corresponds to the 2030 reference LDV ICEV configuration provided by NAS[32].

[c] "LDV EIA" refers to projected 2030 average new LDV fuel efficiency[41].

Supplementary Table 3. Alternative case assumptions of energy consumption by vehicle occupancy. See Supplementary Discussion for details.

Number of passengers	Proportion of total U.S. VMT[25]	Estimated AT energy consumption relative to LDV average by case			
		Reference[a]	1	2	3
1	61.68%	0.466	0.559	0.811	1.000
2	24.85%	0.559	0.811	1.000	1.000
3	7.00%	0.811	1.000	1.000	1.345
4	3.89%	1.000	1.000	1.345	1.810[b]
5	1.64%	1.000	1.345	1.810[b]	2.436[c]
6+	0.95%	1.345	1.810[b]	2.436[c]	3.277[d]
All	100.00%	0.551	0.694	0.924	1.101
Average relative to reference		1.000	1.261	1.678	1.999

[a] See Table 1 in main text.
[b] Equal to square of reference 6+ occupancy vehicle
[c] Equal to third power of reference 6+ occupancy vehicle
[d] Equal to fourth power of reference 6+ occupancy vehicle

Supplementary Table 4. Cost assumptions for passenger cars using 2010 vehicle costs (adjusted to 2012$) from NAS[32]

	Capital cost		Energy use per 100 mi.			Cost per 100 mi.			Annual total cost of ownership		
Technology	**Total**	**Annual**	**Gasoline (gallons)**	**Electricity (kWh)**	**Equi-valent mpg**	**Fuel or elec-tricity**	**Main-tenance**	**Insurance**	**12,000 mi./yr**	**40,000 mi./yr**	**70,000 mi./yr**
ICEV	$28,190	$6,859	3.741		26.73	$12.65	$4.97	$6.86	$9,797	$16,651	$23,995
HEV	$32,492	$7,906	2.327		42.97	$7.87	$4.97	$6.86	$10,270	$15,785	$21,695
HFCV	$37,344	$9,087		37.54	90.56	$7.29	$4.97	$6.86	$11,381	$16,735	$22,472
BEV	$45,290	$11,020		23.14	146.95	$2.36	$4.97	$6.86	$12,723	$16,697	$20,955

Supplementary Table 5. Cost assumptions for passenger cars using 2030 vehicle costs (adjusted to 2012$) from NAS[32]

	Capital cost		Energy use per 100 mi.			Cost per 100 mi.			Annual total cost of ownership		
Technology	**Total**	**Annual**	**Gaso-line (gal)**	**Elec-tricity (kWh)**	**Equiva-lent mpg**	**Fuel or elec-tricity**	**Main-tenance**	**Insur-ance**	**12,000 mi./yr**	**40,000 mi./yr**	**70,000 mi./yr**
2010 ICEV	$28,190	$6,859	3.741		26.73	$12.83	$4.97	$6.86	$9,818	$16,722	$24,119
2010 ICEV + RR	$28,216	$6,866	3.498		28.59	$11.99	$4.97	$6.86	$9,724	$16,395	$23,541
2010 ICEV + RR + 5% WR	$28,266	$6,878	3.385		29.55	$11.60	$4.97	$6.86	$9,690	$16,251	$23,281
2010 ICEV + RR + 10% WR	$28,414	$6,914	3.271		30.57	$11.21	$4.97	$6.86	$9,679	$16,131	$23,044
2010 ICEV + RR + 10% WR + AERO	$28,628	$6,966	3.140		31.85	$10.76	$4.97	$6.86	$9,677	$16,004	$22,782
2010 ICEV + RR + 15% WR + AERO	$28,875	$7,026	3.031		32.99	$10.39	$4.97	$6.86	$9,692	$15,914	$22,580
2010 ICEV + RR + 20% WR + AERO	$29,220	$7,110	2.922		34.23	$10.02	$4.97	$6.86	$9,731	$15,848	$22,402

2030 ICEV	$30,794	$7,493	1.819		54.97	$6.24	$4.97	$6.86	$9,661	$14,719	$20,139
HEV	$31,470	$7,657	1.270		78.73	$4.35	$4.97	$6.86	<u>$9,599</u>	$14,131	$18,986
HFCV	$32,199	$7,835		27.20	124.98	$3.64	$4.97	$6.86	$9,691	$14,021	$18,662
BEV	$33,969	$8,265		17.50	194.32	$1.89	$4.97	$6.86	$9,912	<u>$13,754</u>	<u>$17,870</u>

Supplementary Table 6. Cost assumptions for light trucks using 2010 vehicle costs (adjusted to 2012$) from NAS[32]

	Capital cost		Energy use per 100 mi.			Cost per 100 mi.			Annual total cost of ownership		
Techno-logy	**Total**	**Annual**	**Gasoline (gallons)**	**Electricity (kWh)**	**Equi-valent mpg**	**Fuel or elec-tricity**	**Main-tenance**	**Insurance**	**12,000 mi./yr**	**40,000 mi./yr**	**70,000 mi./yr**
ICEV	$34,688	$8,440	5.307		18.84	$17.94	$4.97	$6.86	<u>$12,013</u>	$20,348	$29,279
HEV	$39,969	$9,725	3.301		30.29	$11.16	$4.97	$6.86	$12,484	<u>$18,921</u>	$25,818
HFCV	$47,390	$11,531		54.37	62.53	$10.56	$4.97	$6.86	$14,218	$20,487	$27,204
BEV	$59,243	$14,415		33.52	101.41	$3.43	$4.97	$6.86	$16,245	$20,517	<u>$25,093</u>

Supplementary Table 7. Cost assumptions for light trucks using 2030 vehicle costs (adjusted to 2012$) from NAS[32]

	Capital cost		Energy use per 100 mi.			Cost per 100 mi.			Annual total cost of ownership		
Technology	**Total**	**Annual**	**Gaso-line (gal)**	**Elec-tricity (kWh)**	**Equiva-lent mpg**	**Fuel or elec-tricity**	**Main-tenance**	**Insur-ance**	**12,000 mi./yr**	**40,000 mi./yr**	**70,000 mi./yr**
2010 ICEV	$34,688	$8,440	5.307		18.84	$18.19	$4.97	$6.86	$12,043	$20,449	$29,455
2010 ICEV + RR	$34,715	$8,447	4.962		20.15	$17.01	$4.97	$6.86	$11,907	$19,982	$28,634
2010 ICEV + RR + 5% WR	$34,770	$8,460	4.841		20.66	$16.59	$4.97	$6.86	$11,871	$19,830	$28,357
2010 ICEV + RR + 10% WR	$34,938	$8,501	4.720		21.19	$16.18	$4.97	$6.86	$11,862	$19,705	$28,108
2010 ICEV + RR +	$35,152	$8,553	4.531		22.07	$15.53	$4.97	$6.86	$11,837	$19,498	$27,707

10% WR + AERO											
2010 ICEV + RR + 15% WR + AERO	$35,431	$8,621	4.415		22.65	$15.13	$4.97	$6.86	$11,857	$19,407	$27,496
2010 ICEV + RR + 20% WR + AERO	$35,822	$8,716	4.299		23.26	$14.74	$4.97	$6.86	$11,904	$19,343	$27,313
2030 ICEV	$37,552	$9,137	2.746		36.41	$9.42	$4.97	$6.86	$11,686	$17,635	$24,009
HEV	$37,968	$9,238	1.958		51.07	$6.71	$4.97	$6.86	$11,463	$16,655	$22,218
HFCV	$40,556	$9,868		41.58	81.76	$5.56	$4.97	$6.86	$11,955	$16,824	$22,041
BEV	$43,536	$10,593		26.76	127.04	$2.89	$4.97	$6.86	$12,360	$16,482	$20,899

Supplementary Table 8. Oil price sensitivity for LDVs in 2030 (12,000 mi./yr case)

	Fuel cost per 100 mi.		**Annual total cost of ownership**	
Gasoline cost:	*$2.40/gal*	*$4.19/gal*	*$2.40/gal*	*$4.19/gal*
Technology	**Low oil price**	**High oil price**	**Low oil price**	**High oil price**
2010 ICEV	$10.71	$18.70	$10,290	$11,250
2010 ICEV + RR	$9.95	$17.38	$10,177	$11,068
2010 ICEV + RR + 5% WR	$9.67	$16.89	$10,156	$11,022
2010 ICEV + RR + 10% WR	$9.39	$16.40	$10,160	$11,001
2010 ICEV + RR + 10% WR + AERO	$9.01	$15.74	$10,167	$10,975
2010 ICEV + RR + 15% WR + AERO	$8.74	$15.27	$10,198	$10,982
2010 ICEV + RR + 20% WR + AERO	$8.47	$14.80	$10,255	$11,014
2030 ICEV	$5.35	$9.34	$10,280	$10,759
HEV	$3.78	$6.60	$10,228	$10,566

Supplementary Table 9. Hydrogen price sensitivity for LDVs in 2030 (12,000 mi./yr case)

	Fuel cost per 100 mi.			**Annual total cost of ownership**		
Cost of hydrogen:	*$1.5/kg*	*$2.5/kg*	*$4.0/kg*	*$1.5/kg*	*$2.5/kg*	*$4.0/kg*
	Low	**Reference**	**High**	**Low**	**Reference**	**High**
HFCV	$2.69	$4.49	$7.18	$10,475	$10,690	$11,013

Supplementary Table 10. Electricity price sensitivity for LDVs in 2030 (12,000 mi./yr case)

	Fuel cost per 100 mi.			**Annual total cost of ownership**		
Cost of electricity:	*10.1 ¢/kWh*	*10.8 ¢/kWh*	*13.2 ¢/kWh*	*10.1 ¢/kWh*	*10.8 ¢/kWh*	*13.2 ¢/kWh*
	Low (High oil/gas resource)	**Reference**	**High (GHG $25/tCO$_2$)**	**Low (High oil/gas resource)**	**Reference**	**High (GHG $25/tCO$_2$)**
BEV	$2.18	$2.33	$2.85	$10,973	$10,992	$11,055

Supplementary Table 11. Per mile cost comparison among vehicle options

Year	Vehicle type	VMT (mi./yr)	Annual cost							Cost (¢) per mile
			Vehicle capital	AV capital[a]	Maintenance[b]	Insurance	Fuel	Profit[c]	Total	
Private vehicles										
2014	ICEV	12,000	$6,859	N/A	$596	$823	$1,539	$0	$9,818	81.8
2030	HEV		$7,657	N/A	$596	$823	$523	$0	$9,599	80.0
	BEV		$8,265	N/A	$596	$823	$227	$0	$9,912	82.6
	HEV (AV)		$7,657	$1,217	$691	$823	$523	$0	$10,911	90.9
Shared CDVs										
2014	ICEV	40,000	$6,859	N/A	$1,988	$2,744	$5,131	$2,508	$19,230	48.1
		70,000	$6,859	N/A	$3,479	$4,802	$8,979	$3,618	$27,736	39.6
2030	ICEV	40,000	$7,493	N/A	$1,988	$2,744	$2,494	$2,208	$16,927	42.3
		70,000	$7,493	N/A	$3,479	$4,802	$4,365	$3,021	$23,160	33.1
	HEV	40,000	$7,657	N/A	$1,988	$2,744	$1,742	$2,120	$16,250	40.6
		70,000	$7,657	N/A	$3,479	$4,802	$3,048	$2,848	$21,834	31.2
ATs										
2030	BEV	40,000	$8,265	$1,217	$2,281	$2,744	$757	$2,289	$17,553	43.9
	BEV	70,000	$8,265	$1,217	$3,991	$4,802	$1,324	$2,940	$22,539	32.2
	Small BEV[d]		$6,810	$1,217	$3,991	$4,802	$899	$2,658	$20,377	29.1

Assumptions:

[a] Full cost of AV capital in 2030 is assumed to be $5,000; annual cost is amortized using the same capital recovery factor as for vehicle capital

[b] Assume maintenance cost scales with VMT, as well as with capital cost of AV equipment

[c] Profit margin of 15% assumed for shared CDVs and ATs

[d] Assume small BEV has 68% of energy consumption of standard-sized BEV passenger car, and that vehicle capital cost scales as square root of energy consumption. See text for discussion of sensitivity.

Supplementary Table 12. Parameter estimates used in this paper

Parameter	Value	Units	Notes	Reference
Energy/GHG parameters				
Energy content of gasoline	116,000	Btu/gal	Lower heating value (LHV); used to calculate equivalent mpg	(32)
	5.047	MMBtu/barrel	Heat content; used to calculate fuel volumes	(41)
Energy content of crude oil	5.850			
GHG intensity of gasoline	10.770	$kgCO_2e/gal$	Estimated U.S. average in 2014	(32, 41, 53, 54)
	10.363		Projected U.S. average in 2030	
	9.675		Projected CA average in 2030	(55)
GHG intensity of natural gas	74.88	gCO_2e/MJ (LHV)	Estimated U.S. average in 2010-2011 (assume same through 2030)	(32, 41, 53, 54)
GHG intensity of electricity	557.5	gCO_2e/kWh	Estimated U.S. average in 2014	(32, 41, 53, 54)
	509.9		Projected U.S. average in 2030 (EIA)	
	385.0		Projected U.S. average in 2030 (EPA proposed rule)	(41, 53, 56)
	249.0		Projected CA average in 2030	(55)
Hydrogen production efficiency	74	%	Natural gas reforming (2015)	(57)
	75		Electrolysis (2020)	
GHG intensity of hydrogen	364.3	gCO_2e/kWh	Natural gas reforming	(32, 54, 57)
	679.8		Electrolysis using EIA electricity GHG intensity (2030)	(32, 41, 53, 54, 57)
	513.4		Electrolysis using EPA electricity GHG intensity (2030)	(41, 53, 56, 57)

	332.1		Electrolysis using CA electricity GHG intensity (2030)	(55, 57)
VMT				
Private vehicles	11,914	mi./yr	U.S. average in 2014	(41)
	12,184		U.S. average in 2030	
Taxis	42,000		New York City owner-driver taxi in 2005	(16)
	72,000		New York City fleet taxi in 2005	
	64,600		Average New York City taxi in 2005	
	39,410		Average New York City taxi miles spent with passengers in 2005	
	70,000		Average Denver taxi in 2012	(58)
	70,000		Average New York City taxi (year not given)	(26)
	90,000		Average San Francisco taxi in 2012	(59)
	35,602		Average Irish taxis and limousines in 2008	(17)
Cases used in paper	12,000		CDV base case	Author estimates
	40,000		AT low case	
	70,000		AT high case	
Lifetime VMT	152,138	mi.	Average passenger car	(13)
	179,958		Average light truck[a]	
	231,000		Average Irish taxi/limousine	(17)
VMT survival fractions				
Passenger cars	2.3	%	250,000 mi. lifetime	(13)
	0.2		300,000 mi. lifetime	
Light trucks	22.4		250,000 mi. lifetime	
	7.7		300,000 mi. lifetime	

	2.9		350,000 mi. lifetime	
Irish taxis/limousines	24		300,000 mi. lifetime	(17)
Vehicle final fuel efficiencies				
On-road efficiency reduction	15	%	Applied to ICEVs only	(60, 61)
ICEV	3.741	gal/100 mi.	Passenger cars in 2010 (used for 2014)	(32)
HEV	2.327			
HFCV	37.54	kWh/100 mi.		
BEV	23.14			
ICEV	5.307	gal/100 mi.	Light trucks in 2010 (used for 2014)	
HEV	3.301			
HFCV	54.37	kWh/100 mi.		
BEV	33.52			
2010 ICEV + RR	3.498	gal/100 mi.	Passenger cars in 2030	
2010 ICEV + RR + 5% WR	3.385			
2010 ICEV + RR + 10% WR	3.271			
2010 ICEV + RR + 15% WR	3.140			
2010 ICEV + RR + 15% WR + AERO	3.031			
2010 ICEV + RR + 20% WR + AERO	2.922			
2030 ICEV	1.819			
HEV	1.270			
HFCV	27.20	kWh/100 mi.		
BEV	17.50			
2010 ICEV + RR	4.962	gal/100 mi.	Light trucks in 2030	
2010 ICEV + RR + 5% WR	4.841			
2010 ICEV + RR + 10% WR	4.720			

2010 ICEV + RR + 15% WR	4.531			
2010 ICEV + RR + 15% WR + AERO	4.415			
2010 ICEV + RR + 20% WR + AERO	4.299			
2030 ICEV	2.746			
HEV	1.958			
HFCV	41.58	kWh/100 mi.		
BEV	26.76			
2014 new passenger car	30.15	mpg	On-road efficiency	(41)
2014 new light truck	22.44			
2014 new LDV	26.04			
2030 new passenger car	45.24			
2030 new light truck	32.60			
2030 new LDV	38.63			
2030 fleet-average passenger car	37.59			
2030 fleet-average light truck	28.01			
2030 fleet-average LDV	32.58			
Other vehicle parameters				
Number of LDVs in stock	225.57	million	2013	(41)
	226.99		2014	
	257.58		2030	
Fraction of passenger cars in fleet	54.0	%	2014	
	55.9	%	2030	
Number of U.S. car share members	1.229	million	January 2014	(48)
Number of licensed U.S. drivers	219	million	2014	(41)
U.S. taxi and limousine drivers	233	thousand	2012	(49)

Number of rental vehicles	1.964	million	2013	(46)
Number of 2014 fleet vehicles	2.825	million	Corporate	(47)
	2.877	million	Government	
	505.3	thousand	Police	
	2.400	million	Rental	
	159.1	thousand	Taxi	
Costs				
Incremental cost of AV technology	150,000	$	Current cost including LIDAR[b] system (~50% of total)	(62, 63)
	7,000-10,000		Projected 2025 (Level 4)	(10)
	4,500-5,000		Projected 2030 (Level 5)	
	3,000-4,000		Projected 2035 (Level 5)	
	1,000-1,500		"As economies of scale are achieved"	(64)
	5,000		Assumed cost in 2030	Author estimate
New York City taxi driver annual revenue	97,250	2012$[c]	57% of gross revenues (implies multiple drivers; see next entry)	(16)
Average taxi driver annual income	~23,000	2012$	U.S. median	(49, 65)
Base 2010 ICEV cost (used for 2014)	28,190	2012$	Passenger car	(32)
	34,688		Light truck	
Incremental cost of decreased rolling resistance tires (RR)	27		6.5% fuel reduction in 2030 "mid-range" case	
Incremental cost of improved aerodynamics (AERO)	214		4.0% fuel reduction in 2030 "mid-range" case	
Vehicle longevity	5	yr	Mandatory retirement of New York City taxis	(16)

	5-9		Taxi longevity in "most major cities" in U.S.	
	6.6		Average longevity of Irish taxis	(17)
	5		Assumed AT longevity and vehicle loan term	Author estimate
New vehicle loan five-year interest rate	16.2	%/yr	1981 (high)	(66)
	3.8		2009 (low)	
	4.0		2014	(67)
	8.0		Long-term average	Author estimate
Capital recovery factor	24.33	%/yr	Assuming five-year loan, above long-term average and monthly payments	Author calculation
Maintenance cost	4.97	$/100 mi.	U.S. average	(68)
Insurance cost	1,029	$/yr	Assumes 15,000 mi./yr	
Incremental cost of passenger car weight reduction (WR) in 2030 "mid-range" case:				
5.0%	49	2012$	3.3% fuel reduction	(32)
10.0%	197		6.5% fuel reduction	
15.0%	444		9.8% fuel reduction	
20.0%	790		13.0% fuel reduction	
Incremental cost of light truck weight reduction (WR) in 2030 "mid-range" case:				
3.8%	526	2012$	2.4% fuel reduction	(32)
7.5%	223		4.9% fuel reduction	
11.3%	503		7.3% fuel reduction	
15.0%	894		9.8% fuel reduction	
Incremental cost of vehicle technologies:				
HEV	4,302	2012$	Passenger cars in 2010 (used for 2014)	(32)
HFCV	9,155			
BEV	17,100			
ICEV	2,604		Passenger cars in 2030 "mid-range" case	
HEV	3,280			
HFCV	4,010			

BEV	5,780			
HEV	5,281		Light trucks in 2010 (used for 2014)	
HFCV	12,702			
BEV	24,555			
ICEV	2,864		Light trucks in 2030 "mid-range" case	
HEV	3,280			
HFCV	5,868			
BEV	8,848			
Fuel costs:				
Gasoline cost	3.38	2012$/gal	U.S. average in 2014	(41)
	3.43		U.S. average in 2030	
	2.40		U.S. average in 2030 (Low oil price case)	
	4.19		U.S. average in 2030 (High oil price case)	
Electricity cost	0.1022	2012$/kWh	U.S. average in 2014	
	0.1081		U.S. average in 2030	
	0.1008		U.S. average in 2030 (Low case: High oil/gas resource)	
	0.1323		U.S. average in 2030 (high case: GHG25 = $25/tCO_2$)	
Hydrogen cost	2.00	$/kg	Low end of 2020 range estimate	(40)
	4.00		High end of 2020 range estimate	
	1.50		Low end of 2030 range estimate	Author estimates
	4.00		High end of 2030 range estimate	
	3.50		Reference cost in 2014	
	2.50		Reference cost in 2030	

[a] This standard term encompasses pick-up trucks, vans and sport-utility vehicles (SUVs).

[b] LIDAR = laser imaging, detection and range[69].

[c] Converted using ratio of Consumer Price Indices[42].

Supplementary Table 13. Autonomie simulation parameters

Parameter	Units	Nissan LEAF (five seats)	Two seats	One seat
Frontal area	m^2	2.60	1.56	1.56
Drag coefficient	N/A	0.285	0.285	0.285
Vehicle mass	kg	1,550	1,085	814
Maximum propulsion power	kW	80	56	45
Gross battery capacity	kWh	23.83	16.68	13.40
Usable battery capacity	kWh	20.85	14.60	11.73
Electrical accessory load	W	1,000	800	600
Final drive ratio	N/A	7.938	7.938	7.938
Tire size	N/A	205/55R16	145/80R12	145/80R12

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