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

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Autonomous vehicles (AVs) are conveyances to move passengers or freight without human intervention. AVs are potentially disruptive both technologically and socially[1–3], with claimed benefits including increased safety, road utilization, driver productivity and energy savings[1–6]. Here we estimate 2014 and 2030 greenhouse-gas (GHG) emissions and costs of autonomous taxis (ATs), a class of fully autonomous[7,8] shared AVs likely to gain rapid early market share, through three synergistic effects: (1) future decreases in electricity GHG emissions intensity, (2) smaller vehicle sizes resulting from trip-specific AT deployment, and (3) higher annual vehicle-miles travelled (VMT), increasing high-efficiency (especially battery-electric) vehicle cost-effectiveness. Combined, these factors could result in decreased US per-mile GHG emissions in 2030 per AT deployed of 87–94% below current conventionally driven vehicles (CDVs), and 63–82% below projected 2030 hybrid vehicles[9], without including other energy-saving benefits of AVs. With these substantial GHG savings, ATs could enable GHG reductions even if total VMT, average speed and vehicle size increased substantially. Oil consumption would also be reduced by nearly 100%.

Many automakers and Google plan to rapidly commercialize AVs (refs 4,8,10), although it will take time to gain widespread market share. AV functionality ranges from lane-keeping and parking assistance features to full control without human input[7]. As of 2014, four US states and Washington DC allow AV testing on roadways, with thirteen more contemplating similar laws; Nevada is the first state offering ‘certificates of compliance’ for non-testing use of AVs (ref. 4). For more background information, see Supplementary Note and Supplementary Table 1.

The US Energy Information Administration (EIA; ref. 11) projects GHG intensity decreases between 2014 and 2030 in gasoline (3.8%) and electricity (8.5%), due to growing renewable energy contributions. However, GHG policies may lower intensities further. The US Environmental Protection Agency (EPA) has proposed a rule to lower average GHG intensity of electricity 30% by 2030 (ref. 12), whereas in California (CA) GHG electricity intensities may fall 55% by 2030 as a result of several policies[13]. We considered GHG intensities of gasoline and electricity based on 2014 and 2030 EIA projections, and 2030 GHG electricity intensities from EPA and CA (applied across the US). Also considered were GHG emissions for hydrogen produced from natural gas reforming, water electrolysis or other methods[14]; the former two were estimated using GHG energy intensities from EIA for natural gas, and EPA and CA for electricity.

Combining GHG energy intensities with vehicle technology efficiencies produced a wide variety of GHG emissions intensities per mile. Passenger car and light truck fuel efficiencies were combined using fleet mix ratios projected for 2014 and 2030 (ref. 11). As shown in Fig. 1 (see Supplementary Table 2 for additional data), there is a 52% decrease in GHG emissions in moving from 2014 internal combustion engine vehicles (ICEVs) to 2030 ICEVs, a further 29% decrease in moving to hybrid-electric vehicles (HEVs), and (depending on hydrogen production assumptions) a 6% increase to 32% decrease in moving to hydrogen fuel-cell vehicles (HFCVs). Although HFCVs and battery-electric vehicles (BEVs) can have similar GHG emissions per mile, assuming EIA GHG energy intensities, for BEVs the lower EPA and CA GHG electricity intensities produce the lowest GHG emissions of all vehicle types, ranging from 11–23% of 2014 ICEVs.

In 2009, US vehicle occupancy was 1.63 passengers averaged across VMT (ref. 15). Moreover, 62% of VMT involved one passenger, and 25% involved two passengers (see Table 1). ATs are anticipated to be deployed according to each trip’s occupancy need (‘right-sizing’) because it is cost-effective for owners (capital and operating costs are lower) and passengers (who pay only for needed seats and storage). Tellingly, companies[16,17] and researchers[4,5,9] are all exploring low-occupancy AV concepts.

As BEVs offer the lowest GHG intensities, right-sized BEV energy use was modelled, based on a reference five-seat Nissan LEAF. For two-passenger trips, a 40% narrower vehicle was modelled, plus smaller reductions in vehicle mass, engine power, battery capacity and accessory loads that would accommodate only required passengers and cargo. For single-seat vehicles, frontal area was held constant, but additional reductions in mass, power and battery capacity were made. Simulation results for BEVs indicate energy consumption relative to an average-sized light-duty vehicle (LDV) of 47% for one-passenger vehicles, and 56% for two-passenger vehicles. For three-passenger trips, standard-sized passenger cars were assumed (with energy consumption 81% of the LDV average), whereas for four- and five-passenger trips, standard-sized LDVs were assumed. For the largest size class in Table 1 (6.9 passengers), average efficiencies of light trucks with seating for 6+ people[9] were used (energy consumption 135% of the LDV average). Across all trips, the resulting average BEV energy use of right-sized ATs relative to LDVs was 55%.

Further energy (and cost) savings could be obtained if ATs are employed in conjunction with ride-sharing, increasing average occupancy but decreasing total VMT: a 10% decrease in single-occupancy VMT (with a corresponding increase in double-occupancy VMT) is estimated to decrease average energy consumption by ∼3%; see Supplementary Discussion for details.

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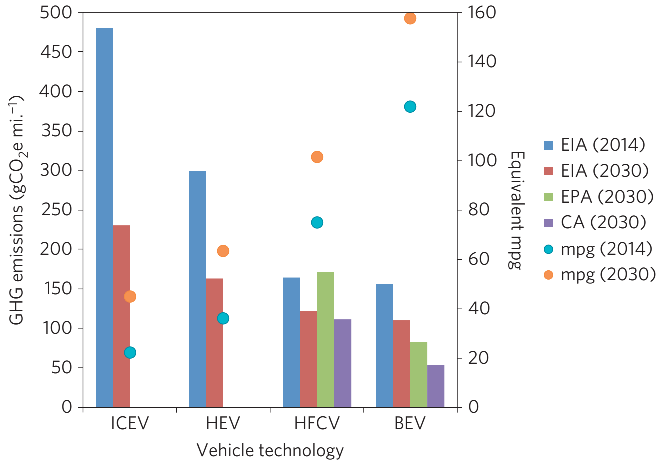

Figure 1 | GHG emissions (coloured bars, left-hand axis) and vehicle efficiencies (symbols, right-hand axis) versus vehicle technology and GHG intensity assumptions. GHG energy intensities: EIA, US Energy Information Administration for gasoline, electricity and natural gas-produced hydrogen; EPA, US Environmental Protection Agency proposed rule for electricity; CA, California policy for electricity. Electricity-produced hydrogen was assumed for EPA and CA.

ATs, like conventional taxis, are estimated to travel annually roughly three to six times farther than CDVs, resulting in operating expenses (fuel, maintenance, insurance) that dominate total ownership cost. The consequence is a powerful financial incentive favouring energy-efficient vehicles.

In Fig. 2, total annual ownership costs are shown for different vehicle technologies as a function of annual VMT. Results are plotted using each vehicle technology's annual projected capital and operating (especially energy) costs in 2014 and 2030. Supplementary Tables 4 through 7 provide detailed results. Results are shown without right-sizing, because capital costs of smaller vehicles were not available in ref. 9. However, trends are robust at high VMT across a wide range of capital cost assumptions; see Supplementary Discussion and Supplementary Figs 2 and 3.

At 12,000 mi. yr^{-1}, the minimum total annual cost in 2014 (solid lines) is an ICEV with 22 miles per gallon (mpg), whereas in 2030 (dashed lines) the minimum is an HEV (36 mpg). The minimum cost technology depends on the relative prices of gasoline, hydrogen and electricity, but total cost differences are relatively minor (±5%) among these in 2030, indicating that projected annual costs for privately owned vehicles will be similar for ICEVs, HEVs and HFCVs, and slightly higher for BEVs.

At higher annual VMT, the curves shift abruptly towards minimum cost for higher-efficiency vehicles. In 2014, HEVs are cheapest at 40,000 mi. yr^{-1}, and BEVs (122 mpg equivalent) at 70,000 mi. yr^{-1}. In 2030, economics favour even more efficient vehicles, with BEVs (158 mpg equivalent) representing the minimum cost at $\geq$40,000 mi. yr^{-1}, and other technologies having significantly higher costs. Among the technologies modelled, total cost decreases with increasing efficiency, suggesting further cost-effective efficiency improvements beyond those in ref. 9 might be possible.

The marginal cost per mile of 2030 BEVs is 14.2US¢, or 82% of 2030 HEVs and 52% of 2014 ICEVs. Lower operating costs suggest possible rebound effects: for the same annual cost as 2030 HEVs, passengers in BEVs could increase annual VMT by 8,500 mi. yr^{-1}.

For discussion of lifetime VMT, BEV range, and sensitivities to battery degradation and energy costs, see Supplementary Discussion, Supplementary Figs 1 and 4 and Supplementary Tables 8 through 10.

The EIA baseline[11] projects that <1% of US LDVs in 2030 will be HFCVs or BEVs. The combination of low-GHG electricity and favourable BEV economics at high VMT facilitates ATs with lower GHG emissions per mile of any vehicle technology considered here; see Fig. 3. Together with right-sizing, these factors yield 2030 per-mile GHG emission reductions per AT deployed of 87–94% below the reference 2014 ICEV, depending on GHG electricity intensity assumptions. Even relative to 2030 HEVs, GHG emission reductions for ATs are 63–82%. Therefore, regardless of reference point, ATs can provide substantially reduced per-mile GHG emission intensities. Because oil provides <1% of US electricity generation[11], ATs also enable nearly 100% per-mile reduction in oil consumption relative to gasoline-based vehicles.

Without consideration of AT benefits, researchers have estimated that AVs could reduce energy use per vehicle by up to ~80% from platooning, efficient traffic flow and parking, safety-induced light-weighting, and automated ride-sharing[1–3,9,18]. ATs could therefore amplify these savings, lowering GHG emissions per vehicle by 93–96% relative to 2030 HEVs. On the other hand, previous research has suggested that possible use by unlicensed drivers, increased occupied and unoccupied VMT, and higher-speed travel could double VMT and increase energy use almost threefold[2,3]. Moreover, people could choose larger vehicles to increase comfort: we considered a case where vehicle energy consumption corresponded to an occupancy two levels higher than assumed in Table 1 (that is, a one-person vehicle would have the efficiency assumed for a three-person trip, and so on), producing an average 68% increase in energy consumption compared to our base case (see Supplementary Discussion and Supplementary Table 3). However, even in the unlikely scenario where increased VMT, higher-speed travel, and larger vehicles inflate energy use fivefold, GHG emissions of ATs could still be lower than conventionally driven 2014 ICEVs by 38–69%, and up to 8% lower than 2030 HEVs.

Taxis charge much higher rates per mile than CDV owners incur, because a significant portion of fares provides income to the driver

Table 1 | Proportion of 2009 US vehicle occupancies by VMT and estimated AT energy consumption relative to battery-electric LDVs in 2030.

Number of passengers	Proportion of total 2009 US VMT (ref. 15) (%)	Estimated AT energy consumption (final energy per mile) relative to 2030 battery-electric LDV average
1	61.68	0.466*
2	24.85	0.559*
3	7.00	0.811†
4	3.89	1.000‡
5	1.64	1.000‡
6+ (average: 6.860)	0.95	1.345§
All (average: 1.626)	100	0.551

*Author calculations using Autonomie[25]. See Methods for details. †Equal to passenger car average efficiency[9]. ‡Equal to average LDV efficiency[9]. §Equal to average 6+ person capacity light truck efficiency[9].

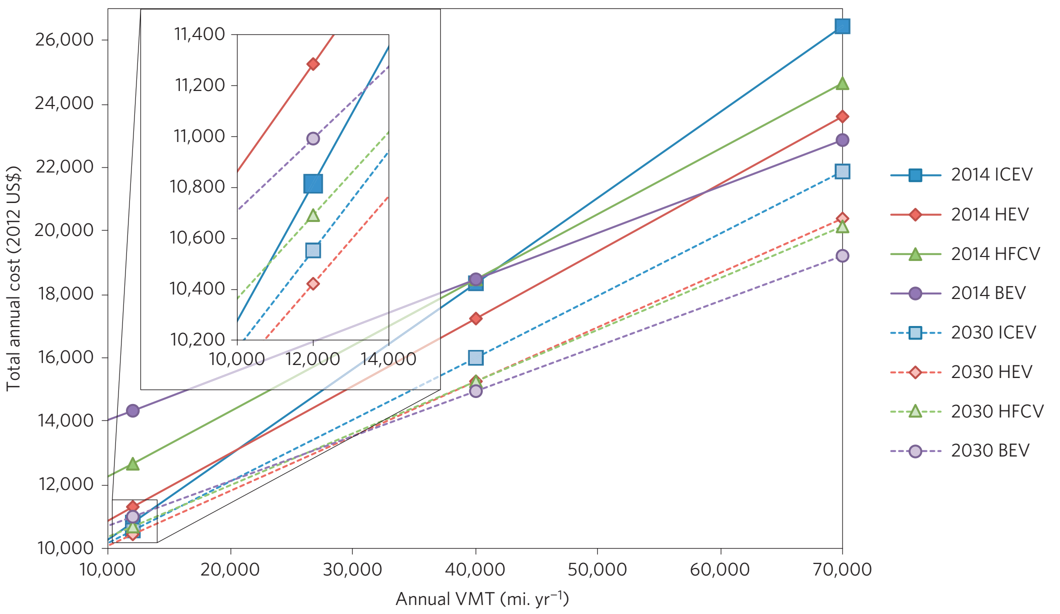

Figure 2 | Total annual cost of LDVs versus annual VMT in 2014 and 2030 for four vehicle technologies. In 2014, economics strongly favour ICEVs at 12,000 mi. yr^{-1}, the average VMT of CDVs; in 2030, HEVs have lowest total ownership cost, with ICEVs and HFCVs being slightly higher, and BEVs costliest. At the higher VMT expected for ATs, greater efficiency become economically favourable, with BEVs becoming the lowest total cost vehicle at 70,000 mi. yr^{-1} in 2014 and ≥40,000 mi. yr^{-1} in 2030.

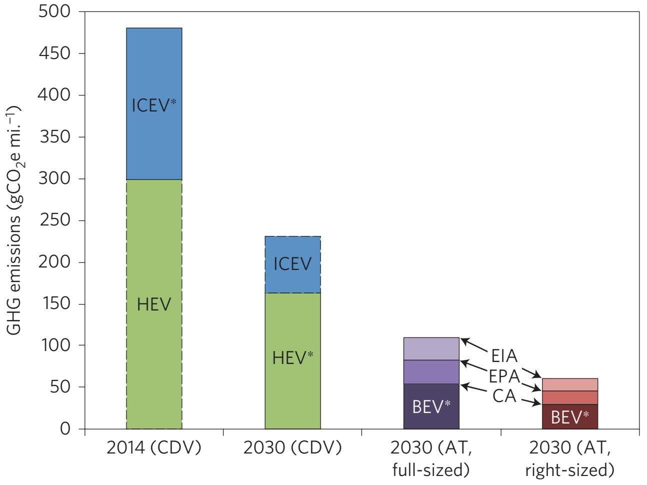

Figure 3 | GHG emissions intensities per mile for CDVs in 2014 and 2030, and ATs in 2030. Cost-optimal vehicle technologies indicated by asterisks. Both full-sized (purple) and right-sized (red) ATs are shown, each with three sets of electricity GHG intensity assumptions. Right-sized ATs have per-mile GHG emissions intensities 87–94% below 2014 ICEVs, and 63–82% below 2030 HEVs, depending on electricity GHG intensity.

and owner. In New York City in 2005, only 24% of taxi fares went towards vehicle costs (capital, fuel, maintenance and insurance), with 57% going to drivers[19]. With US$2.65/mi. average 2012-adjusted fare and 64,600 mi. yr^{-1} VMT, driver income constitutes US$97,600 yr^{-1}, which could more than cover the incremental cost of AV technology. This cost is at present ~US$150,000 (refs 4,20), but costs are projected to fall to <US$10,000 by 2025 (ref. 8). However, even using current costs, if financed using identical model assumptions for vehicle capital, this would amount to US$36,500 yr^{-1}, 37% of New York City taxi driver income and 21% of total taxi fares. Therefore, ATs could replace CDV taxis at current AV technology costs and even possibly lower fares, providing an important early market niche. And in 2030, costs per mile are markedly lower for high-VMT shared vehicles (~30–50 US¢/mi.) than private vehicles (~80 US¢/mi.), with AV technology itself assumed to add 3–4 (shared) to 11 (private) US¢/mi. to total cost. See Supplementary Discussion and Supplementary Table 11 for details.

Given the attractiveness of ATs, we examined their impact if they expanded to a portion of the US LDV sector. All manufacturers working on AVs plan to release vehicles with some autonomous features by 2017, and Google has announced plans to release a fully functional AV by 2017 (ref. 4), with Tesla following suit in 2020 (ref. 21). However, although some researchers are optimistic about AVs becoming generally available by 2025 (ref. 8), and perhaps dominating the LDV market by the 2030s (refs 10,22), others are more cautious[23,24].

Therefore, instead of projecting AT penetration levels in 2030, the size of GHG reductions per AT deployed was estimated. Assuming no changes in overall LDV fleet VMT, every 10 billion VMT displaced by ATs (equivalent to 820,000 privately owned LDVs, ~5% of 2030 LDV sales and ~0.3% of the LDV fleet) would decrease GHG emissions by 2.1 to 2.4 MtCO$_2$ yr^{-1} and save ~7 million barrels per year of oil. If displacement grew to 10% of US VMT, annual reductions could equal 65 to 75 MtCO$_2$ yr^{-1} and ~0.6 million barrels of oil per day. Although ATs may never occupy more than a small niche of LDVs (at present, only ~4% of LDVs are shared; see Supplementary Discussion), it is possible that the cost, convenience and environmental benefits of ATs may eclipse those of privately owned vehicles. Consequently, the majority of LDVs could become ATs by 2050, representing very significant decreases in GHG emissions (~70–90%) and oil consumption (~100%) relative to baseline projections[11].

Although our results depend on a number of assumptions, we believe they are robust, and have explored many potential issues and sensitivities in the Supplementary Discussion. As AV costs fall, it may become difficult for CDV taxis to compete, and ATs may become ubiquitous, perhaps expanding well beyond the historically small portion of total LDVs comprised of shared vehicles. However, if CDV taxis vanish, the social impacts may be considerable.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

S.S. performed vehicle powertrain calculations; J.B.G. performed all other calculations and analysis. J.B.G. and S.S. wrote the manuscript and made any appropriate revisions.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.B.G.

Competing financial interests

The authors declare no competing financial interests.

Methods

Overview. Supplementary Table 12 presents parameter assumptions. Ref. 9 provided current and future efficiencies of ICEVs, HEVs, HFCVs, and BEVs. Hydrogen- and electricity-based vehicle efficiencies were converted to equivalent mpg of gasoline. Refs 9,11,12,26 provided current and projected future US GHG emissions (including upstream emissions) for gasoline, natural gas and electricity. Ref. 13 provided 2030 California electricity GHG emissions estimates that were used to estimate best-case US electricity GHG reductions. Hydrogen was assumed produced by natural gas steam reforming or electrolysis, using conversion efficiencies from ref. 9. US occupancy by fraction of total VMT came from ref. 15. Validated models within the powertrain simulator Autonomie[25] estimated the energy use of hypothetical small-occupancy BEVs based on a five-seat Nissan LEAF reference, but with 40% reduced frontal area corresponding to single-seat width, and vehicle mass, engine power, battery capacity and accessory loads reduced by smaller amounts. VMT of 12,000 mi. yr^{-1} was assumed[11] for CDVs, and 40,000–70,000 mi. yr^{-1} for ATs based on New York City[19] and Denver[27] taxis. To estimate total vehicle ownership costs, we developed a model using capital costs from ref. 9, fuel costs from refs 11,28, maintenance and insurance costs from ref. 29, and longevity from ref. 19.

GHG intensities. The National Academy of Sciences (NAS) provided 2010 reference greenhouse gas (GHG) energy intensities for gasoline, natural gas and electricity[9]. We used data from the Energy Information Administration (EIA; refs 11,30) to estimate 2014 and projected 2030 GHG intensities from gasoline and electricity (GHG intensities for natural gas were projected to change by $<1\%$, so were held constant). The US Environmental Protection Agency (EPA) proposed rule GHG energy intensity target for 2030 (30% reduction from 2005) was provided by ref. 12, whereas projections for 2030 California gasoline and electricity were obtained from scenario S2 in Greenblatt[13]. All GHG emissions included upstream estimates provided by NAS (ref. 9) or Greenblatt[13]. Argonne National Laboratory (ANL) provided confirmatory life-cycle GHG emission estimates[26]. GHG intensities of hydrogen were obtained using conversion efficiencies from the US Department of Energy (DOE; ref. 28), based on natural gas steam reforming and electrolysis. For the latter, both EPA and California (CA) GHG electricity intensities were analysed, but only CA electricity resulted in a lower overall GHG intensity of hydrogen than natural gas-based hydrogen. Hydrogen GHG intensities based on EPA electricity were included in Fig. 1 in the main text, but GHG intensities based on EIA data were omitted from analysis because they were much higher, comparable to those of a 2030 hybrid-electric vehicle (HEV).

Vehicle occupancy. We used data from the Federal Highway Administration (FHA; ref. 15) to estimate the fraction of total US vehicle-miles travelled (VMT) by number of passengers (occupancy); this data was provided by state, and aggregated to US totals. Results of this analysis are presented in Table 1 in the main text.

Right-sizing. We used the powertrain simulation tool Autonomie[25] to model hypothetical small-occupancy battery-electric vehicles (BEVs). The modelled reference vehicle was a Nissan LEAF, the top-selling, five-seat BEV introduced in 2010, with more than 142,000 vehicles sold worldwide[31]. One- and two-seat vehicle models were constructed based on LEAF parameters, but reducing the frontal area by 40% to accommodate a one-seat width. Reduction was less than 50%, owing to the assumption that a portion of the vehicle's width remained constant to provide a sufficient safety margin. Vehicle mass, engine power, battery capacity and electrical accessory loads were also reduced by smaller amounts; see Supplementary Table 13. For comparison, the two-seat Smart BEV has approximately the same mass, motor power and battery capacity as the two-seat simulated vehicle shown here, but the frontal area is intermediate between the two- and five-seat versions. Specifically, the Smart Electric Drive Coupe has a curb mass of 950 kg, peak power of 55 kW, and battery capacity of 17.6 kWh (ref. 32); the estimated frontal area of the 2002 model was 2.02 m^2 (ref. 32); the current model may be somewhat larger.

Using these input parameters, energy consumption for each vehicle model was calculated for three different EPA test drive cycles: the Urban Dynamometer Driving Schedule (UDDS), simulating an urban route with frequent stops; the Highway Fuel Economy Test (HWFET), simulating the higher speeds of highway driving; and the US06 Supplemental Federal Test Procedure, used to represent aggressive, high-speed and/or high-acceleration driving behaviour, rapid speed fluctuations, and driving behaviour following startup. A weighted sum of the UDDS (55%) and HWFET (45%) results yielded the standard EPA efficiency rating[33].

BEV efficiencies relative to an average light-duty vehicle (LDV) were estimated assuming 56% passenger cars and 44% light trucks in 2030 (ref. 11).

For the largest size class in Table 1 in the main text (6.9 passengers), average efficiencies of large light trucks in NAS (ref. 9) were used: Dodge Grand Caravan minivan (seating for seven) and Ford F-150 pick-up truck (seating for six in 'Super Cab' model). (The Saturn Vue sport-utility vehicle included in NAS (ref. 9) is also considered a light truck, but was omitted from our analysis because it seats only five.)

Annual VMT. Annual VMT estimates for CDVs were provided by EIA (ref. 11), whereas annual VMT for taxis in New York City and Denver were provided by Schaller[19] and Metro Taxi[27], respectively, and ranged from 39,410 to 72,000 mi. yr^{-1}. The New York City Taxi and Limousine Commission[34] also provided an estimate for New York City taxis (70,000 mi. yr^{-1}) that was similar to the Schaller[19] average of 64,600 mi. yr^{-1}. Although we expect that autonomous taxis (ATs) will be more efficient than human-driven taxis in identifying and driving to passengers, thus possibly driving VMT even higher, we explored two AT cases in our analysis (40,000 and 70,000 mi. yr^{-1}), along with a CDV reference case (12,000 mi. yr^{-1}).

A San Francisco taxi estimate from Gordon-Bloomfield[35] was higher (90,000 mi. yr^{-1}), but increasing the VMT range was deemed unimportant, as all significant conclusions were observed at 70,000 mi. yr^{-1}. Although not directly comparable, the average annual VMT for Irish taxis and limousines in 2008 (35,602 mi. yr^{-1}; ref. 36) was below the low end of this range; however, 40% of Irish taxis and limousines travel 40,000 mi. yr^{-1} or more, consistent with our estimate.

AV and taxi economics. We used estimates from Naughton[20] and Troppe[6] for the current incremental cost of AV technology. IHS (ref. 8) provided estimates of the eventual cost of this technology through 2035. Schaller[19] provided an estimate of driver revenue for New York City taxis, adjusted to 2012 dollars using the historical consumer price index published by the US Bureau of Labor Statistics (BLS; ref. 37). This index was also used to adjust other cost data reported for years prior to 2012.

For vehicle loan rates, Car Loan Pal[38] provided historical rates of five-year new car loans between 1980 and 2011; BankRate[39] provided a rate estimate for 2014. Based on this data, we assumed a long-term average interest rate of 8.0% for five-year loans, corresponding to an annual capital recovery factor of 24.33%, assuming monthly payments. This factor was used to estimate annual capital costs of both CDVs and AV technology.

Vehicle costs, fuel costs and fuel efficiencies. We developed a model of total ownership cost of vehicles with potentially high annual VMT. Using cost and efficiency estimates from NAS (ref. 9), fuel cost estimates from EIA (ref. 11) and DOE (ref. 14) and maintenance and insurance estimates from the American Automobile Association[29], we calculated the annual total cost of ownership C_{total} (US\$/yr) as:

$$C_{\text{total}} = \text{CRF} \times C_{\text{capital}} + \text{VMT} \times (E_{\text{vehicle}} \times C_{\text{energy}} + C_{\text{maint}} + C_{\text{ins}})$$

where CRF = capital recovery factor (%/yr), C_{capital} = cost of vehicle capital (US\$), VMT = annual vehicle-miles travelled (mi. yr^{-1}), E_{vehicle} = vehicle energy efficiency (gal/mi. or kWh/mi. as appropriate), C_{energy} = cost of energy (US\$/gal or US\$/kWh), C_{maint} = cost of maintenance (US\$/mi.), C_{ins} = cost of insurance (US\$/mi.).

NAS (ref. 9) provided estimates of a wide variety of passenger car and light truck vehicle technologies in 2010 and 2030. Technologies included internal combustion engine vehicles (ICEV), HEVs, hydrogen fuel-cell vehicles (HFCV) and BEVs. Hydrogen- and electricity-based vehicle efficiencies were converted to equivalent mpg of gasoline, using final energy lower heating values of gasoline and hydrogen, and final energy content of electricity. Further efficiency improvements included for 2030 were increased rolling resistance (RR) tyres, vehicle weight reductions (WR) and improved aerodynamics (AERO). All fuel efficiency estimates provided by NAS were expressed as EPA ratings[40], but we have reduced these fuel efficiencies for ICEVs by 15% according to guidance published by EIA (ref. 41). For BEVs, which have idle shutoff, regenerative braking and high efficiency across a wide range of tractive loads, we have found evidence for less difference between EPA rated and real-world fuel economy compared with ICEVs (ref. 42). We also expect this to be the case for other advanced powertrains, including HEVs and HFCVs. Therefore, for this analysis we retained the EPA ratings for all of these powertrains.

We compared efficiency estimates against those of EIA (ref. 11) for 2014 new vehicles and 2030 new vehicles and fleet averages. This source was also used to estimate the number of LDVs in 2030 and the fraction of passenger cars and light trucks composing the 2030 fleet.

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