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Fully automated vehicles: A cost of ownership analysis to inform early adoption

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Abstract

Vehicle automation and its uptake is an active area of research among transportation academics. Early adoption rate also influences the results in other areas, e.g. the potential impacts of vehicle automation. So far, most of the interest in the uptake of *fully* automated, driverless vehicles has focused on private vehicles only, yet full automation could be beneficial for commercial vehicles too. This paper identifies the vehicle sectors that will likely be the earliest adopters of full automation. Total costs of ownership (TCO) analysis is used to compare the costs (and benefits) of vehicle automation for private vehicles among different income groups and commercial vehicles in the taxi and freight sectors in the UK. Commercial operations clearly benefit more from automation since the driver costs can be reduced substantially through automation. Among the private users, households with the highest income benefit more from automation because of their higher driving distances and higher perceived value of time, which can be used more productively through full automation.

Keywords

Vehicle automation; driverless car; autonomous car; total cost of ownership; travel time use; early adoption

Fully automated vehicles: A cost of ownership analysis to inform early adoption

1. Introduction

Fully automated, autonomous, driverless or self-driving cars are currently at the peak of Gartner's technology hype cycle (Gartner 2015), indicating intense attention from the media and expectation from the members of the public. Since Google's demonstration of the much publicised self-driving car in 2012, the question is no longer about 'if' but about 'when' they become available in the market. All the major mainstream vehicle manufacturers are known to have an automated vehicle program, with some claiming the availability of fully automated vehicles in the showrooms by 2020. All of these activities have generated acute interest among transport researchers and professionals about the potential impacts of vehicle automation on the transportation system. Most of the attention has been in the context of how full automation could substantially improve road safety (Department for Transport 2015a), change the way we travel (Wadud et al. 2016) or change the way we own or share vehicles (Krueger et al. 2016), ultimately also affecting energy use and carbon emissions (Wadud and Anable 2016) and resulting in other broader societal impacts (Correia et al. 2016). Nearly all the researchers focus on one specific impact of automation (e.g. Fagnant and Kockelman 2014, Spieser et al. 2014 for shared mobility, European Transport Safety Council 2016 looking at safety impacts, Miller 2015 investigating impact on insurance industry, etc.) while others attempt to model the aggregate impacts on travel and energy demand (e.g. Wadud et al. 2016).

One area that is very important in understanding the potential impacts of vehicle automation is the uptake of fully automated vehicles. Studies on temporal evolution of uptake of automated vehicles generally follow Rogers' innovation diffusion curve (Rogers 1995) which can be expressed through the well-established Bass, Generalized Bass or S-shaped growth curves (KPMG 2015, Lavasani et al. 2016). On the other hand, some studies investigate the willingness to pay for various vehicle automation features, including full automation (Bansal and Kockelman 2016). All of these studies focus only on passenger travel, i.e. they study the uptake of full automation in passenger vehicles. Despite the attention on passenger car travel so far, early adopters of full automation could well be in other areas, e.g. in freight and logistics sector, where there is already some experimentation with advanced technologies such as drone delivery by Amazon. Recent experimentation of automated platooning of vehicles on motorways also primarily include trucks, rather than cars (e.g. SARTRE in Europe). Commercial mobility service providers such as Uber and Lyft are also very active in the vehicle automation area.

The role played by the early adopters in product satisfaction and its communication is crucial for later success in mass adoption and thus substantially affect the shape of uptake curve of any new technology, including fully automated vehicles. It would therefore be useful to understand which sectors of the road transport system would likely adopt full automation first. However, little is known about the potential early adopters of full vehicle automation, especially in relation to personal and commercial vehicles. This research aims to fill this gap, by comparing the Total Cost of Ownership (TCO) of fully automated vehicles in different vehicle sectors in the UK. To our knowledge this is the first study to develop such costs for different vehicle groups under a full automation scenario. We also extend the traditional TCO analysis by including the costs of time spending driving personal vehicles and incorporate the potential heterogeneity in TCOs for different income groups.

The paper is organized as follows. Section 2 draws insights from the literature on factors affecting vehicle purchase and the application of TCO analysis in this context. Section 3 describes the method and data used for the analysis, including the assumptions made. Section 4 presents the results for different scenarios and also tests the sensitivity of the results with respect to some of the input parameters. Section 5 draws conclusions.

2. Insights from literature

There are a number of factors that affect vehicle purchase decisions. These factors and their relative importance substantially vary between consumer and vehicle types. Lane and Potter (2007) divide these influencing factors into two groups: situational and psychological. Situational factors include vehicle economics, regulatory environment, vehicle performance and suitability, and existing infrastructure: often these can be measured objectively. On the other hand, psychological factors are difficult to quantify and can include attitude, lifestyle, personality and self-image for private purchases. Although business purchases (fleet, freight trucks) put more emphasis on situational factors - especially vehicle and wider logistic economics - psychological factors such as risk perception, corporate culture, and company image can still have a role to play (Lane and Potter 2007). A recent survey in the UK found that fuel economy/running costs, size/practicality and vehicle price were the three most important factors to the consumers while purchasing their most recent private car (Lane and Banks 2010). All of these fall within the situational factors, and underline the importance of vehicle economics in making a purchase. We therefore focus primarily on the vehicle purchase and use economics to identify the potential adopters for whom vehicle automation can be beneficial early on.

Total cost of ownership (TCO) analysis is the vehicular counterpart of life cycle cost analysis which is well known in business procurement and project appraisal. TCO analysis is primarily used to compare the relative economic advantages of different competing vehicle technologies. The technique has become especially popular in the context of alternative powertrains in vehicles, with numerous studies applying the method to compare the costs of conventional internal combustion engine vehicles with Hybrid Electric Vehicles, Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles or Fuel Cell Vehicles (e.g. Lipman and Delucchi 2006, Thiel et al. 2010, Contestabile et al. 2011, Wu et al. 2015, Palmer et al. 2017). While comparative TCO is not the only factor that affects the adoption of different technologies (e.g., range anxiety is an important factor for Battery Electric Vehicles), Tran et al. (2013) show that financial costs and benefits are still the most important factor in the UK. Therefore, we opt for TCO analysis to understand the comparative cost advantages for different vehicle user groups, with an implicit assumption that those vehicle sectors with the largest cost advantages are likely to be the earliest adopters.

The technique for conducting a TCO analysis is relatively straight forward: TCO is the sum of all the costs related to a car purchase and driving it over the period that one owns it. Lipman and Delucchi (2016) include the following in their TCO analysis: vehicle purchase (as annual depreciation), fuel, insurance, maintenance and repair, engine oil, replacement tire, safety and emissions inspection fee (MOT in the UK), parking, tolls etc. Battery costs are also included when conventional vehicles are compared with electric vehicles. Social costs of emissions and noise are generally not included in TCO analysis since they are often not considered (or, at best, qualitatively considered) in individual vehicle purchase decisions. While TCO analysis may not have been very popular in vehicle purchase literature in mainstream transport research, components of the TCO analysis are still used to characterize the vehicle attributes in vehicle choice models, which are more popular in the discipline (e.g. Hackbath and Madlener 2013). As such TCO analysis are useful not only in their own right (as in here) but also as input to discrete choice type models to predict future market share. Results of TCO analysis can also be incorporated directly in the Generalized Bass type technology diffusion models (e.g. Lavasani et al. 2016), or system dynamics models for vehicle uptake (e.g. Shepherd et al. 2012) – all of which use relative costs of competing technologies as an input. As such it is an important parameter in understanding potential adoption of the automated vehicles in future.

3. Methods and data

3.1 Sectors and time period modelled

In order to understand the potential early adopters of full automation, we include both commercial and private vehicles for comparison. While most of the attention was on personal vehicles (cars and SUVs) so far, manufacturers are also quietly working on full automation capabilities in trucks; e.g. Uber has recently demonstrated delivery of goods using a fully automated truck on motorways (Davies 2016). Taxis are another commercial application which can benefit from 'driverless' full automation, where the additional costs of automation can be spread over the larger driving distances. We therefore include taxis and three types of trucks to represent the commercial applications. For personal use sector, we recognize the heterogeneity of the population and use average representative consumer from five income quintiles, with different incomes and car travel patterns.

TCO analysis can – in theory – be carried out on a vehicle lifetime basis, equivalent annual basis, or average length of ownership basis. Given it is unlikely that one person keeps a car during its entire useful life, the financial basis of a purchase decision often involves only the period the car is expected to be used by one owner. The average length of ownership of a car is around 4 years in the UK; most of the cars that are bought as new are also traded in within 4 years of purchase (Leibling 2008). As such conducting the analysis for a 4 year period can be quite useful for personal vehicles and many TCO analyses use the average length of ownership as the analysis time period. However, our objective is to compare the TCOs of different vehicle types including cars, taxis and freight vehicles, which can all have different average lengths of ownership. For example, rigid trucks (single-unit trucks) have an average ownership length of 5 years, while for articulated trucks (trailer-trucks) it is 6 years (Road Haulage Association 2014). Therefore we carry out the analysis on the annual equivalent cost basis.

A major uncertainty regarding the effects of full automation in the personal vehicle sector is whether people will continue to own cars, or whether mobility services will become the dominant mode for personal travel. Although relative cost effectiveness – similar to TCO – will remain an important determinant, other situational and psychological factors will strongly affect the choice between ownership and mobility services. Especially, fully automated models for on-demand mobility, mobility as a service, or last mile services to public transport (e.g. Yap et al. 2016) are still not well understood. As such, we investigate only the personal ownership model here.

3.2 Mileage data

The travel statistics for car drivers for different income quintiles are drawn from the 2014 National Travel Survey (NTS) of the UK, but refers to England due to non-availability of data in other countries within the UK (Department for Transport 2015b). NTS aggregate average tables for income quintiles include non-car owning households too, and thus underestimates the car travel by car owning households. As such, we independently source the information from the NTS micro-dataset. Table 1 presents the key variables of interest: the average number of miles a car is driven in car-owning households of the five income quintiles. Table 1 also presents the average number of hours and distances driven by the main driver in the households. This information is used to determine the average number of hours a car is driven in each of the five quintiles. Average mileage for different truck types are from Road Haulage Association (RHA 2014). Taxi mileage statistics from official sources is not available: 33,000 miles a year appear a plausible number, estimated from a taxi drivers survey (Insure Taxi 2016) and Guildford Borough Council (2016).

[Table 1 here]

3.3 Vehicle cost data

NTS does not collect vehicle running costs information from the respondents. Therefore, for passenger cars, cost estimates are collected from motoring service provider AA, which breaks down the running costs for five different vehicle segments, based on purchase prices (Table 2). One of the largest costs of vehicle ownership is the depreciation costs, i.e. the loss in the value of the car over time. The AA depreciation costs appear more generous than some consumer reports (including AA's own report), which indicate a depreciation of around 55% (between 50-60%) at the end of 3 years, resulting on average an 18.5% depreciation per year (Holder 2015). Given a new car is owned for around 4 years on average (Leibling 2008), we use a total depreciation of 60% over the first 4 years, at an average of 15% a year during that period.[1] This reflects a 40% salvage value at the end of the first 4 years of ownership. We make an assumption that these five vehicle groups correspond to the average car used by the five income quintiles. The annual cost estimates for commercial trucks are again taken from Road Haulage Association (RHA 2014), which provides itemized cost estimates for different truck types in the UK, including driver costs and fuel costs (Table 3).

[Table 2 here]

[Table 3 here]

For taxis, it is difficult to get an official, reliable cost estimate similar to those for trucks or private cars. We assume most of the running costs of a taxi are similar to a mid-range private car, with some differences in the fixed costs. Taxis accrue additional costs for insurance (requires passenger liability too) and vehicle inspection costs (MOT every six months, as opposed to every year for personal vehicles). We assume insurance costs to be three times (Guildford Borough Council 2016). We also assume the cost of capital to be 3%, consistent with commercial truck operations. Driver earnings vary substantially in the taxi trade (£12,000 – £20,000, National Career Services, 2016) and the median is around £17,500 per year (Payscale 2016). Individual taxis are often used in two shifts, and on average a taxi is driven by 1.3 drivers (Guildford Borough Council 2016), as such the average

[1] Depreciation is not linear, and a new vehicle depreciates the highest in its first year of use (sometimes as high as 30%). Since a new car owner generally tends to keep her car for 4 years, the annual average TCO – and therefore annual average depreciation – over those 4 years are of interest, not the first year of depreciation.

earning for a year's worth of operation is £22,500. Taxis also run three to four times more than private cars (~33,000 miles a year), and they depreciate quicker than personal vehicles. We therefore use an average depreciation of 18% a year, which is 20% more than the depreciation of private cars (15%). Table 3 include the breakdown for taxi operations.

3.4 Fuel efficiency related benefits

Wadud et al. (2016) and Wadud and Anable (2016) identify several mechanisms through which different levels of automation can improve or aggravate energy and carbon efficiency of automation: congestion mitigation, ecodriving and eco-routing, vehicle platooning on motorways, deemphasized performance, vehicle rightsizing and lightweigthing, higher speed limits and increased feature. These mechanisms are categorised further into individual vehicle or network-wide impacts. Given network-wide impacts are expected only when automation penetrates a substantial share of the vehicle stock and our interest is on early adopters when uptake is naturally very low, we ignore the fuel saving mechanisms that are dependent on the network effects and include individual vehicle level mechanisms for fuel efficiency effects. This narrows down the mechanisms to ecodriving and ecorouting (0-20% reduction in fuel consumption), de-emphasized performance (5-23% reduction) and increased features (0-11% increase). However, it is unlikely that the vehicle manufacturers will risk de-emphasizing performance at early stages of vehicle automation, given high end vehicles – for which performance is very important – are more likely to have automation first. At the same time, recent ecodriving literature show that the 20% improvement used by Wadud et al. (2016) is quite optimistic, and report only around 5% improvement through ecodriving in most cases (Jamson 2016). We therefore remain conservative in our estimates and use a 5% improvement in energy efficiency for our primary TCO calculations, with 10% for sensitivity analysis.

3.5 Travel time related benefits

Fully automated vehicles offer a different type of 'cost' saving for personal travel. One of the biggest costs of driving is the waste of travel time that does not generally enter the TCO analysis. In the UK, on average a driver spends 274 hours a year behind the wheels, which cannot be used for any useful purpose as currently driving requires full attention from the driver the entire time. However, full automation can relieve the driver of his/her driving duties, so that the driving time can now be used for other in-vehicle activities. Combined with the proliferation of mobile information and communication technologies, this extra time can be used to improve individual productivity, which has been estimated to be £20B for the whole of UK (KPMG 2015). These potential benefits, or at least a share of it, would certainly be included in the benefit-cost trade-off during the purchase of a fully automated vehicle. We incorporate this in our TCO analysis by monetizing the wasted travel time in current cars using literature derived values of travel time saved (VTTS) as an additional cost of driving, and add them to the out-of-pocket costs of Table 2.

The VTTS is expected to be reduced substantially while in a fully automated car given the potential to engage in useful activities during driving or riding (Wadud et al. 2016).[2] So far there are no

[2] Note that the 'usefulness' of time in a vehicle will likely increase if one can use time in a more productive way, and as such, the 'wastefulness' of travel time will decrease. Travel time is seen as wasteful from a generalised travel cost perspective and VTTS is used to measure this wastefulness; as such VTTS will be less negative – or reduced – when time can be used more productively.

estimates available for VTTS in fully automated vehicles, however, there is evidence that VTTS for rail travel in the UK (after controlling for income) is smaller than the VTTS for cars. Ian Wallis Associates Ltd. (2014) also find that car passengers VTTS can be up to 40% smaller than car drivers, while Department for Transport's (2015c) Webtag guidance also suggests 25% reduction in VTTS for car passengers compared to car drivers. The possibility for engaging in other useful activities as a passenger in a train or a car is the reason behind this reduction in VTTS. Our base case reduction in VTTS is 40%, following Ian Wallis Associated Ltd. (2014), while we also test the sensitivity of TCO with respect to different levels of improvements in the usefulness of in-vehicle travel time, with a lower bound of 25% and upper bound of 60%.[3]

The Webtag guidance (Department for Transport 2015c) for appraisal of transport projects suggest an average VTTS for three different trip purposes: work/business (£24.78), commute (£7.42) and other (£6.59).[4] The VTTS also increases with increasing income, as such the VTTS for different representative consumers for the five income quintiles will also be different. We assume the Webtag suggested VTTS corresponds to the VTTS of the middle (third) income quintile, and use a unit income elasticity of VTTS as per Fosgerau (2005) to derive VTTS for different quintiles, broken down by trip purposes. These are presented in Table 4. We also include a very high income group, the 99th percentile, since the high costs of automation (see section 3.7) may only be affordable by this group initially.

[Table 4 here]

Since the VTTS varies by trip purpose, we also need the shares of driving hours spent for these three purposes. The NTS aggregate tables show the average shares of travel distances for different trip purposes: work/business-14.1%, commute-24.8% and other-61.1%. But these contain all travel (including those by public transport or non-motorized modes). We therefore again draw from NTS microdataset the share of car mileage for different purposes in the five different income groups. These are presented in Table 5, which shows that the shares of work and commute related mileage increase with higher income.

[Table 5 here]

On the commercial vehicle side, the benefits are more directly quantifiable. Full automation can make it possible for trucks or taxis to operate without any human driver present in the vehicle. Driver salaries are a large share of direct costs in commercial vehicle operations (nearly one- third for freight trucks in the UK) and are directly incorporated in the TCO running cost calculations. Commercial truck drivers, however, do not only drive the truck, but also can assist in loading and unloading, and as such there may be a need for additional resources at origins and destinations to compensate for driverless vehicle operations. As such, we assume only 60% of the driver salary costs can be reduced, the other 40% is still required at origins and destinations for loading and unloading purposes. For taxis we maintain the same assumption that although drivers can be fully replaced,

[3] Note that our approach of including cost savings through reduced VTTS for personal use goes beyond traditional TCO analysis and has a 'generalized travel cost' feel to it.

[4] Note that "commute" means personal trips to get to or return from work, "work/business" means trips while on "work or business" (e.g. my daily trip to the university is a commute, but a trip to London to attend a job-related meeting is work/business).

there will be an additional cost amounting 40% of driver salaries, possibly in back office infrastructure, additional equipment in vehicles for ensuring safety etc. We believe this is a conservative estimate and for sensitivity tests, we include a scenario where 80% of the driver costs can be reduced for trucks and taxis.

3.6 Insurance benefits

The principal benefit of vehicle automation is the potential for drastic improvements in safety. 94% of the road deaths and injuries result from human error in the UK, and full automation will reduce these accidents (Department for Transport 2015a). A reduction in the accidents and associated fatalities and injuries is expected to lower the overall insurance claims and as such the insurance premiums as long as the insurance market is a competitive one. At nearly full penetration, it is not implausible to expect near eradication of human driving related accidents (although computer software related accidents could increase, which would still be negligible compared to current incidents), and thus a substantial reduction in insurance premiums. For example, Celent (2012) estimate a 90% reduction in insurance premiums when automation is widespread. However, insurance industry benefits from the 'volume' effect, i.e. at a high penetration level, car travel as a whole becomes safer for everyone. At early stages of automation – when only a very small share of the total traffic is automated – this volume effect is not realized and as such the reduction in premiums may not be that high. At present UK insurance industry offers a 10% discount if a car has collision avoidance system (Palmer 2015), and a 20% reduction for fully automated vehicles appears reasonable at early stages. On the other hand, fully automated vehicles will certainly be more expensive compared to a non-automated one (see next section), which will drive up the pre-discount insurance costs (at present around 30% of the costs of insurance premium is for the car, 70% for the person, Miller 2015). We use this information (discount on total premium, share of premium for the car and additional premium for higher ‘value’ of the car) to derive the additional insurance costs (or benefits) for the five private vehicle groups. Given the lack of any guidance in literature on potential breakdown of insurance costs in the commercial sector, we assume that the reduction in safety-related insurance premium is nullified by the increases due to higher value of the automated vehicles, i.e. the insurance costs remain the same as before.

3.7 Costs of full automation

Fully automated vehicles require additional equipment on board compared to the vehicles on road today. These include accurate GPS systems for vehicle positioning, LIDARs and video cameras for monitoring the vehicles' surroundings, ultrasonic sensors for monitoring close objects, odometry sensors for distance measurement, connectivity features to exchange information with the outside environment (other cars or infrastructure) and on-board computing systems. All of these add to the cost of the currently non-automated car, but the costs of the technology are expected to fall rapidly with further developments and mass production. For example, Google's first generation automated test vehicles were estimated to have equipment worth US$200,000 (£137,000). The most expensive equipment in those fully automated cars was the LIDAR, which cost around US$80,000 (£54,800). However, the supplier of those LIDAR, Velodyne, now offers a version that costs only around one-tenths that price, indicating a very steep learning curve in bringing down the costs (Yadron 2016). Tesla, on the other hand, has focused on a sensing system without any LIDAR, making it much cheaper (Tilleman and McCormick 2016). Tesla's currently *limited* automated drive capability on highways comes at an additional purchase cost of USD 4,000 (£2,750) only, although the sensors and hardware costs are not included in this. The test car made by the Oxford University also does away with LIDAR and include additional equipment worth £5,000, which was expected to fall down to £100, which appear overly optimistic (Lee 2013).

For commercial availability, KPMG (2015) estimates that full automation capability will cost around £5,000 in the UK by 2015, which possibly is quite optimistic. This is much lower than Bansal and Kockelman's (2016) assumption of US$30,951 (£21,200) premium in 2020 and US$23,950 (£16,400) in 2025, which appear to be too high for any commercial success. Although the cost of development will indeed be high, car manufacturers will likely initially absorb some of these additional costs in order to gain an initial market share, which can be crucial for introducing any new technology. For example, Volvo (Burke 2016) estimates that the 'software' will be sold at an additional USD 10,000 (£6,850). Therefore, possibly more realistic is Boston Consulting Group's (2015) prediction that the first commercially available fully automated cars to be available in the US market will command an additional price of US$9,800 (£6,700) in 2025. Most manufacturers, however, expect the first fully automated vehicles will become available around 2020 and costs are likely to be higher in 2020. We assume a 10% learning rate to bring down the costs between 2020 and 2025 and back-cast Boston Consulting Group's (2015) estimate to US$16,600 (£11,400) as the additional premium in 2020. With a more conservative 5% learning rate the premium becomes US$13,700 (£9,400) in 2020 for our sensitivity test. We also include a high cost scenario of £15,000 for sensitivity analysis. Taxis incur similar costs as private cars. For trucks, we assume a starting premium of £18,000, £14,000 and £11,500 for three scenarios for the small rigid trucks, increasing by £1,000 for larger trucks to account for additional sensors. These costs are annualized using the previous depreciation factors for TCO calculations. On top of the costs of automation, we include the additional costs of financing (costs of capital) using the same interest rates as in Tables 2-3.

3.8 Other cost elements

TCO also includes vehicle running costs such as maintenance and repair, tyres and parking. The effects of full automation on these are not well understood. Lower acceleration and deceleration in a fully automated vehicle may reduce wear and tear and as such reduce maintenance costs a little, yet during the early stages of introduction labour and equipment costs of repair could be high. Parking fees can also be avoided if fully automated vehicles drive and park themselves at locations with zero or lower parking charges, however some of the savings possible will likely be reduced due to the additional fuel costs of empty running. Although researchers have attempted to model some of these changes (e.g. Fagnant and Kockelman (2015)), we believe net changes in these individual cost elements will likely be small, and the uncertainties too large for these to be quantified. Also, these cost elements are only a small share of total costs of car travel (3.7% for the highest income quintile, 9.4% for the lowest) and excluding them from our calculations of changes in TCO are unlikely to substantially affect the final results.

3.9 Scenario definition

Following the discussions in the previous sections, the additional costs and benefits of full vehicle automation are included in the TCO through three scenarios: optimistic, baseline (most-likely) and pessimistic. The scenarios are defined in Table 6. In addition we run a sensitivity analysis with respect to several input variables.

[Table 6 here]

4. Results and discussion

4.1 Travel time costs

Table 7 presents the results for TCO calculations for private vehicles after including the cost of travel time to the out-of-pocket running costs of Table 2. It is clear that the cost of wasted driving time (using income-dependent VTTS) can be quite large in comparison to out-of-pocket running costs: between 40% in the lowest quintile to 64% in the highest quintile and 114% for the 99th percentile. Once we include these costs of wasted driving time to the annual TCO to get the true annual 'personal' cost of driving, it increases substantially, by £7,310 for the highest income quintile, and £13,030 for the wealthiest 1% of the population. While these additional time costs are generally not taken into account during vehicle purchase decisions now, given the driving time is wasted in a similar way in all vehicles, full vehicle automation is expected to change this picture.

[Table 7 here]

4.2 Changes in TCO in the baseline scenario

Table 7 also presents the TCO analysis for full automation for the baseline scenario of automation costs and benefits. Although automated vehicles will be quite expensive to begin with, once the additional capital costs are spread over the life of the vehicle (through depreciation), annual additional costs of technology are not dramatically high. For example, in the middle income quintile, full automation would add 33% to the out-of-pocket costs ((1710+194)/5856), but for highest income quintile it is only 17%. For low income quintiles full automation would still add a hefty 58% to the *out-of-pocket* costs. However, once we consider the TCO in a non-automated car to include the time costs, the additional purchase costs of technology alone becomes smaller in share: 10% for the highest income quintile ((1710+194)/18770) and 41% for the lowest income quintile. Fuel saving benefits do not appear substantial in the overall changes in TCO, neither does insurance related benefits or costs during the initial stages of introduction. However, as mentioned earlier, insurance costs could get much lower in later stages of market maturity, when automation becomes more widespread.

For our baseline case of 40% improvement in the usefulness of travel time in fully automated vehicles, the time use related benefits dwarf any fuel efficiency benefits. Since there is a wide variation in income and driving distances (hence, driving times too) between different income groups, the benefits also vary between the groups: from £532 in the lowest income quintile to £2,924 in the highest income quintile. Higher income households have a higher value of time, spend more time driving, and spend a higher share of travel for business-related reasons, therefore these households clearly benefit more through productive use of their time resulting from automation. The changes in TCO resulting from full automation shows that the average household in the highest income quintile (and, naturally in the 99th percentile) would have an £1,150 reduction in TCO, because of the large travel time use benefits. For the other four income quintiles, travel time use benefits do not overcome the additional costs of the technology – which are still high initially – and as such do not justify the purchase of fully automated cars during the initial years. Considering all the benefits and costs (out-of-pocket + travel time productivity), full automation still costs 30% more annually for a representative household in the lowest income quintile, but provides a benefit of around 6% in the highest income quintile.

For trucks and taxis, the TCO results for the baseline case are more striking (Table 8). Even in our relatively conservative baseline assumption of 60% reduction in driver costs, TCO falls substantially due to full automation: around £11,000 for taxis up to £19,000 for trailer-trucks; these represent reductions of 30% and 15% respectively. Although larger trucks benefit more in absolute reduction in TCO, in relative terms taxis and smaller trucks benefit more - this is because the driver costs are a larger share of TCO in smaller trucks and taxis.

[Table 8 here]

Overall, in both absolute and relative terms, the benefits from automation for commercial (taxi or freight) application is much larger than that for personal use. For example, a 30% reduction in TCO is expected for taxis or such mobility service providers, compared to a 14% reduction for the average household in the 99th percentile, which stands to benefit most among different income groups. Even trailer trucks, with the lowest return among all commercial applications could benefit from a 15% reduction in TCO from full automation. In absolute terms also, the benefits are much larger for commercial applications. This, in conjunction with the observation that commercial and business purchases put more emphasis on situational factors than psychological factors, indicates that full automation will likely be very attractive for these applications and they are likely to be amongst the earliest adopters.

4.3 Scenario analysis

Figs. 1 and 2 present the results of the TCO analysis for the three scenarios for personal and commercial applications. For personal vehicle use, the average households from all five income quintiles face an increase in TCO in the pessimistic case. This is primarily the result of the very low productivity improvements and higher technology costs in this scenario. However, households in the richest percentile still benefit from full automation, as evident from the reduction in their TCO. For the optimistic scenario - where usefulness of travel time is higher and costs of technology lower than the baseline case - households in the fourth and fifth quintile could start benefitting from fully automated vehicles, indicating a potentially larger initial demand in this case. The average household in the middle income quintile also marginally breaks-even in the optimistic scenario. Unlike private vehicles, all of the commercial applications considered enjoy larger and more robust benefits from full automation in all three scenarios (Fig. 2).

[Fig. 1 here]

[Fig. 2 here]

4.4 Sensitivity Assessment

For the passenger vehicles, the usefulness of the travel time (i.e. the reduction of VTTS) and the additional costs of technology are important elements of total travel costs in our approach of TCO analysis. Similarly, the elasticity of VTTS with respect to income also plays an important role in monetizing the travel productivity related benefits of fully automated vehicles. Given the scenario analysis above investigates only the combined effects of variations in these factors, it is important to test the sensitivity of our results independently with respect to these. Fig. 3 presents the sensitivity of our results with respect to the usefulness of travel time, keeping all other parameters the same as in the baseline scenario. It is clear that the benefits possible through the productive use of travel time in an automated environment have a large effect on the overall TCO results and the attractiveness of these vehicles for personal use. At a very high level of productivity (80%) of in-vehicle travel time (i.e. a large reduction in VTTS) fully automated vehicles can break-even for an average household in the third income quintile (although by a small amount), whereas at a low level of productivity (25%), only the average household in the 99th percentile would find automation reasonably beneficial from a TCO perspective. Given the importance of this parameter on the TCO and thus potential adoption, it would be useful to conduct primary research on how the value of in-vehicle time could change in the presence of full vehicle automation.

[Fig. 3 here]

The second key parameter is the additional costs of vehicle automation (Fig. 4). Within the range of our three scenarios (£9,400 to £15,000) for private vehicles, the TCOs do not switch from positive to negative or vice versa for any of the income groups (except for the 4th income quintile at a cost of £9,400), indicating relatively low sensitivity – possibly because these costs are spread over the life of vehicle use and the range of uncertainty is not large. We also test an additional premium of £4,000 for full automation: although it is highly unlikely to happen during the early phases of introduction – which was our main focus – additional premium for a mass produced fully automated vehicle may need to eventually come down to this level (similar to the costs of high end driver assistance and collision avoidance now). At such a low premium, full automation can break even for an average household down to the 2nd lowest income quintile, indicating the potential for a high uptake if costs can be brought down significantly through mass production and the associated learning.

[Fig. 4 here]

Depreciation is another parameter which has some uncertainty associated with it, since there is currently no second hand market for fully automated vehicles, which determines the salvage value. At a higher depreciation the additional costs of automation is larger, as such the TCO of fully automated vehicles are also larger. As shown in Fig. 5, the results do not appear much sensitive to the alternate depreciation rates – only the households in the 4th income quintile switches to a beneficial TCO when depreciation rate is lower. Closely related to depreciation is vehicle holding period. Fig 6 presents the effects of holding period and a depreciation consistent with that holding period. The base case scenario of 4 year holding with 60% depreciation is compared with a 10 year holding period with full depreciation at the end of use. As expected, a longer holding period spreads the additional costs over longer duration and thus makes it more affordable. The results for the income groups are not too sensitive though, with a switch only for the households in the 4th income quintile.

[Fig. 5 here]

[Fig. 6 here]

The results are also not very sensitive to the income elasticity of VTTS (Fig. 7). Although absolute numbers change for the average households in each income group, the households do not switch from a reduction in TCO to an increase in TCO or vice versa.

[Fig. 7 here]

5. Conclusions

This paper sought to answer the question, where does full automation offer the greatest benefits, personal or commercial applications? We used TCO analysis to compare the costs of owning and driving fully automated vehicles with non-automated vehicles for personal cars, taxis and trucks. It does appear that the benefits of automation, as a ratio of initial TCO, is much higher for commercial applications and it makes sense for them to adopt full automation earlier. However, it is still not clear when full automation will be available in trucks, which results in some uncertainty. There are also potential logistic challenges that may need to be overcome (e.g. loading and unloading at origin and destination). On the other hand, there is a 30% shortage of skilled drivers in the UK trucking sector (All party parliamentary group for freight transport, 2015) and a 10% shortage in the US (Carey 2014), indicating full automation could be very attractive for this sector.

While full automation in personal vehicles does offer substantial benefits for households in the wealthiest percentile, these benefits are still small in comparison to the benefits for commercial taxi operations. As such, taxis and such mobility service providers (private hire, on-demand vehicles) appear to be the prime candidate for early adoption of full automation in smaller vehicles. It may well be possible that traditional taxis, ride hailing services (e.g. private hire cabs in the UK or Uber or Lyft) and car clubs could all merge to provide fully automated mobility on-demand services. It is therefore no wonder that Uber and Lyft are actively involved in the development of vehicle automation, with Uber having started testing its driverless fleet in Pittsburgh, USA this year (BBC 2016). However, automated driving in commercial applications like taxis or trucks is likely to face some political opposition due to the potential for large scale unemployment among the commercial drivers. For example, there were 297,600 drivers of taxis or private hire vehicles in England alone and around 400,000 goods vehicle drivers in the UK (Department for Transport 2016). In the US, the trucking sector employs around 3.5 million professional drivers (truckinfo.net 2016), while Uber alone currently has more than a million drivers globally (BBC 2016). All of these jobs will likely be at risk when automation becomes widespread.

An important question in the adoption and uptake of vehicle automation is whether its introduction will follow an ‘everything somewhere’ or ‘something everywhere’ model. In an ‘everything somewhere’ model full automation in a limited spatial scale (e.g. taxis or small city cars in low speed urban environment) becomes available first. This is the model pursued by Google and Uber. On the other hand, in a ‘something everywhere’ model, high automation – whereby cars can drive without any human intervention in motorways or limited specific conditions – would be introduced first, at a wide spatial scale. It appears more likely that high automation will be available before full automation in urban environments because of the complexity of urban driving, and mainstream automakers appear to favour this approach. Such highly automated vehicles would still be attractive and beneficial to the high income groups from a TCO perspective as the time use related benefits can still be realized in long-distance travel, but may not be attractive for taxi or mobility service operations, which primarily operate in an urban environment. In such a scenario, niche buyers and users from the highest income groups could be the earliest adopters of high automation and then full automation as a result of their familiarity with high automation. Still, as we demonstrate here, mobility service providers can have large benefits, and 'everything somewhere' model could yet appear in parallel or even earlier. As such, the supply side is immensely important in determining the early adopters.

Within personal use application, we recognized the heterogeneity in the benefits to different socio-economic groups and conduct the TCO analysis for average representative households in different income quintiles (and the wealthiest percentile). The use of average household from each quintile simplifies our calculation, but has some limitations. Each household's travel pattern and vehicle choices are unique and non-income factors can be correlated with income (e.g. high income households are overrepresented in London). As such an average cannot do justice to the variations that are possible within each income quintile. However, it is quite possible – and recommended – to apply this TCO approach to the whole sample of NTS car-owning households to get individual travel pattern and time spent driving in order to understand the distribution of potential users for whom full automation becomes attractive. What is clear from this analysis is that households that have a higher value of time and that drive more have more to benefit from vehicle automation. This finding is not only UK specific and will likely hold in general. For example, in the US where driving distances and income are both higher than in the UK, full automation could become beneficial to households in lower income quintiles, too.

TCO analysis is useful in understanding the potential early adopters or potential adopters in general, yet it does not provide the full picture. A beneficial TCO analysis alone does not guarantee the purchase of automated vehicles, as there are many other factors in play. In the context of vehicle automation, these other factors can be quite important, too. For example, full automation may not be very useful to those with motion sickness, since the productivity benefits may not be realized by them. In the opposite spectrum, it is also likely that the elderly and the disabled – those who cannot drive now – may find full 'driverless' automation immensely beneficial, much beyond any financial advantages revealed by the TCO. Giving up the control of driving the vehicle to a computer and acceptance of the 'driverless' technology is another important barrier that can affect the adoption of these vehicles. A simple TCO analysis cannot capture any of these effects and the combination of TCO and these 'other' situational and psychological factors will determine the adoption rate and willingness to pay for vehicle automation. However, it is a reasonable proposition that, *ceteris paribus*, households or businesses with a larger reduction in TCOs will be willing to adopt earlier and willing to pay more for full vehicle automation compared to those with a smaller reduction or an increase in TCOs.

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Fully automated vehicles: A cost of ownership analysis to inform early adoption

Figures

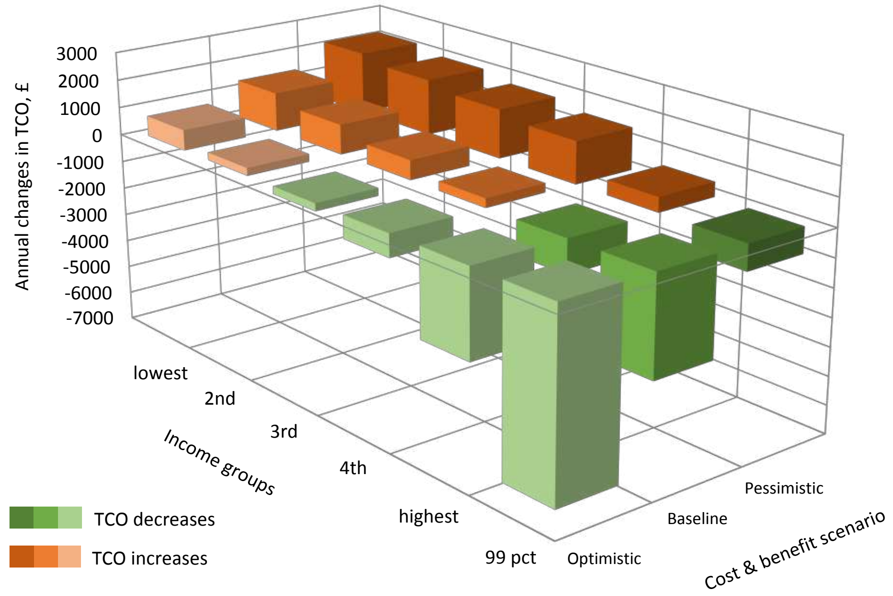

Fig. 1 Changes in TCO for private vehicles under different automation cost and benefit scenarios

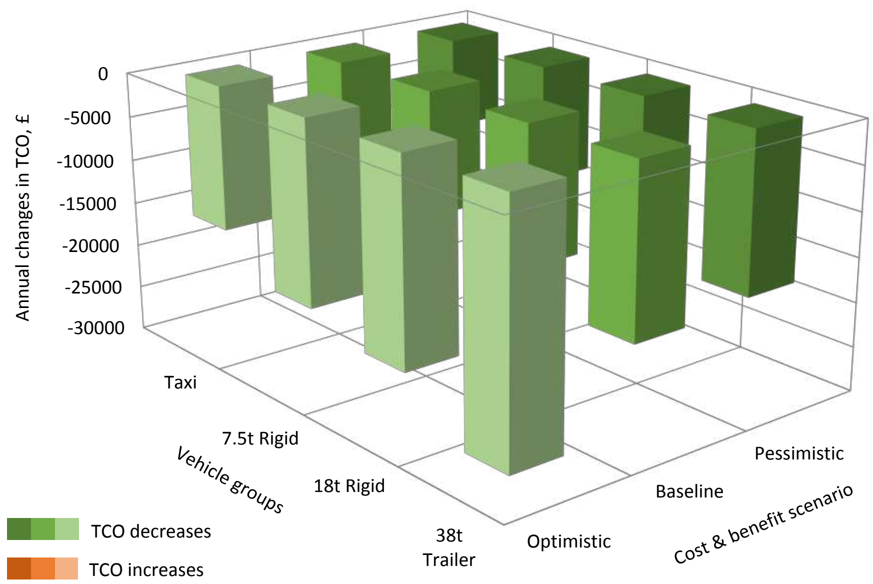

Fig. 2 Changes in TCO for commercial vehicles under different automation cost and benefit scenarios

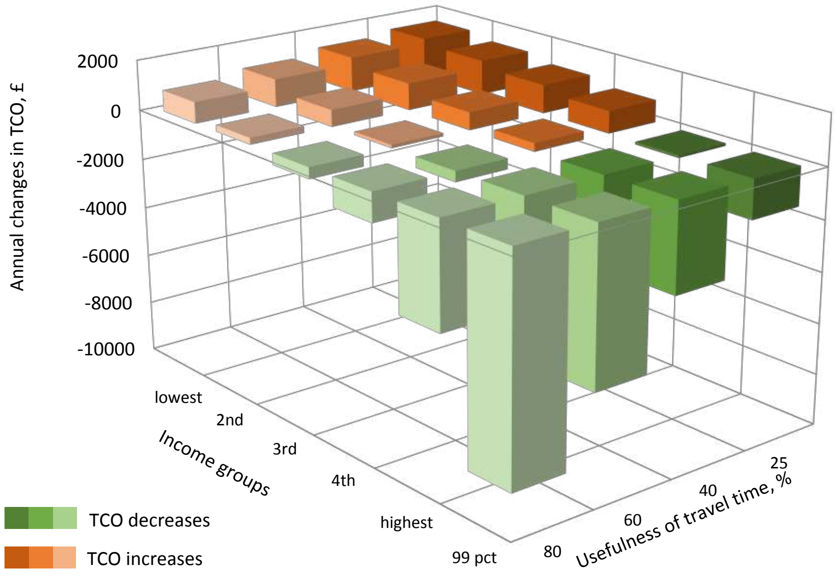

Fig. 3 Sensitivity of changes in TCO for private vehicles with respect to usefulness of travel time

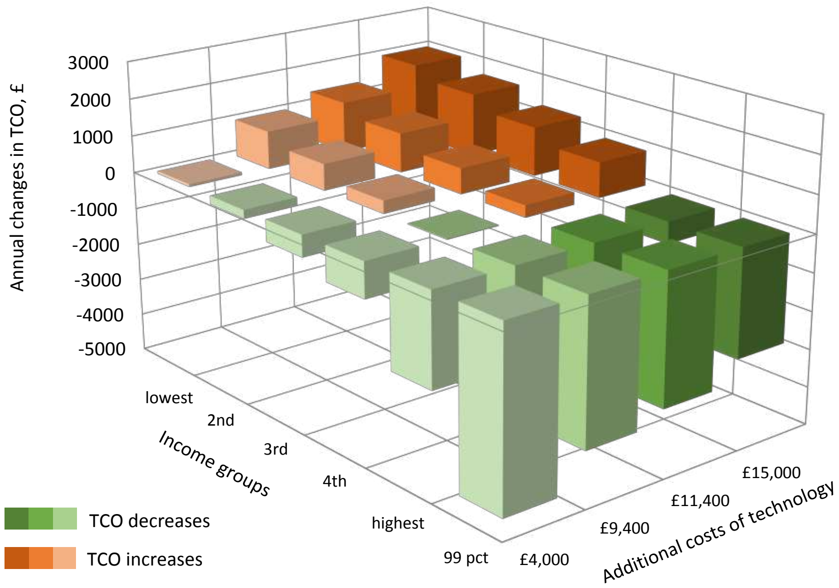

Fig. 4 Sensitivity of changes in TCO for private vehicles with respect to additional cost of technology

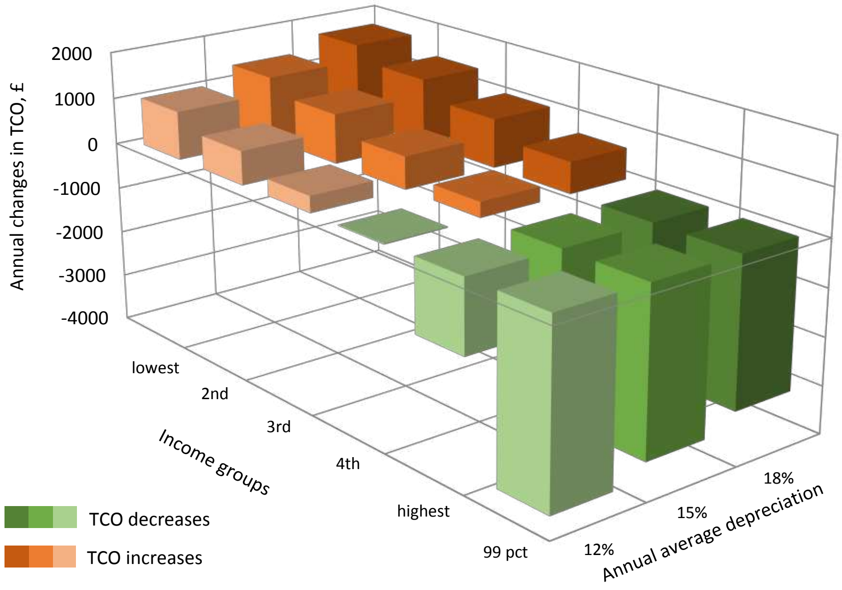

Fig. 5 Sensitivity of changes in TCO for private vehicles with respect to depreciation

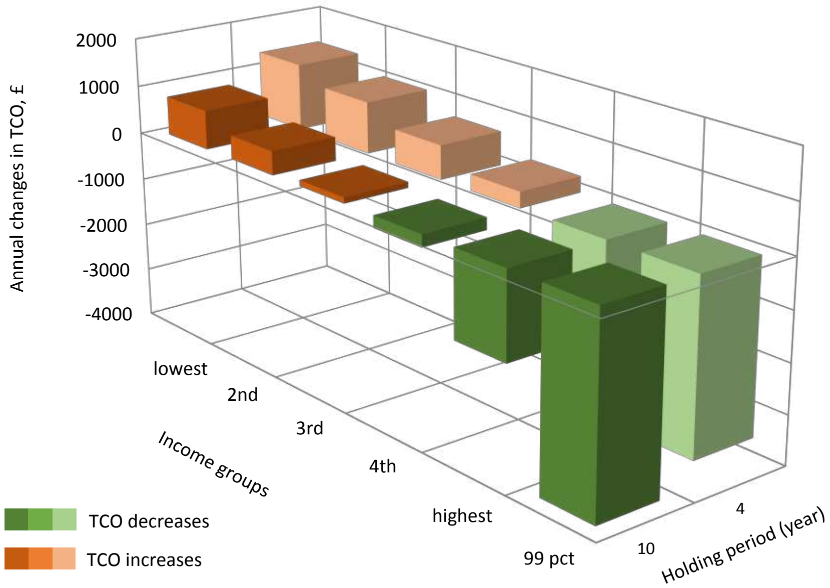

Fig. 6 Sensitivity of changes in TCO for private vehicles with respect to holding period

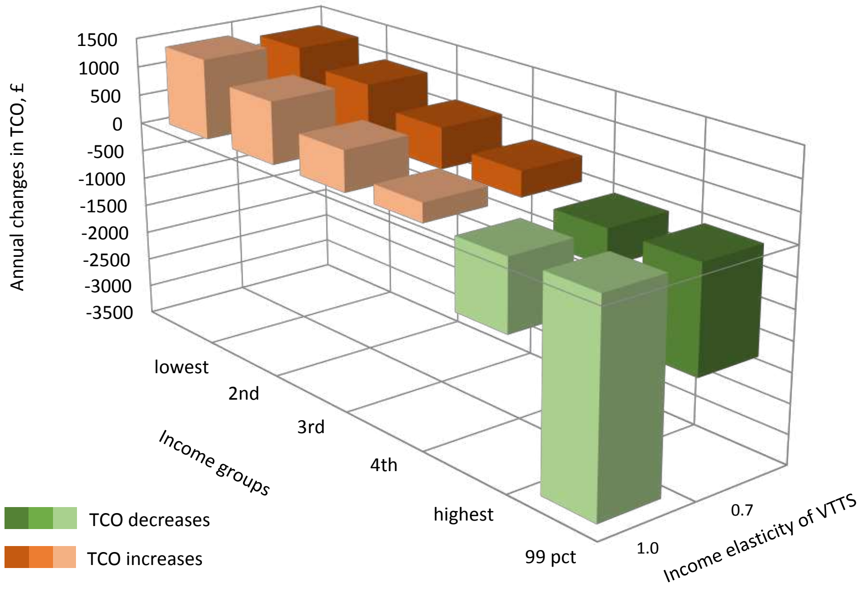

Fig. 7 Sensitivity of changes in TCO for private vehicles with respect to income elasticity of VTTS

Fully automated vehicles: A cost of ownership analysis to inform early adoption

Tables

Table 1. Average driving distances and driving hours in car-owning households for five income quintiles

	Lowest quintile	2nd quintile	3rd quintile	4th quintile	Highest quintile
Driving distance per main driver (miles/year)	5,015	5,533	6,591	7,484	8,080
Driving distances per car (miles/year)*	6,394	6,950	7,710	8,512	9,329
Driving hours per main driver (hours/year)	237	249	274	291	297
Driving hours per car* (hours/year)	302	313	321	331	343
Average household income (£/year)	15,504	23,173	28,358	36401	60,027
Household size	2.8	2.9	2.7	2.7	2.4

Source: derived from National Travel Survey (2014), microdata for England

* A private vehicle may be driven by others in the household, in addition to the main driver

Table 2. Breakdown of annual costs of private vehicles

Vehicle costs	Up to £13000	£13000 - £18000	£18000- £25000	£25000 - £32000	Over £32000
Miles driven*	6,394	6,950	7,710	8,512	9,329
Standing charges, £/year	*2,223*	*3,180*	*4,291*	*5,673*	*9,048*
VED (Road Tax)	110	145	180	283	609
Insurance	360	409	481	571	762
Cost of capital	203	251	355	494	877
Depreciation	1,500	2,325	3,225	4,275	6,750
Breakdown cover	50	50	50	50	50
Running costs, pence per mile	*16.71*	*18.85*	*20.30*	*22.32*	*25.85*
Petrol/Diesel	9	10.82	12.02	13.23	14.82
Tyres	1.37	1.57	1.94	2.32	3.35
Service labour costs	2.1	2.07	2.09	2.04	2.34
Replacement parts	2.24	2.39	2.25	2.73	3.34
Parking and tolls	2	2	2	2	2
Total out-of-pocket cost, £/year	*3,291*	*4,490*	*5,856*	*7,573*	*11,460*

Source: AA 2016 and NTS (2014)

* assuming driving distances for each quintiles from Table 1 corresponds to the 5 vehicle groups

Table 3. Cost breakdown for commercial operations, (trucks and taxis) in the UK

Vehicle	Taxi	7.5 Tonne Rigid truck	18 Tonne Rigid truck	38 Tonne Trailer-truck
Vehicle price	20,000	38,000	58,000	63,000
Depreciation Period	5	5	6	6
Miles per annum	33,000	45,000	50,000	73,000
Standing costs, £/year	*30,690*	*44,005*	*54,130*	*72,730*
Wages	22,500	27,500	29,000	33,000
Depreciation	3,870	7,600	9,650	10,500
VED Licences	220	165	650	1,200
Vehicle Insurance	1,500	1,600	2,100	3,400
Trailer				2,730
Interest on Capital	600	1,140	1,730	1,900
Overhead per vehicle	2,000	6,000	11,000	20,000
Running costs, p/mile	*18*	*39.74*	*51.31*	*74.24*
Fuel	12.02	30.94	39.61	58.24
Tyres	1.94	1.70	2.70	4.50
Repairs & maintenance	4.34	7.10	9.00	11.50
Total out of pocket cost, £/year	*36,729*	*61,888*	*79,785*	*126,925*

Source: RHA (2016), AA (2016)

Table 4. Value of travel time saved for different quintiles and trip purposes

	Lowest quintile	2nd quintile	3rd quintile	4th quintile	Highest quintile	99th percentile
Work/business, £/hr	13.06	18.85	24.78	31.81	59.01	105.19
Commute, £/hr	3.91	5.65	7.42	9.52	17.67	31.50
Other, £/hr	3.47	5.01	6.59	8.46	15.69	27.97

Source: own calculations from Department for Transport (2015c), Table 1, and Fosgerau (2005)

Table 5. Share of driving for different quintiles and trip purposes

	Lowest quintile	2nd quintile	3rd quintile	4th quintile	Highest quintile	99th percentile*
Work/business, %	8.44	8.71	10.85	9.53	11.06	11.06
Commute, %	23.25	28.17	35.46	40.03	41.34	41.34
Other, %	68.66	63.08	53.41	50.04	47.72	47.72

Source: derived from National Travel Survey 2014 microdataset (Department for Transport 2015b)
* assumed the same as 5th quintile due to small sample size in NTS

Table 6. Cost and benefit input in different scenarios

	Optimistic	Baseline	Pessimistic
Costs of automation			
38t Trailer truck	12,500	15,000	20,000
18t Rigid truck	12,000	14,500	19,000
7.5t Rigid truck	11,500	14,000	18,000
Taxi	9,400	11,400	15,000
Private car	9,400	11,400	15,000
Driving time benefits			
Commercial driver salary reduction	80%	60%	60%
Private car productive use of time	60%	40%	25%
Fuel efficiency benefits	10%	5%	5%

Source: own calculations

Table 7. TCO for fully automated vehicles for different income groups for baseline scenario

	Lowest quintile	2nd quintile	3rd quintile	4th quintile	Highest quintile	99th percent
Total out-of-pocket cost in current car, £/year	3,291	4,490	5,856	7,573	11,460	11,460
Cost of wasted travel time in current car, £/year	1,329	2,000	2,833	3,666	7,310	13,030
TCO current car, £/year	4,620	6,490	8,689	11,239	18,770	24,490
Annualised cost of automation, £/year	1,710	1,710	1,710	1,710	1,710	1,710
Additional interest on capital, £/year	194	194	194	194	194	194
Additional insurance cost/benefit, £/year	26	-10	-35	-59	-106	-106
Annual fuel saving, £/year	-29	-38	-46	-56	-69	-69
Productive use of travel time, £/year	-532	-800	-1,133	-1,466	-2,924	-5,212
Changes in TCO, £/year	1,370	1,057	689	322	-1,195	-3,484
% changes in TCO	29.6	16.3	7.9	2.9	-6.4	-14.2

Source: own calculations

Table 8. TCO for fully automated commercial vehicles

	Taxi	7.5 Tonne Rigid truck	18 Tonne Rigid truck	38 Tonne Trailer-truck
TCO current, £/year	36,729	61,888	79,785	126,925
Annualised cost of automation, £/year	2,280	2,800	2,417	2,500
Additional interest on capital, £/year	342	420	435	450
Annual fuel saving, £/year	-198	-696	-990	-2,126
Driver salary reduction, £/year	-13,500	-16,500	-17,400	-19,800
Changes in TCO, £/year	-11,076	-13,976	-15,539	-18,976
% changes in TCO	-30.2	-22.6	-19.5	-15.0

Source: own calculations