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Too Far? Autonomous vehicles, travel demand, and carbon dioxide emissions in Sweden

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ABSTRACT

This article envisions that by the middle of this century fully self-driving Autonomous Vehicles (AVs) are available for private use. By considering how AVs can affect the utility of being in the vehicle, and accounting for the utility of being able to transport oneself to and from various locations, we derive the consumer surplus of having an AV and evaluate that against the cost of adopting the technology. This break-even calculation is used to evaluate AV purchase and consequent impacts on increase in travel demand and lifecycle CO_2 emissions for different income groups for different assumptions concerning the Value of Travel Time, transport demand elasticity, AV technology costs, interest rates, and the possibility to work in the car or not. The modelled results show that all income groups purchase AV given low technology cost, and the highest income groups purchase AV under most conditions. Changes in demand elasticity and the value of travel time have the largest effect on vehicle miles traveled, which could be as much as 50 additional kilometers daily per driver. Even in a scenario consistent with the Paris Agreement, this implies an annual carbon footprint of 0.42 – 0.86 metric tons of CO_2 per driver from personal car travel in Sweden.

1. Introduction

Sweden has set the goal of reaching net zero CO_2 equivalent territorial emissions (carbon neutral) by 2045, and negative emissions thereafter (Bonde et al., 2020). The country's coalition government has a strong political agreement about creating targets for consumption-based emissions (Nohrén et al., 2022). One area that is specifically targeted is transportation. The market share of Battery Electric Vehicles (BEVs) in Sweden is growing, but the production of BEVs is associated with a certain non-zero amount of carbon dioxide emissions from their supply chain (Arendt et al., 2022; Morfeldt et al., 2021).

The ongoing development of Autonomous Vehicles, or AVs, is currently a major trend in the Swedish and international transportation sectors. Today, some vehicles already have technology that makes it possible for the driver to select some version of automated driving mode, and the UN and the European Union have created regulations to legalize automated driving mode at certain levels, and under certain conditions (European Commission, 2022; UNECE, 2022). In Sweden, the Government has recognized the large impact that AVs could have on the transportation system, on individual travelers, and on urban infrastructure, and is in the process of researching policies to govern these potential changes (Hammes, 2019; Pernestål et al., 2020; Wallsten et al., 2021). However, Sweden's implementation of the UNECE regulations means that individuals and companies currently need to apply to the Swedish Transport Agency for permission to operate automated vehicles on public roads (Swedish Transportation Agency, 2022).

In this study, we envision that in 2045, when Sweden aims to be carbon-neutral, self-driving AVs are reliable, and available for private use. We define AV as a level 4 or 5 vehicle according to the SAE guidelines [1]. What is critical for our analysis is not the existence of 100 % autonomy, but that the car can be operated in an autonomous mode for essentially all driving circumstances, thereby freeing the driver of driving tasks and allowing them to do something else while in the vehicle. To analyze the impact that these vehicles could have on travel demand and upstream supply chain emissions in such a future, one needs to consider the way that time spent travelling in cars is subjectively valued, or the Value of Travel Time (VoTT) (Becker, 1965; DeSerpa, 1971). If the car can drive reliably by itself under most conditions, in theory drivers will be able to make use of their time in the

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vehicle by doing work-related tasks on a laptop computer or other device, watching television, or even sleeping (Pudāne et al., 2018; Wadud and Huda, 2019). We aim to examine an introduction of AVs where there are no policies in place to promote car- or ride-sharing, or other measures to limit travel demand, to improve the understanding of how AVs, through their impact on VoTT, could affect travel demand and associated emissions in Sweden.

In a high-income country such as Sweden, the VoTT typically makes up a large portion of the overall cost of travelling, known as the Generalized Travel Cost (GTC) (Small and Verhoef, 2007). Following the general logic of price responsive demand, if the cost of travel decreases (*ceterus paribus*), then the demand for travel will likely increase. Thus, if the magnitude of VoTT decreases, causing the GTC to decrease, the demand for travel, and its related emissions, will increase.

1.1. *Research questions*

This study contributes to the existing body of knowledge on AVs and the effects of changes in VoTT by explicitly evaluating the willingness to adopt AV technology and, given that adoption, calculating the impact of vehicle kilometers travelled and the resulting carbon footprint. We do this by including work and leisure time in the same model framework, considering that AVs can affect the value of the (dis-)utility of being in the vehicle, and accounting for the utility of being able to transport oneself to and from various locations. From this, we derive a consumer surplus calculation that is based not only on changes in GTC, but also on the utility gained from induced travel. This is then used for a break-even calculation that informs AV purchase, and the related increase in travel demand and lifecycle CO_2 equivalents emissions.

In the literature review section, we catalogue selected previous research on the measurement of and possible changes in VoTT, as well as the relationship between VoTT and income, and VoTT and travel demand, respectively. To our knowledge, the user benefit of induced travel has not been combined with the interrelated mechanisms of the cost of technology and changes in VoTT in an integrated framework to estimate the proportion of a population that is willing to purchase the technology, the potential impact on travel distance and CO_2 emissions. Thus this article makes a contribution to modelling the travel demand impacts of AVs based on empirical travel survey data from a heterogeneous population with differentiated VoTT.

The research questions that we seek to answer are:

What is the relationship between income, VoTT, induced travel, and break-even costs for AV purchase?

How could AV purchase affect travel distance and its associated carbon footprint for individuals in Sweden?

This paper is structured as follows: Section 2 is a Literature Review, Section 3 details the Methods and Data used, Section 4 shows the Results, Section 5 is a Discussion, and Section 6 is the Conclusion.

2. Literature review

2.1. *VoTT history and measurement*

VoTT can be described as how much a person values the time they spend travelling, usually presented in monetary units per unit time, and is an important part of the economic appraisal of transportation infrastructure projects (Ortúzar and Willumsen, 2011). The concept of value of time dates back to Becker who suggested that a person's opportunity cost of time was equal to their wage rate (Becker, 1965). The value of time concept was later reformulated and developed by Johnson (1966), Oort (1969) and De Serpa (1971) to consider time spent travelling, or VoTT.

Today, more qualitative factors are being taken into account when calculating VoTT, moving away from Becker's wage-based estimations (Jain and Lyons, 2008). *The VoTT for different trip purposes* – for example shopping, commuting, driving children to various activities – is now considered to be important for determining an accurate value (Correia et al., 2019), as well as the level of comfort that the person experiences during travel (Kouwenhoven and de Jong, 2018).

The VoTT differs due to the travel situation and comfort, as well as in terms of the statistical approach used to estimate the number *(*Wardman et al., 2016*)*. For example, for commuting trips, Börjesson and Eliasson (2014) estimated the VoTT at 9.8 €/hour in Sweden, Correia et al. (2019) at 7.47 €/hour in Netherlands and Wardman et al. (2016) at 7.12 €/hour in the UK. Furthermore, the VoTT rate can be estimated from stated preference surveys as well as revealed preference studies. Wardman et al. show in their 2016 meta-analysis of VoTT studies in Europe that there are differences between revealed and stated preferences for VoTT, and that revealed preferences tend to be somewhat higher in magnitude.

The most recent official evaluation of VoTT in Sweden was compiled in 2010 (WSP, 2010). A series of stated preference surveys between 2007 and 2009 were used to determine VoTT rates for different segments of the Swedish population, and how those rates differed by trip purpose and safety levels of the traffic environment. The VoTT for commuting trips is generally found to be higher than for other types of trips (Swedish Transport Administration, 2020).

2.2. *VoTT and income*

The elasticity of VoTT with respect to income is uncertain, but there is some empirical support for it being around unity or somewhat less (Mackie et al., 2001; Wardman et al., 2016). Many transport authorities assume an income elasticity of unity when accounting for income growth in the analysis of long-term projects (UK Department for Transport, 2019). In Sweden, Börjesson and Eliasson (2014) analyzed two VoTT studies that were conducted 13 years apart and found that elasticity with respect to VoTT increases with income, being close to zero when below the median income and unity or higher above the median income. Wadud (2017) and Taiebat et al. (2019) differentiate VoTT according to income level using a VoTT income elasticity of unity in the context of AVs. Thus, we adjust VoTT to reflect different income quintiles of that society, using the Swedish Transport Administration's VoTT for the median income quintile and a VoTT income elasticity of unity.

2.3. *Changes in VoTT due to AVs*

When analyzing the impact that AVs may have on VoTT one needs to consider both the reason for the impact, and its magnitude. The reason for the impact depends on what the traveler can do in the vehicle, and the magnitude depends on the utility they gain from that activity. It is important to remember here that there are no revealed preference studies available yet for VoTT in AVs, but there is a wealth of research based on different proxies and stated preference approaches (Bansal and Kockelman, 2017; Gao et al., 2019; Harb et al., 2018; Pudāne et al., 2019; Wadud and Huda, 2019; Wardman et al., 2019; Yap et al., 2016). Correia et al. (2019) found that the reduction in VoTT for commuting trips is likely to be higher than the reduction in VoTT for other types of trips.

The key reason for a reduction in VoTT is that the former driver can now use the time in the vehicle for something that they consider to be useful. Some authors suggest that changes in subjective well-being may cause notable changes in VoTT (Singleton, 2019), as travelers gain utility from relaxing or enjoying the passing scenery. Others suggest that the changes will come from being able to multitask in the vehicle (Malokin et al., 2019). This level of impact on VoTT is also dependent on the traveler using their travel time for work, which might not always be the case (Cyganski et al., 2015; Wadud and Huda, 2019).

The size of the impact on VoTT is even more difficult to approximate since there is no actual on-road experience of operating an AV in an everyday situation and it is difficult to generalize insights from stated preference studies that concern a yet-to-be experienced technology. Many articles present different assumptions regarding VoTT reduction, but because the size of the reduction depends largely on the scenario context, the assumptions range from 0 % to 100 % reductions (Singleton, 2019). However, without considering AVs explicitly, the International Transport Forum suggests that VoTT could be reduced by 20–25 % if the traveler is able to put their time to worthwhile use (ITF, 2019). In addition, stated preference studies have found that commuting VoTT can be significantly reduced when driving an autonomous vehicle: Gao et al. (2019) posit a 13–45 % reduction during commuting depending on different conditions, Steck et al. (2018) found a 31 % reduction compared to driving manually, and Kolarova et al. (2019) found a 41 % reduction compared to driving manually. Zhong et al. (2020) found a range of reductions from 18 −32 % in VoTT during commuting with an AV, depending on the urban density of the driving situation.

2.4. VoTT and Travel Demand

Several studies have modelled the potential impacts of AVs using similar frameworks as the one used here. Wadud et al. (2016) did an analysis based on the potential relative reduction in VoTT cost for UK drivers together with assumptions about GTC elasticities. They estimated a 4 −60 % increase in travel demand due to AV purchase. Taiebat et al. (2019) empirically estimated the demand function as well as VoTT from the US National Household Travel Survey (NHTS). They estimated a 2 −47 % increase in travel demand, based on assumptions concerning how AVs would affect fuel economy and VoTT (Taiebat et al., 2019).

These studies build on the assumption that AVs will be adopted by the whole population. However, Wadud (2017) analyzed under what conditions (costs and income level) AVs would pass a break-even Net Present Value calculation and found that this depends on income level since the VoTT is dependent on income.

3. Methods and data

This section explains the components of the demand model and the data used to populate it.

3.1. Generalized travel cost

Generalized Travel Cost (GTC) captures the full levelized cost of traveling per unit distance. GTC can be broken down into fixed cost, being vehicle depreciation with respect to calendar age; and variable cost, being fuel cost, maintenance, and VoTT. Travel purpose and income are captured by VoTT, as was explained in Section 2. While the use of GTC for estimating changes in travel behavior has been criticized by some (Wardman and Toner, 2018), it is widely used for transport modelling by various national authorities (Ortúzar and Willumsen, 2011; Swedish Transport Administration, 2020; UK Department for Transport, 2019).

There are two key aspects of GTC that will change because of AVs: VoTT and the capital cost of the vehicle. We assume that everyone in the population that we are modelling already owns a car, so the change in capital costs comes from the purchase of an equivalent car that has AV technology. Thus, it is the cost of AV technology that makes up the difference in capital cost. These costs are likely to be associated with the sensors (lidars, radars, cameras, etc.) and the processing power needed for automated driving (Wadud, 2017). There is also a great deal of uncertainty around the decrease in cost of AV technology over time compared with raised consumer expectations in terms of the vehicle performance (Compostella et al., 2020).

A reduction in GTC tends to induce more travel, in the same way that the demand for a normal consumer good (i.e. travel) tends to increase if the price (GTC in our case) drops. This mechanism is clear from, for example: (1) the rebound effect, in which increased fuel efficiency tends to lead to a lower marginal cost of traveling, which in turn leads to increased mileage (Small and Van Dender, 2007); and by (2) the traveling induced by new infrastructure, where the reduced time of going from A to B tends to generate more travel (Goodwin, 1996). In the latter example, the general cost of traveling is reduced due to reduced travel time cost per km since the speed is higher. Hence, the rebound effects and the induced travelling phenomena are interlinked (Hymel et al., 2010; Small and Van Dender, 2007).

3.2. Break-even estimate for purchasing an AV

To simplify and to estimate the willingness to pay for an AV in a partial equilibrium framework, we assume that the cost of the AV technology is marginal in relation to total consumption and the total use of time, consistent with standard partial equilibrium model assumptions (Mas-Colell et al., 1995)[2]. This means that the marginal utility of consumption remains constant and the VoTT remains independent of travel time. Consequently, the monetary value of the utility obtained from AV use, i.e. the Consumer Surplus, can easily be estimated through the reduction in VoTT and the benefit of additional travel using the ‘rule of half’ (European Commission Ed, 2015).

The impact on traveling distance, d_{CAV}, can be estimated using an isoelastic demand function.

$$d_{CAV} = d_0 \left(\frac{k + \frac{VoTT_{CAV}}{s}}{k + \frac{VoTT_0}{s}} \right)^{\varepsilon} \tag{1}$$

where ε is the long-run variable cost elasticity with respect to GTC, d is daily distance traveled by car, k is the variable travel cost per unit distance, and $\frac{VoTT}{s}$ is VoTT per unit distance. *0* represents the situation without AV adoption, and AV with AV adoption.

The willingness to pay, i.e. the change in Consumer Surplus, obtained with an AV (ΔCS_{AV}) can be estimated as the reduction in VoTT multiplied by the current distance travelled plus the benefit obtained from the induced travel, which can be estimated with the rule of half (European Commission, 2015; Williams, 1976). The rule of half implies a linearization of the isoelastic demand curve between the equilibrium point obtained with the conventional vehicle and the equilibrium point obtained with an AV. Hence, the willingness to pay for an AV can be estimated as

$$\Delta CS_{CAV} = \frac{VoTT_0 - VoTT_{CAV}}{s} \bullet d_0 + \frac{\left(\frac{VoTT_0 - VoTT_{CAV}}{s} \right) \bullet (d_{CAV} - d_0)}{2} \tag{2}$$

The second term on the right-hand side is the increase in the willingness to pay for an AV depending on the induced travel. This has not been considered in previous AV purchase studies (Wadud, 2017a; Wadud and Mattioli, 2021), in which only the first term on the right-hand side has been considered.

Using heuristics, this can be understood as follows: the light grey section in Fig. 1 shows the Consumer Surplus for a conventional vehicle, CS_{CONV} (for a linear demand curve). The light grey dotted section shows the benefit of the VoTT reduction given that the travel distance remains fixed. The dark grey dotted section shows the user benefit resulting from induced travel with AV. Both dotted sections taken together are the Consumer Surplus with AV, CS_{AV}.

We assume that a person will purchase an AV if the CS_{AV} is larger than the technology costs. In other words, the purchase decision is based on an individual Cost Benefit Analysis (CBA), similar to the reasoning used by Wadud (2017).

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[2] As discussed below, we assume that the levelized AV cost is between SEK 8 and 134 per day (depending on the interest rate and technology cost assumptions). In most cases, these numbers are a relatively small share of the expected income in 2045 in the population considered in the analysis.

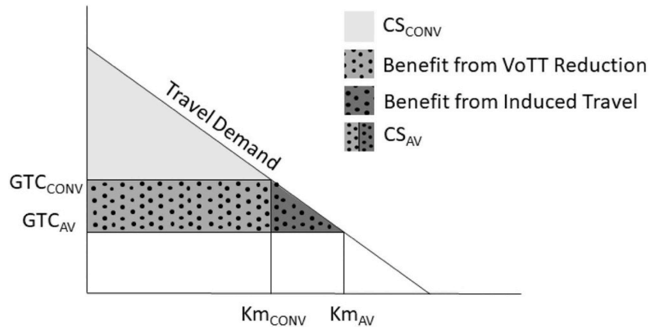

Fig. 1. The Rule of Half, showing the theoretical relationship between GTC, travel distance, and travel demand.

3.3. The numerical model and its parameterization

3.3.1. Overview

Based on the modelling approach presented in Section 3.1, we develop a numerical model to estimate the share of drivers within a population that would be willing to purchase an AV. We make a range of different assumptions about the impact of AVs on VoTT, the cost of AV technology, travel demand elasticity with respect to GTC, and the interest rate used for the car purchase.

According to Eq. (2), an AV will be chosen if the increase in Consumer Surplus for AV technology is equal to or larger than the levelized technology cost. The estimation is done for 10 representative drivers, depending on income quintile and the possibility of remote working (i.e., working in the car). See below for further information. The maintenance and fuel costs for a BEV are based on calculations made with data from the Swedish Transport Administration's ASEK 7.0 report, which sets out the "principles and values that are recommended to be used in social cost-benefit analyses in the Swedish transport sector" (Swedish Transport Administration, 2020, p. 352). We assume that all drivers have a maintenance cost of 0.20 SEK per kilometer, and a fuel cost (for electricity) of 0.59 SEK per kilometer (Swedish Transport Administration, 2020). In reality, the maintenance cost would differ between different vehicles, but because maintenance is a relatively small proportion of the GTC we leave this potential difference aside.

Note that we only consider personal costs and benefits for the driver of the vehicle. We do not consider the costs and benefits for any other potential users of the car, for example other household members), nor do we consider external costs such as those related to congestion and emissions.

3.3.2. Technology cost assumptions

The cost of AV technology is critical when considering its adoption, but it is very uncertain what the necessary AV technology costs today and how that cost will develop over the coming decades. For example the CEO of Volvo Cars has said that level 4 technology would add USD 10,000 to the vehicle cost in 2021 (Edelstein, 2017; Lesage, 2016). Further, the price of the "self-driving capability" for newly ordered Teslas as of February 2020 was USD 7000, and while technically these vehicles are level 2, there is official Tesla rhetoric that the system has a hardware capability of level 4 (Hawkins, 2019). However, it is difficult to know how accurate these statements and prices are for the actual costs, as much of the information concerning technology costs is kept confidential by most automobile manufacturers. There are also estimates of the additional costs for AV technology in academic literature (see Table 1). Note that the costs for AV technology presented in Table 4 are in addition to the price of a conventional vehicle, and it is assumed that every traveler has the same costs in terms of vehicle price. In our scenarios presented below, we will assume a range between SEK 30,000 and SEK 310,000 in 2045.

Table 1
Costs of AV Technology (advanced level 4 or level 5) from the academic literature.

Study Author	Low cost	Medium cost	High cost	Year
Bansal and Kockelman (2017)	–	SEK 80,600	–	2045
Wadud (2017)	SEK 112,500	SEK 136,400	SEK 179,400	2020
Lavasani et al. (2016)	SEK 28,000	SEK 50,000	SEK 94,000	2025
Compostella et al. (2020)	SEK 30,500	SEK 95,000	SEK 280,000	2030 –2035

3.3.3. VoTT assumptions

The use of VoTT in transportation infrastructure appraisal is often disaggregated for different modes and other circumstances, but for distributional reasons not disaggregated with respect to income for different individuals (Börjesson and Eliasson, 2019, 2014). However, when using VoTT to simulate and analyze consumer purchase and the associated travel impact of technologies, as we are doing in this study, it needs to be linked to income in order to generate reliable insights (see the subsection on VoTT and income in Section 2).

We take the predicted VoTT for 2040 from the Swedish Transport Administration (Swedish Transport Administration, 2020), and extrapolate it forward to 2045. We assume that it is representative for the median driver in the population and adjust the VoTT according to different income quintiles. Further, we assume an income growth of 1.5 % per year up to 2045, in line with the estimated growth in GDP in the Swedish Transport Administration's scenarios (Swedish Transport Administration, 2020). We then applied these income- and time-adjusted VoTTs to the respective trips. For a median driver, the VoTTs that we use are SEK 157 per hour for commuting trips, SEK 104 per hour for other purposes, and SEK 192 per hour for all long-distance travel.

As discussed in *Section 2* , the VoTT is likely to drop if an AV is used, and drop more if one can work in the car (Correia et al., 2019). Based on the literature cited in the introduction, we assume that VoTT may decrease by between 15 –50 % for non-commuting trips as well as for commuting trips for those who cannot work remotely; and between 25 –60 % for commuting trips for those who can work remotely. The lower level is based on International Transport Forum (2019), and assumes automation only has a limited effect on VoTT and thus on vehicle kilometers travelled (VKT). The upper level is consistent with stated preference studies. For example, Kolarova et al. (2019) found a 41 % reduction in commuting VoTT. However, as discussed by Singleton (2019), the uncertainty range is large, which we aim to capture with our interval assumption.

Studies by Harb et al. (2018) and Harb et al. (2022) focus on the combined effect of VoTT impacts and travel demand elasticities. In their revealed preference studies, they analyzed households with access to a simulated AV (a chauffeured vehicle) and found that the study subjects increased their VKT substantially.

The different VoTTs are connected in that Commuting VoTT is assumed to be 10 % larger than non-commuting, hereafter known as "Other VoTT". Thus, if the Commuting VoTT Reduction is 25 %, the Other VoTT Reduction will always be 15 %. This is because we assume that there is a strong positive correlation between how people value their time while commuting and while traveling for other purposes.

3.3.4. Travel demand elasticities

There are plenty of studies that try to empirically estimate the size of the rebound effect. The empirical findings suggest a long-run rebound effect of around 0.1 –0.3, (an elasticity of travel distance with respect to fuel cost) meaning that a 10 % increase in fuel efficiency generates a 1 –3 % increase in annual vehicle mileage (Andersson et al., 2019;

Dimitropoulos et al., 2018). Other studies have suggested that the long-run induced travel demand elasticity could be somewhere between −0.5 and −1 (an elasticity of travel distance with respect to travel time), in the sense that a 10 % reduction in travel time tends to induce 5 −10 % increase in travel volume (Andersson, Rosqvist, L, 2011; De Jong and Gunn, 2001; Goodwin, 1996).

Further, the rebound effect tends to decline with income (Greene, 2012; Small and Van Dender, 2007). This suggests that changes in GTC are a determinant of the travel response to changes in fuel cost, and not fuel cost per se. The share of fuel cost in the GTC declines as VoTT increases with income, and if we assume a constant demand elasticity with respect to GTC, the demand response to fuel cost changes will decrease as the income increases, consistent with Small and Van Dender (2007) and Greene (2012). Hence, for this reason we will assume that demand elasticity with respect to GTC is constant in relation to income.

3.3.5. *Interest rate and annualized costs*

For calculating the annualized AV technology cost, we need to make assumptions about the interest rate used for the vehicle purchase and the economic lifetime of the car. For the economic lifetime of the car, we assume 10 years, in accordance with the Swedish Transport Administration (2020).

Regarding the interest rate, we make the following assumptions:

- 5 % for car purchasing decisions (Swedish Transport Administration, 2020).
- Bank loans for general consumption in Sweden have varied between about 4 % per year and 8.5 % per year over the period 2006 and 2022 (Statistics Sweden, 2023).
- Bank loans for housing in Sweden have varied between about 1.5 % per year and 6.5 % per year over the period 2006 and 2022 (Statistics Sweden, 2023).

3.4. *Summary of parameter span analyzed in the model*

Based on the assessment of the critical uncertainties in the suggested model, we use the ranges shown in Table 2 for a sensitivity analysis. The reduction in VoTT and the elasticity of travel demand with respect to GTC affect the impact on CS_{AV}, while the technology cost and interest rate affect the cost of AV technology.

These five parameters are discretized into different bins: AV Technology Cost into 8 equally sized bins, Interest Rate into 10 equally sized bins, Elasticity of travel demand into 10 equally sized bins, and Reduction in VoTT into 8 equally sized bins, for each type of VoTT. This results in 30,720 parameter combinations in the sensitivity analysis .

3.4.1. *Emissions due to car use*

By 2045, the Swedish car fleet is expected to be close to fully electrified in order to meet the net zero target (Hunhammar et al., 2021; Morfeldt et al., 2021). In the modeling, we assume that all AVs will be BEVs. Thus, tailpipe CO_2 emissions will be zero, but there are still emissions associated with the production of the vehicles and their components (for example, the battery, steel, aluminum, glass and plastics), and in the supply of the electricity to run them. The environmental impact of BEVs could be substantial: Arendt et al. (2022) estimated that 45.8 % of the costs of the EU's goal of low-carbon development by 2050 could be attributable to materials for electric vehicle batteries. That cost includes not only damage cause by greenhouse gases, but also land use, non-renewable resource depletion, and freshwater consumption (Arendt et al., 2022).

In this study, we use CO_2-equivalent emissions factors for travel demand in Sweden from Morfeldt et al. (2021), who use a prospective Life Cycle Analysis (LCA) approach. The two background scenarios considered are: (1) global policies advance to meet the targets in the Paris Agreement; and (2) business as usual, with global policies staying on the same trajectory as they are now on according to existing stated policies (see Table 3). The emission factors for BEV are considerably smaller in case 1 than 2.

The emissions associated with the AV technology (computers, lidars, radars, cameras, etc.) are assumed to be balanced by the possible increased operational efficiency of an AV (Gawron et al., 2018; Mohan et al., 2020; Wadud et al., 2016) so they are not explicitly considered in the analysis .

3.5. *Population*

For calibrating the population characteristics, we used the finest grained self-reported data on mode of transportation and trip distances from the Swedish National Travel Survey that stretches over the period 2011 −2016 (Transport Analysis, 2023). We selected respondents who reported the following information: income, trip purpose, trip distance, if they travelled in their own car, and ability to work remotely. Of the 38, 258 respondents in the initial dataset, 9305 respondents had reported the relevant information and thus met the criteria for the study.

This population of 9305 respondents was disaggregated into five income quintiles and each quintile was divided into one group who could work remotely and one who could not work remotely (being a proxy for if the respondent could work in the car) as shown in Table 4. The reported income in the national travel survey was adjusted to 2016 for inflation using the consumer price index (Swedish Transport Administration, 2020). Within each quintile, we calculated the current average traveling distances of car drivers for commuting and other purposes, for both long (>100 km) and short distance (≤100 km) trips, as shown in Fig. 2.

4. Results

In this section, we analyze the effects on changes in VoTT on the purchase of an AV, the consequential impacts on travel demand, and finally the impacts on carbon footprint.

4.1. *Purchase of AV*

The willingness to pay for an AV is estimated as the difference in the Consumer Surplus (ΔCS_{AV}) between purchasing or not purchasing an AV. The violin shapes in Fig. 3 show the ΔCS_{AV} for all possible values of the sensitivity analysis, broken down by income quintile. If ΔCS_{AV} is larger than the average daily cost of the AV technology, then we assume an AV is purchased. The average estimated daily levelized cost of the AV technology (between SEK 8 and 134 per day) is shown by the dotted lines. The higher dotted line corresponds to the case in the sensitivity analysis when the discount rate is high (10 %) and the AV technology

Table 2
Range of Sensitivity Analysis Variables.

Value range	Variable
15 −50 %	Reduction in Other VoTT
−0.33 −1.33 %	Elasticity of travel demand
25 −60 %	Reduction in Commuting VoTT
KSEK 30 −310	AV Technology Cost
1 −10 %	Interest rate

Table 3
Emissions Scenarios.

Year	Coefficient	Scenario
2020	153 $gC0_2$/ km	Used for calculating emissions for an internal combustion engine vehicle in 2020.
2045	21 $gC0_2$/km	The global energy system develops towards meeting the goals of the Paris Agreement.
2045	50 $gC0_2$/km	Stated policies stay the same.

Table 4
Working from Home, proportion per quintile.

Quintile	Work Remotely	Share of income quintile
Q1	Yes	10 %
	No	90 %
Q2	Yes	15 %
	No	85 %
Q3	Yes	26 %
	No	74 %
Q4	Yes	39 %
	No	61 %
Q5	Yes	67 %
	No	33 %

cost is high (SEK 310 thousand), while the lower dotted line corresponds to the case when the discount rate is low (1 %) and the AV technology cost is low (SEK 30 thousand). The violin shapes get wider if there are more data points at that $\Delta CS_{AV,}$ so for example there are many data points between a ΔCS_{AV} of SEK 25 −50 per day in the first income quintile. The highest ΔCS_{AV} for each quintile is realized when the reduction in VoTT is large and when the travel demand elasticity is largely negative.

A representative individual in each quintile will purchase an AV if the technology cost is low, which is shown in the graph by the fact that none of the violin shapes stretch below the minimum technology cost line, meaning that ΔCS_{AV} is always larger than the cost of the technology in those cases. Further, if the technology cost is high, it will never be beneficial for a representative individual in the two lowest income quintiles to purchase an AV, since neither of the violin shapes that depict the data points in the lowest quintiles ever stretch above the maximum technology cost line, meaning that ΔCS_{AV} is smaller than the cost of the technology. For the other three quintiles, whether it will be beneficial to adopt an AV or not depends on the combination of VoTT assumption and the travel demand elasticity. These relationships are examined in more detail in Supplementary Materials 2.

4.2. *Increase in travel demand*

The increases in the population's average travel distance due to the four parameters tested are shown in Fig. 4. The figure shows the distribution over different parameter combinations, keeping the value of the parameter on the x-axis constant. The top and bottom ends of the line correspond to the 95th and 5th percentiles in each distribution, and the dot to the median. In this way, we can see how sensitive the population's aggregated impact on travel distance is to a specific parameter. Elasticity of travel demand has the strongest effect on the distance travelled, followed by the Other VoTT Reduction. Also, the cost of the technology has a clear non-negligible impact; when the cost is small the median increase in aggregate travel distance is about three times as large as when the cost is high. This is different compared to the effect on the purchase, where the importance of the elasticity of travel demand is relatively weak and the dependence on AV technology cost is relatively strong (see Figure SM 1).

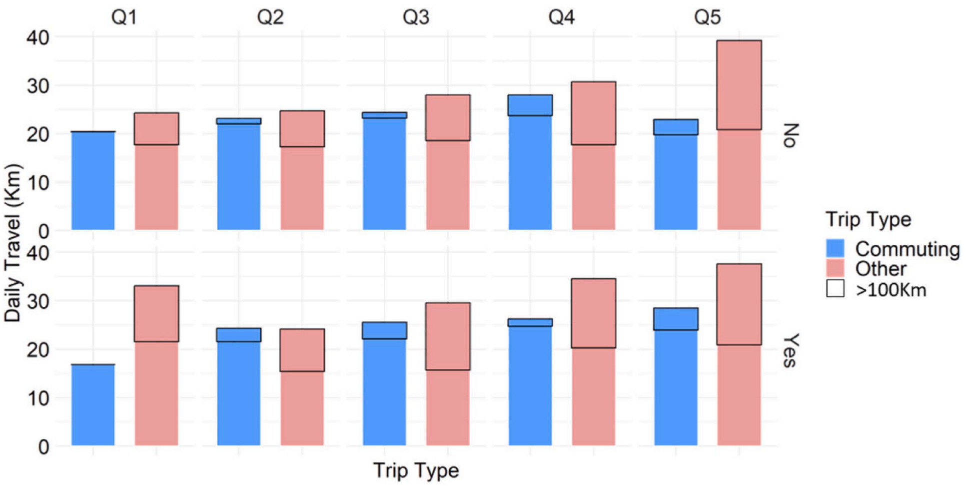

Fig. 2. Average distance travelled per day by trip type, trip distance, and ability to work from home.

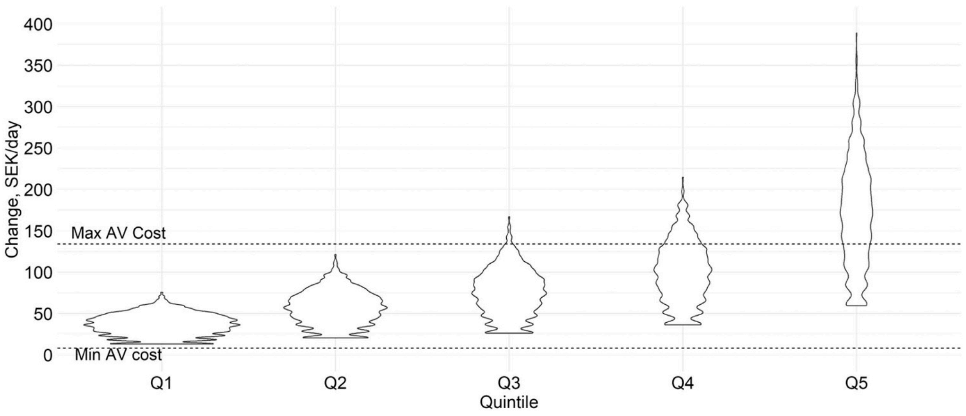

Fig. 3. : Change in daily Consumer Surplus of using an AV by quintile compared with the daily average cost of purchasing the AV technology (dotted lines).

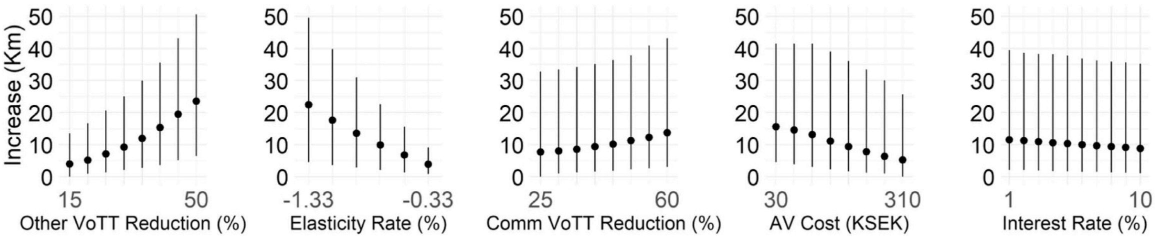

Fig. 4. **:** Increase in daily travel after AV introduction, by sensitivity analysis variable.

4.3. *Lifecycle emissions*

The present-day emissions from car driving by the studied population are about 3 metric tons of CO_2 equivalents per year (based on National Travel Survey data with emissions factor for 2020). The studied population in this case includes the 9305 individuals in the Swedish National Travel Survey who met the requirements for our data analysis (see Section 3.4). For 2045, when (we assume) AVs are available, the emissions are estimated in two cases taken from Morfeldt et al. (2021): a case in which emissions from the production and charging of electric vehicles develops in line with a scenario consistent with the Paris Agreement; and a case in which emissions from the production and charging of electric vehicles develops in line with currently stated policies. In the Paris Agreement scenario, the emissions factor is 21 g of CO_2 per km, and in the Stated policies scenario, the emissions factor is 50 g of CO_2 per km. The violin diagrams in Fig. 5 become wider when there are more cases of the sensitivity analysis at a certain point on the y-axis, as in Fig. 3. The line and dot show the 5th-95th percentile range and median, respectively, as in Fig. 4.

For the Paris Agreement scenario in 2045, our analysis shows emissions between 0.42 and 0.86 metric tons CO_2 equivalents depending on the change in VoTT, the elasticity of travel demand, the interest rate on the investment in the vehicle, and the cost of AV technology. The top 5 % of this emissions range is from 0.70 – 0.86 metric tons of CO_2 equivalents, and the median is 0.49 metric tons of CO_2 equivalents, as seen in Fig. 5. In the Stated policies scenario, in 2045 the emissions are between 0.99 and 2.04 metric tons of CO_2 equivalents with the top 5 % from 1.67 – 2.04, and the median at 1.17 metric tons of CO_2 equivalents. The top 5 % of emissions in both scenarios are strongly dependent on a large negative travel demand elasticity, i.e. between −1.33 % and −1.13 %, and relatively dependent on a medium (more than 35 %) Other VoTT reduction.

4.3.1. *Working from home three days per week*

We have assumed that individuals who can work remotely can also work in the car, but we have not yet considered that these are the same individuals who can work remotely at home, commute less, or even not commute at all (Bieser et al., 2021; Hook et al., 2020). To address this, we test a case where those who report that they can work remotely do so three days per week. This will reduce their weekly travel and the benefit of adopting AV technology.

As shown in Fig. 6, the difference in emissions when those who can work remotely choose to work from home for three days per week is quite small. The median emissions, visualized by the dot in the center of the violin graphs, decrease by less than 1 %. The maximum level of emissions, shown in Fig. 6, decreases by about 8 %.

The reason why the impact of working from home three days per week is relatively small is that the distance devoted to commuting is smaller than the distance devoted to other travel purposes (Fig. 2), and that those who can work remotely are a relatively small share of the total population (Table 4). Further, the possibility to work remotely is also correlated with income, and this is why the maximum level of emissions, which is created by the highest income quintiles who emit the most, decreases more than the median level in the working from home scenario.

Other studies have found that when people telecommute, they tend

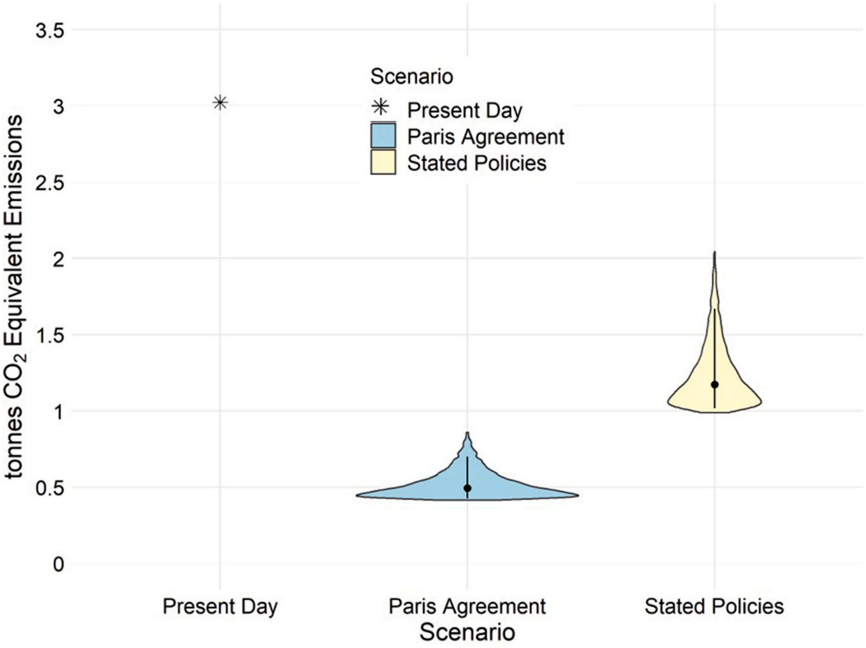

Fig. 5. **:** Average travel-related emissions per driver.

Fig. 6. **:** Average emissions per car under different policy scenarios and if people who can work in the car also work from home three days per week.

to increase their travel for other purposes than commuting, and potentially choose to live further away from their workplace and thereby increase the commuting distance on the days they actually do commute (Bieser et al., 2022). This type of rebound-like effect may be substantial, but in general it is found to be smaller than the reduced distance (or energy use) needed for commuting (Bieser et al., 2021; Hook et al., 2020). Hence, if this rebound effect were to be considered in our analysis, the emissions would likely end up between the scenarios where working from home is possible and where it is not possible. As discussed above, the difference in carbon footprint between these two scenarios is small.

5. Discussion

5.1. Limitations

This model is based on simplifying assumptions about individuals' choices and behaviors, and on uncertain, though academically rigorous, assumptions about parameter values. A starting point for the analysis is that the individuals act rationally in their decision-making, considering only economic factors when choosing to purchase an AV or not. In addition, we assume that they are aware of and consider the value of the savings that could be made from an AV in terms of reduced VoTT. There are potentially many more factors that could sway the decision of the traveler toward purchase, such as social status or pressure (Rezvani et al., 2018) as well as safety aspects. There could also be factors that push the decision away from purchase, for example, lack of trust in AV technology (Gao et al., 2019; Yap et al., 2016). All of these different factors would be interesting to consider in future research on AV adoption and associated changes in travel demand, especially when linked to empirical travel survey data as we do here.

Further, we assume that the capital cost of AV technology is the same for every income group. In reality, it is plausible that those with higher incomes purchase more advanced and expensive forms of AVs (and the opposite for those with a low income), and thus AV technology cost would make up a larger portion of the total GTC per km.

When calculating the GTC per km of an AV, we assumed there would be no changes in fuel, maintenance, or insurance costs between now and 2045 because of potential increased efficiencies due to the car being fully autonomous. This could underestimate the benefits associated with AV purchase, thus potentially making our calculations slightly conservative.

5.2. Discussion of the results

It was established in the data collection and the related analysis that respondents in all income groups drive more for other purposes than for commuting purposes. Further, those in the higher income quintiles can work remotely more often, and they also tend to have, on average, longer travel distances (see Fig. 2), which is a common finding in other similar countries (ITF, 2023). Thus, without doing any further analysis, we can say that as long as all income groups have the same AV technology cost and relative change in VoTT, the higher income groups will, on average, have a larger (absolute) economic incentive to purchase an AV.

In addition, higher income people tend to have a higher VoTT than people with a lower income. This makes it even more likely that individuals with a higher income are more likely to adopt AVs, because they 'save' more money in absolute terms when there is a percentage-wise reduction in VoTT due to AVs. This is demonstrated in Fig. 4, which shows the individual cost-benefit analysis where the change in Consumer Surplus when using an AV is compared to the cost of AV technology. Most people in the highest income quintile would purchase an AV if their decision-making was based on an AV's estimated impact on Consumer Surplus vis-a-vis the cost of purchasing the technology. When we use the data in the Travel Survey to parameterize our model, those in the highest quintile who can work from home then see the largest increase in travel distance, which is shown in Fig. 5.

Just changing travel behavior related to commuting does not have a large effect on emissions. Working from home three days a week, even if it is a nation-wide initiative, does not generate a large drop in emissions. More importantly, even with policies in place to meet the Paris Agreement and everyone who could working from home three days a week, the per capita emissions of the studied population would still be somewhere between 0.42 – 0.86 metric tons of $C0_2$ equivalents per year from personal car travel, exceeding the 2045 carbon neutrality goal.

This highlights the importance of curbing long-distance travel demand related to non-commuting trip purposes. Long-distance travel could also be on highways, which are already suggested as a good initial use case for AVs under certain conditions (He et al., 2022). Since long-distance VoTT is higher, the VoTT savings when using an AV are higher across all income groups compared with shorter distance trips.

Kilometer-based taxes could be a potential way to curb these trips. This would cause an increase in GTC_{AV} for those income groups who purchase an AV, and thus cause a decrease in kilometers travelled. Kilometer taxes have already been suggested as a relevant policy measure for when AVs are introduced by Sweden (Pernestål et al., 2022, 2020; Zhao et al., 2021). Such taxes have previously been implemented for conventional vehicles at the national level in New Zealand, and in certain states in the US and Australia (ITF, 2023). As Pernestål et al. (2022) point out, questions regarding issues such as public acceptability and interactions with other existing policies should be answered before such a tax is introduced. The International Transport Forum (ITF) suggests that charging a lower level of tax for those living in rural areas could make kilometer taxes more acceptable to the public, because those who need to drive longer distances are not unfairly overtaxed (ITF, 2023). This is relevant for conventional traffic and current habitation patterns, but it could become problematic if there is a surge in people moving to the countryside or suburban areas because they are willing to drive further distances in their AV.

6. Conclusions

The introduction of AVs in Sweden could have major effects on travel demand and associated emissions. As shown in our modelling, it could lead to large increases in travel distance due to lower VoTT. This could have serious effects on congestion, and cause increases in tailpipe emissions if the vehicle is not electric. Further, it is likely to increase the overall energy needs of the transport sector as well as the carbon footprint of the system, whether the vehicles are electric or not.

In this study, we contribute to the existing body of AV-related academic literature by including the consumer benefit from induced travel due to AV in our model, and by using Swedish data to parameterize the model and simulate potential travel demand changes in Sweden. Our results show that those with a higher income tend to drive more, and for longer distances. If the potential increased car use due to the introduction of AVs is deemed large, a kilometer tax could be a good way to curb travel.

We can also see that working from home for three days a week only causes a small decrease in emissions. This could be useful information for policymakers, and it could also be an interesting area of future research in the post-COVID-19 era. There might be more data available now on who is able to work from home, and if they prefer to or not (relating back to public acceptability). The situation concerning who can work from home may also change in the future due to changing job market circumstances. With this in mind, it would be interesting to investigate how different scenarios in which lower- and middle-income quintiles are affected by the possibility of remote working in the future, and what consequences that may have on travel demand. We focus on the lower- and middle-income quintiles here since a relatively small proportion of those respondents reported being able to work from home prior to COVID-19, so there is a large potential for emissions reductions in terms of their commuting behavior if they were to be able to start working from home.

The results presented in this paper may be useful for other researchers as well as policy analysts when considering future scenarios involving AVs, and travel demand, especially in countries that are demographically similar to Sweden.

CRediT authorship contribution statement

Ella Rebalski: Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization. **Daniel J. A. Johansson:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ets.2024.100006.

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