Benefits and Costs of Autonomous Trucks and Cars

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Abstract

Autonomous vehicles are currently developed, and are expected to be introduced gradually. Society needs a basis for decisions regarding market interventions. This study identifies, quantifies and values the benefits and costs of autonomous trucks and cars considering generalized costs, external effects and social marginal cost pricing to consumers with Swedish data. The results show that the greatest benefits are saved driver costs for trucks and decreased travel time costs for car drivers. In the example calculations, capital costs may increase by 22 percent for cars and 36 percent for trucks for benefits to exceed costs in 2025. Subsidies are not needed since the producers and consumers get the major benefits and pay the costs.

Keywords

Autonomous Vehicles, Self-Driving Vehicles, Benefits, Generalized Cost, Social Marginal Cost, Policy

1. Introduction

The vehicle industry is developing new technologies for trucks and cars to be autonomous, also referred to as automated or self-driving vehicles that are expected to be introduced gradually and gain market shares. When commercial success is up to the manufacturers, the benefits and costs to society as a whole are crucial not only for the technology's success but also for the implementation of the right policies and public investments. Questions include whether policies should be proactive, promote development with rapid adjustment of regulations, and give subsidies if the technology has net benefits to society, or whether institutions should evolve gradually in response to innovation within the industry. We study the relative importance of the different identified effects when autonomous vehicles (AVs) are introduced, in particular the dominance of saved

driver costs for both trucks and cars. The applied methodology is common for evaluating infrastructure investments; in this study it is applied to the introduction of a new technology for transportation. We use today's knowledge to quantify the magnitude of benefits and costs related to AVs.

The purpose of the study is to estimate the relative importance of identified effects of autonomous trucks and cars, the distribution of effects, and whether benefits are greater than costs, by using theory, previous studies and the unit values for transportation costs applied in Sweden. In an example calculation, some studied alternatives based on Swedish statistics and forecasts are compared with a reference scenario. A number of assumptions about effects are altered in a sensitivity analysis to find out which effects are crucial.

The real effects of creating or using resources, excluding any redistribution effects, based on changes in generalized cost are presented. We consider whether social marginal cost pricing to consumers prevails on the markets concerned, both to estimate all effects accurately and to be able to analyse how the effects for society as a whole and the effects for producers and consumers on the transport markets are interrelated. Based on the latter, it is possible to discuss the policy implications of the result. To our knowledge, no such holistic approach has been applied to quantify the benefits and costs of both freight and passenger transportation on the road. Few studies appear to have aimed to quantify and value the effects on society as a whole including the saved resources for driving cars and trucks.

SAE International [1] has developed taxonomy for driving automation. Lower levels (1 and 2) are already implemented in many modern vehicles with driver assistance and partial automation. Level 3 is an intermediate state with driving automation, where the driver is required to intervene in critical situations. Levels 4 and 5 represent high or full driving automation.

We construct a reference alternative where all vehicles develop to level 2, manually driven vehicles (MDV), and compare this to studied alternatives where AVs with full automation are introduced. Level 3 is assumed transitory, since several car producers, as Ford and Volvo, are avoiding this level, because they consider it difficult for the driver to keep track of traffic and, if necessary, take over from automated driving (Wired [2], Volvo car group [3]). All values are at 2014 price levels. Unit values are provided in SEK as in the sources. Benefits and costs in the example calculations are transferred to euro.

2. Method

In this study, welfare theory is used to analyse all relevant effects to society. We are identifying, quantifying and valuing effects of autonomous trucks and cars. The aim is to determine the relative importance of identified benefits and costs, who receives them, and whether benefits are greater than costs. We use the method cost-benefit analysis (CBA), with the limitation that some effects are difficult to quantify and value. The results from a CBA can be used as a basis for de-

cisions whether the public sector should consider producing on, financing or regulating the market.

The generalized cost (GC) of transportation, used as a key concept in transport economics, is a central term for the identification, quantification and valuation of effects for autonomous trucks and cars. Generalized cost refers to all monetary and non-monetary costs for the transport service user. The benefits of AVs consist of lower generalized costs for the vehicle kilometres (vkm) driven by autonomous trucks and cars instead of MDVs, and of more transportation. Some of the latter will be newly generated, and some will be transferred from other modes of transport. The extent of the effects depends on elasticities. We will use the term social generalized cost (SGC) for generalized cost when all external effects are internalised in the price to the consumer. **Figure 1** illustrates the volume of road transportation with AVs as a function of social generalized cost, and the resulting net benefits if SGC is lower with AVs compared to MDVs. Area A represents the net benefits of lower social marginal costs for existing trips that are transferred from MDVs to AVs. Area B represents the net benefits of new trips on the road.

The benefits of the change in social generalized cost for trips transferred from MDVs on the road to AVs is calculated as

$$Benefit = Q_1 \left(SGC_0 - SGC_1 \right) \tag{1}$$

If social marginal cost pricing prevails, *i.e.* all used resources are considered when deciding to drive another vkm; new vehicle kilometres give a net social benefit to society, as the additional value is higher than the cost. In reality, however, such optimal pricing may not be the case. If the studied (primary) market for driving with trucks and cars or interrelated (secondary) markets do not have social marginal cost pricing and the consumers do not accurately consider all benefits and costs to society of the new vehicle kilometres, adjustment posts need to be added (Boardman *et al.* [4]).

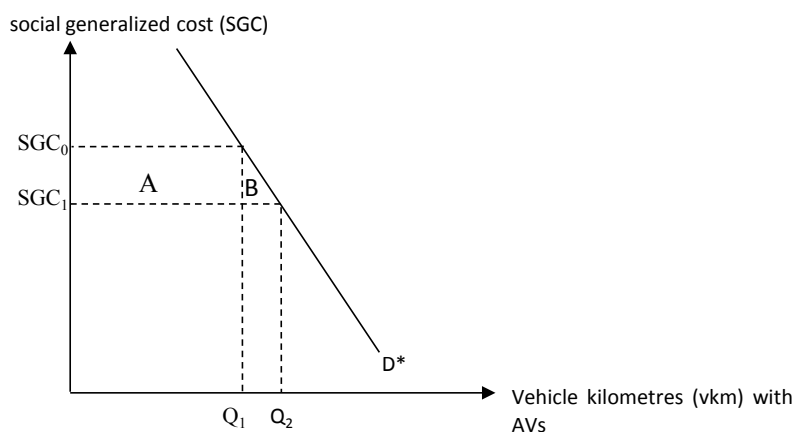The net benefits of the change in generalized cost for new vkm on the road is calculated as

Figure 1. Net benefits of AVs due to lower social generalized cost.

$$Net\ benefit = 0.5(Q_2 - Q_1)(SGC_0 - SGC_1) \tag{2}$$

How much traffic is shifted from MDVs to AVs depends on the relative magnitude of the decrease in *SGC*, the cost of buying a new vehicle, the depreciation rate of the existing fleet, technological and legal restraints and preferences. The rule of half is applied, which is to assume linear demand curves.

If social marginal cost pricing does not apply in all the relevant transport markets, this must be taken into account as added adjustment posts. In order to determine whether such adjustment posts needs to be added in conjunction with new vehicle kilometres by an AV when generalized cost decreases, it must be determined whether or not the consumers of vehicle kilometres by truck and car, as well as freight and passenger transportation by alternative modes of transport, consider the social marginal cost. The social marginal cost may differ from the private marginal cost if infrastructure usage or other external effects are not correctly internalized in the price.

For passenger traffic by private car, the producer and the consumer of the vehicle kilometres is the same. It is then sufficient to study whether negative and positive external effects are internalized by Pigouvian taxes and subsidies (Pigou [5]), so that the decisions are made based on the social marginal cost. Thus for cars, if needed, an adjustment post is added as

$$Added\ post_{car} = (GC_1 - MC_{social1}) * (Q_2 - Q_1) \tag{3}$$

For freight transport by truck, producers and consumers may be different actors. Therefore, the competitive condition and pricing strategies must also be studied. On the one hand, it may be that freight service providers pay a price lower than the social marginal cost of using infrastructure if negative external effects are not internalized by Pigouvian taxes. On the other hand, limited competition, or a cost structure of decreasing average costs, may lead to consumers still paying a price that is higher than the social marginal cost. Thus for trucks, if needed an adjustment post is added as

$$Added\ post_{truck} = (P_{consumer} - MC_{social1}) * (Q_2 - Q_1) \tag{4}$$

Some of the new vehicle kilometres by truck or car will be transferred from substitute markets such as transport by train. If social marginal cost pricing to the consumer does not prevail in these markets, adjustments must be made in the calculation.

A post is added as

$$Added\ post_{substitute} = (MC_{social} - P_{consumer}) * (Q_0 - Q_1) \tag{5}$$

If the price of the mode of transport is lower or higher than the social marginal cost, a benefit of for example saved negative external effects or lost positive external effects must be added. Only if full competition prevails, public sector regulation with Pigouvian taxes or subsidies is enough to achieve social marginal cost pricing for consumers. If the market is a private monopoly or an oligopoly, or a public company with economies of scale and full cost pricing, or private

profit maximization, the price to the consumers may be higher than the social marginal cost.

Capital costs vary depending on both time and mileage. Part of the change in capital costs with AVs compared to MDVs varies with vehicle kilometres and changes generalized cost. Maintenance costs per vehicle kilometre might also be different. However, studies have shown that travellers take little account of marginal capital and maintenance costs when deciding how many vehicle kilometres to drive with their car (Hang *et al.* [6], Glazebrook [7], Shiftan and Bekhor [8]). We choose to apply the total change in the cost of capital and maintenance costs (variable as well as fixed) per vehicle kilometre with AVs compared to MDVs as one effect in the example calculations. In addition, there may be other effects, such as investment in infrastructure, that do not vary directly with the number of vehicle kilometres. These effects should also be included in the analysis.

3. Identification of Effects

3.1. Literature Review

A number of studies have taken a comprehensive approach towards identifying all effects of AVs (Anderson *et al.* [9], Fagnant and Kockelman [10], Gruel and Stanford [11], Litman [12], Milakis *et al.* [13], Wadud [14]).

Anderson *et al.* [9] identify increased safety, reduced congestion and land use, saved energy and increased mobility as advantages, and more travelling, undermined parking revenues and lost jobs as costs. Fagnant and Kockelman [10] estimate the gains in safety, less congestion, fuel efficiency and parking benefits. Legal and liability issues, security and privacy concerning vehicle-related data and vehicle costs are regarded as constraints to achieving the benefits. Gruel and Stanford [11] identify long-term potential impacts of AVs and conclude that there are positive and negative outcomes, and that it is unclear whether they will be a societal net benefit or harm. In all scenarios safety and mobility will increase, better use of travel time and lower fuel consumption are among the benefits but more travelling increases costs. Litman [12] summarizes the benefits as reduced fuel consumption, driver stress and paid drivers' costs, mobility for non-drivers, safety, road and parking capacity and support for sharing vehicles. The costs pointed out are for the vehicles and infrastructure, risks, privacy, increased travelling, social equity and reduced employment.

Milakis *et al.* [13] carry out a literature review and expect road capacity, fuel efficiency, emissions and accident risks to give positive effects. They find that automated vehicles can lead to additional travel demand, and that the impact of potential land use changes, safety, economy, public health and social equity remain unclear. Wadud [14] concludes that the owners of commercial vehicles are most likely to be early adopters because they can save on driver costs and their ratio of benefits to costs is high. For regular cars, the largest gains are among people with the highest income, because they travel more and place a high value on time.

Other studies focus on a certain aspect of AVs, such as fuel consumption and market shares (Brown *et al.* [15], Fagnant and Kockelman [16], Kyriakidis *et al.* [17], Transport Analysis [18] [19], Bansal and Kockelman [20], Harper *et al.* [21], Wadud *et al.* [22], Zakharenko [23], König and Neumayr [24], The Swedish National Road and Transport Research Institute [25], USPS [26], Zaiqiang and Ting [27], Bellem *et al.* [28], and Miliakis *et al.* [29]).

Bansal and Kockelman [20] find that 25 percent will be autonomous by 2045, with the assumption of an annual five percent fall in price at constant willingness to pay compared to 2015. This share will increase to 87 percent on the alternative assumption of a 10 percent annual rate of decline in prices and a 10 percent annual rise in willingness to pay. Litman [12] projects that in the 2030s, 10 - 20 percent of the vehicle fleet will be autonomous with a moderate price premium, while in the 2050s, 40 - 60 percent will be AVs, which by then will have become a standard feature on most cars sold. Milakis *et al.* [13] expect the penetration to range between 1 and 11 percent for 2030, and between 7 and 61 percent in 2050. The Swedish National Road and Transport Research Institute [25] assumes a share of AVs of 18 - 44 percent in 2030 and 39 - 68 percent in 2050.

3.2. Identified Effects

Table 1 summarizes the identified benefits and costs of automated trucks and cars, based on factors mentioned in the reviewed literature. Added adjustment posts when considering imperfect transport markets are the only effect included in this study that has not been found in the literature. It should be noted that we consider saved driver costs and increased transportation as net benefits. Reduced use of resources, including labour, is a benefit to society, as is increased travelling as long as it is priced according to social marginal cost. Most identified effects are quantified in the present study. Some have been excluded because of the difficulty in quantifying them or because of insufficient information. The effects not quantifiable will be further discussed in Section 5.

4. Changed Generalized Costs with Autonomous Trucks and Cars

4.1. Type Vehicles

For freight transport by truck we use three vehicle types: one for long-distance transportation with 6 - 7 axles and a capacity of 40 tonnes (HGV40), one for distribution with two axles and carrying up to 16 tonnes (MGV16), and one for transportation of bulk materials like stone, sand, etc. for construction purposes with three axles and carrying 16 - 24 tonnes (MGV24). Based on Transport Analysis [30], their shares of vkm in 2015 are estimated at 70, 13 and 17 percent respectively. An average speed of 38 km/h for HGV 40, 22.5 km/h for MGV 16 and 22.5 km/h for MGV24 is assumed (own calculation based on the Swedish Transport Administration [31]).

For passenger traffic by road, we use one type of car, where fuel consumption is a weighted average of petrol (70 percent) and diesel (30 percent) according to Transport Analysis [30]. 90 percent of travel by private car is for leisure or commuting to work, and 10 percent of travel is during working hours. In this study, an average speed of 78 km/h (The Swedish Transport Administration [32]) for all kinds of travelling is used, not distinguishing between long- and short-distance travels.

Table 1. Identified benefits and costs for autonomous trucks and cars.

Effect	Freight	Passenger
Quantified and valued effects		
Saved driver costs for freight transported by truck	Benefit	
Saved time-value if the driver in the vehicle can do other things		Benefit
Saved fuel due to convoy driving (platooning)	Benefit	
Saved fuel due to smoother driving	Benefit	Benefit
Reduced environmental emissions due to less fuel consumption	Benefit	Benefit
Increased traffic safety	Benefit	Benefit
Increased transportation due to lower generalized costs	Benefit	Benefit
Added adjustment posts due to transport markets not applying social marginal cost pricing to consumers	Benefit/cost	Benefit/cost
Effects that are calculated in terms of how high they can be for $\Sigma B > \Sigma C$		
Technology development for vehicles	Cost	Cost
Higher capital costs	Cost	Cost
Changed maintenance cost for AVs	Benefit/cost	Benefit/cost
Effects that are not quantified or valued		
Elderly people, disabled people and those without driving licenses can travel by car		Benefit
Perceived change in safety and privacy with AVs	Benefit/cost	Benefit/cost
Changed cost of infrastructure investments	Benefit/cost	Benefit/cost
Changed land use	Benefit/cost	Benefit/cost
Changed congestion	Benefit/cost	Benefit/cost

4.2. Social Generalized Cost with Manually Driven Trucks and Cars

The Swedish Transport Administration [31] recommends unit values for the costs of travel, such as travel time, traffic safety and environmental impacts of transportation, based on research and valuation studies. These values are used on a regular basis in Sweden. In this study time-related costs have been transferred into costs per vehicle kilometre, with the aforementioned average speed for the different vehicle types. The Swedish Transport Administration [31] recommends an increase over time of values such as travel times and environmental impacts because the relative willingness to pay for these is expected to increase with economic growth. The price of fuel is also expected a rising trend due to increased scarcity.[1]

Table 2 shows the unit costs for trucks. The opportunity cost for fuel costs is the product price including VAT, and additionally, the resulting external effects are accounted for in SGC. The variable capital and maintenance costs, the costs for the driver and the value of the goods that is bound during transportation are the remaining parts of SGC.

Concerning passenger transportation, the Swedish Transport Administration [31] recommends values of travel time for car and train that differ between national and regional travelling and between work and private travel. Other unit costs for passenger transport by car are fuel costs, capital costs and maintenance costs, and external costs in the form of accidents, emissions and noise. We use a weighted average of 0.074 litres of fuel per vehicle kilometre, based on the Swedish National Road and Transport Research Institute [33]. Table 3 shows unit costs for passenger traffic by car.

4.3. Social Generalized Cost with Autonomous Trucks and Cars

To calculate how the social generalized cost changes with autonomous trucks and cars, we must make some assumptions about how factors change, based on previous research presented in Section 2.

For long-distance trucks, autonomous driving will reduce fuel consumption because platooning can be established on the road, leading to less wind resistance for the vehicles inside the platoon. In addition, fuel can be saved by smoother driving in general. We estimate that fuel consumption can be reduced by 10 percent for long-distance truck, but not for the other types of trucks, as they typically cannot form platoons. Moreover, we conclude that AVs will not be introduced until they are at least as safe as MDVs, and we make a modest assumption that accidents will be reduced by 10% in the example calculation. With AVs, the entire driver cost will be saved, as there is no need for a driver to be on board, or if the driver is on board, the person can perform other tasks, thus freeing someone else.

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[1]We use the recommended enumeration factors 1.1605 from 2014 to 2025 and 1.4509 from 2014 to 2040 for travel time and environmental impacts, and 1.0722 and 1.1905 for petrol and 1.0829 and 1.2204 for diesel for the years 2025 and 2040.

Table 2. Costs, SEK per vehicle kilometre for the three vehicle types, truck.

	Long-distance (HGV 40)		Distribution (MGV 16)		Construction (MGV 24)	
	2025	2040	2025	2040	2025	2040
Fuel (product price incl. VAT)	2.71	3.06	1.71	1.92	2.09	2.36
Noise	0.46	0.58	1.49	1.86	1.02	1.28
Carbon dioxide	1.15	1.44	0.84	1.04	1.15	1.44
Other emissions	0.63	0.78	1.10	1.38	0.41	0.51
Accidents	0.38	0.48	0.67	0.84	0.38	0.48
Marginal capital and maintenance cost	3.75	3.75	2.95	2.95	3.50	3.50
Driver costs	6.18	6.18	10.84	10.84	9.40	9.40
Time value of transported goods	0.74	0.74	1.24	1.24	0.24	0.24
SGC	16.00	17.01	20.84	22.07	18.19	19.21
Total capital cost (depreciation and interest)	2.83	2.83	3.28	3.28	5.22	5.22

Source: Own calculations based on the Swedish Transport Administration [31].

Table 3. Costs, SEK per vehicle kilometre, car.

	2025	2040
Fuel (product price incl. VAT)	0.58	0.65
Noise	0.21	0.26
Carbon dioxide	0.19	0.19
Other emissions	0.04	0.03
Accidents	0.19	0.23
Marginal capital and maintenance costs	0.95	0.95
Travel time by car, work travel	4.64	5.81
Travel time by car, private travel	1.40	1.74
SGC private travel	3.56	4.05
SGC work travel	6.80	8.12
Total capital cost (depreciation and interest)	2.42	2.42

Source: Own calculations based on the Swedish Transport Administration [31].

Table 4 shows how much the SGC will change in SEK and the percentage of the different changes for a long-distance truck in the years 2025 and 2040. For simplicity, only the most common truck is shown; for the other two types, no change in fuel consumption is assumed but the other factors will differ with the same magnitude as in the table. The decrease in SGC is the difference in SGC $(SGC_0\text{-}SGC_1)$ shown in Figure 1 and in Formula 1. The most important effect for autonomous trucks is the eliminated cost for a driver. This effect represents over 90 percent of the reduction in SGC. The driver is a major cost component

for trucks, and is reduced to zero, whereas the other effects as fuel and accidents are only reduced to the lower values indicated above. Their share of reduction in SGC is somewhat lower in 2040 because it is assumed a bigger decrease in fuel consumption and accidents than in 2025.

Transport Analysis [34] discusses the changed travel time cost for the driver in an autonomous car. They point out that one measure is the difference between car and train of 20 - 40 percent according to the Swedish Transport Administration [31]. They also point out that in the UK, the travel time value is 20 percent higher for the driver than for the passenger, and that initially it might be travellers with relatively high travel time values that choose AVs. We use the difference in travel time value between car and train (the Swedish Transport Administration [31]) as the reduction in travel time cost for drivers of private cars in an AV compared to a MDV. For work travelling, 30 percent of the travel time is assumed devoted to work in an AV. Table 5 shows the change in social generalized cost with AVs compared to MDVs for cars.

The average gain when the driver is freed from driving the car is thus estimated at 24 SEK per hour for 2025 and 30 SEK for 2040. For work travel, the gain is estimated at 109 SEK per hour in 2025 and 136 SEK per hour in 2040, with the assumption that 30 percent of travel time is devoted to work in an AV. Smoother driving with an AV than with a MDV is assumed to result in 10 percent less fuel and emissions. With an AV we assume 10 percent fewer accidents in 2025 and 30 percent in 2040 than today. The most important effect for autonomous cars is the decreased travel time cost. It counts for approximately three fourths of the change in SGC for private travel and more than nine tenths of the change in SGC for work travel by car. The consumer will get this benefit. The same goes for the next highest benefit of decreased fuel consumption. To

Table 4. Change in SGC, trucks.

	2025		2040	
	ΔSGC in SEK	Percent of total ΔSGC	ΔSGC in SEK	Percent of total ΔSGC
Fuel (product price incl. VAT)	−0.27	4.0	−0.31	4.3
Noise	0	0	0	0
Carbon dioxide	−0.11	1.7	−0.14	2.0
Other emissions	−0.06	0.9	−0.08	1.1
Accidents	−0.04	0.6	−0.33	4.8
Marginal capital and maintenance costs	0	0	0	0
Driver costs	−6.18	92.7	−6.18	87.8
Time value of transported goods	0	0	0	0
ΔSGC	−6.67	100	−7.04	100

Table 5. Change in SGC, car.

	2025			2040		
	ΔSGC in SEK	Percent of total ΔSGC private	Percent of total ΔSGC work	ΔSGC in SEK	Percent of total ΔSGC private	Percent of total ΔSGC work
Fuel (product price incl. VAT)	−0.06	14.1	3.9	−0.06	11.4	3.4
Noise	0			−0.03	4.5	1.4
Carbon dioxide	−0.02	4.6	1.3	−0.02	3.3	0.9
Other emissions	−0.004	0.9	0.2	−0.003	0.5	0.2
Accidents	−0.02	4.6	1.3	−0.07	12.1	3.6
Marginal capital and maintenance costs	0			0		
Travel time by car, private travel	−0.31	75.6		−0.39	68.2	
Travel time by car, work travel	−1.40		93.3	−1,74		90.5
ΔSGC private travel	−0,41			−0.57		
ΔSGC work travel	−1.5			−1.92		
		100	100		100	100

what extent reduced emissions will benefit the consumer depends on the internalization of the external effects in the fuel taxes. The only effect that will be external is most of the change in accidents in 2040 because it changes more than fuel consumption. If accidents would change to zero with AVs the effects not internalized would still only account for less than one third of the effects for private travel and one tenths for work travel.

4.4. Capital Costs

It is difficult to predict how much different capital costs will be for AVs compared to MDVs in 2025 and 2040. Fagnant and Kockelman [10] present estimates that a self-driving car may cost 10,000 USD extra when it has a 10 percent market share, but only about 3000 USD extra in the long run when it has 90 percent of the market. According to representatives from Volvo, their self-driving car is expected to cost about 120,000 SEK more than the equivalent MDV at the 2021 launch, but in the long run it will come down towards the same price (Auto Motor & Sport [35]). We do not make any assumptions about the difference in capital costs for AVs compared with MDVs. Instead, our results show how much the capital cost (which in the following includes technology development for vehicles, higher capital costs due to more expensive production costs and changed maintenance cost for AVs) can increase without the costs to exceed the benefits of AVs.

5. Uncertain Effects of AVs

This section will discuss effects of autonomous vehicles that are not quantified or valued in this study. These effects may add to both benefits and costs, and reliable information about their future impact is still lacking.

5.1. Vehicles and Infrastructure

When autonomous vehicles begin to operate in regular traffic, additional costs may arise, related to the trucks and cars. Some may be of transitional character, such as development costs for the new technology, whereas others may be more persistent, such as higher production costs for more advanced vehicles and maintenance. In the longer term, however, production of vehicles may become less expensive, because they can be designed without any devices for driving, and become more productive when the space for the driver of trucks is transferred into more room for cargo. Capital costs for the vehicles may eventually decrease because of learning by doing and economies of scale in the manufacturing industry. The costs of developing the necessary technology for the vehicles and any higher production costs for the vehicles will be included in the price the consumer pays for the autonomous vehicles. As mentioned earlier, we study how much capital costs can increase in order not to completely counteract the quantified and valued net benefits.

In the short term, the digital infrastructure can require more investment, and, as long as the traffic is mixed between AVs and MDVs, special lanes may be needed. Development costs for the new technologies may also be significant. In the longer term, on the other hand, investments in infrastructure may decrease. Private cars can use road and parking capacity more efficiently, requiring less space. Fewer or narrower streets and lanes may come as a result, as well as reduced demand for parking spaces in areas with high land value. However, vehicles parking in other areas could induce more traffic. Zakharenko [23] found that with the introduction of AVs, commuters' cost per kilometre would fall and their welfare would increase, as would travel distance and city size. Land rents would therefore go up in central parts and decrease in more remote areas. The magnitude of the effects on infrastructure and land use is uncertain, as is the question of whether the net effects will add to benefits or costs.

5.2. Other Benefits and Costs

Older people, people with disabilities and those without driving licenses can benefit from being able to ride in an autonomous car. Their improved potential mobility is discussed by Harper *et al.* [21]. Based on travel patterns from 2009 and the assumptions made, they estimate an upper limit for traffic to increase by 14 percent. People without a driving license could increase traffic by a maximum of 9 percent and disabled people by up to 2.6 percent according to their study. AVs may also promote car sharing, both between existing car owners and between new groups. Fagnant and Kockelman [16] present many different scena-

rios and find that for the participating persons each AV could replace up to ten regular cars, adding up to ten percent more vehicle kilometres. The future effects of mobility for new groups and car sharing remain uncertain and have not been possible to quantify or value in this study. Bellem *et al.* [28] studied comfort in automated vehicles and recommended autonomous driving styles that can be perceived as comfortable by participants in a simulation, regardless of their personality or own driving style. Milakis *et al.* [29] used experts to assess the accessibility of AVs. They find benefits highly uncertain, that AVs can spur more dense urban centres, and that it is unlikely that the benefits of better accessibility will be evenly spread among social groups.

The effects on people's perceived safety and concerns for privacy when large amounts of data need to be processed for the required communication are not quantified and valued in this study. People may presume higher risks related to vehicles without a driver and to reduced privacy, at least during an early stage. On the other hand, driver-related mistakes are eliminated. Bansal and Kockelman [20] estimated the willingness to pay among a sample of people in Austin to be 7253 USD for a level 4 AV, and that fewer accidents was the perceived most important benefit and equipment failure the biggest risk. König and Neumayr [24] also identified mixed attitudes towards AVs and that safety and reliability would increase over time. Kyriakidis *et al.* [17] studied 5000 people in 40 countries and 69 percent stated that AVs would reach 50 percent of the market before the year 2050. Risks were related to software, legal issues and safety. It is likely that the new technology will not be introduced on a mass scale until safety is at least as high as with today's vehicles. In this study, this is reflected in lower costs for accidents. Any effects on perceived safety that differs from the assumed change in safety and on the cost for privacy are not quantified in this study.

Problems with congestion can be both enhanced and mitigated. This is determined by how the quantity of travelling, the traffic flow and the number of vehicles change with AVs. Improved mobility may stimulate more traffic, as well as empty vehicles driving to their parking spaces or picking up people sharing cars, which may counteract the positive effects. Transport Analysis [18] has analysed the effects of shorter distances between vehicles on highways and at crossings with traffic signals in Sweden. On highways, mobility will only improve markedly when AVs have significantly outnumbered MDVs. Then, the space between vehicles can be reduced to 0.1 second. At crossings, significant gains will occur with SDV shares of above 80 percent. Zaiqiang and Ting [27] estimated a model with mixed traffic and concluded that with a market share of less than 39 percent, AVs will influence traffic flow negatively and not until the market share exceeds 68 percent will they significantly improve traffic capacity on the road. The shares of AVs used in this study do not reach the levels where the large effects supposedly occur, which is why changed congestion is not quantified.

6. Example Calculations

In this section, values for SGC presented in Section 4 are used to make an example calculation of the magnitude of the effects of automated vehicles in 2025 and 2040. An initial example calculation of benefits and costs of self-driving vehicles on the road was made by the authors for a Swedish Government Inquiry [36]. The present example is a revised and extended calculation.

6.1. Traffic Volumes and Shares of AVs

In the example calculations, traffic volumes are based on official Swedish statistics and forecasts. In 2015, traffic by Swedish registered trucks totalled 3043 million vehicle kilometres on domestic roads. Traffic by foreign vehicles is not registered, but was estimated at 625 million vehicle kilometres in 2010, and rising (Transport Analysis [37]). The Swedish Transport Administration [38] makes forecasts for the development of traffic in Sweden. Their estimates are used to calculate total traffic in 2025 and 2040, without increases due to decreased GC. Increased traffic that will follow as a result of the lower generalized cost associated with AVs (Q_2-Q_1 in Formula 2) is estimated with elasticities.

Table 6 shows the estimated number of vehicle kilometres for the vehicle types and the share of AVs that is assumed for each, excluding the resulting newly generated traffic. This is used to calculate the value of Q_1 in Figure 1. The shares of AVs are based on the literature review. For MGV24 some traffic is assumed to take place in designated closed industrial areas even in the reference alternative.

Transport Analysis [39] estimates that in 2015, 65,854 million vehicle kilometres were driven by passenger cars on Swedish roads. The forecast increase in passenger traffic by car is based on the Swedish Transport Administration [40]. As for trucks, this does not include the increase in traffic that will follow as a result of the lower generalized cost of AVs. Table 7 shows the estimated number of vehicle kilometres for an average car and the share of AVs, excluding the newly generated traffic.

Table 6. Vkm and share of AVs for vehicle types in 2025 and 2040, trucks.

Year	Vehicle type	Total increase	Million vkm (incl. foreign)	Assumed share of AVs	
				Reference alt.	Studied alt.
	long-distance	22%	3160	0%	10%
22,025	distribution	16%	418	0%	5%
	construction	16%	547	10%	20%
	long-distance	65%	4280	0%	50%
22,040	distribution	44%	520	0%	50%
	construction	44%	681	10%	50%

Source: The Swedish Transport Administration [38], and own estimates based on Transport Analysis [30].

Table 7. Vkm and share of AVs in 2025 and 2040, car.

Year	Total increase	Million vkm	Assumed share of AVs	
			Reference alt.	Studied alt.
2025	12%	73.76	0	10%
2040	26%	82.98	0	50%

Source: Annual increases: The Swedish Transport Administration [40]; million vehicle kilometres: Transport Analysis [39].

6.2. Elasticities

Litman [41] has conducted a literature review of elasticities in the transportation sector. Based on this we use a price elasticity of demand of −0.8 for long-distance transportation by trucks. For the other truck types we use −0.5, as they have fewer substitutes. The potential for substituting transportation by train with trucks is considered limited. No reliable measures of cross-price elasticities are found for railway transportation, but according to the Swedish Transport Administration [31], only four percent of long-distance truck traffic could be replaced by train. Accounting for foreign trucks, five percent of the new traffic by HGV40 is assumed to be shifted from rail to road and none for the other two truck types. Based on Transport Analysis [19], convoy driving (platooning) is assumed 10 percent of long-distance transportation in 2025 and 50 percent in 2040. No effect from smoother driving is accounted for MGV 16 and 24.

Price elasticities of demand for transportation by car are based on an analysis of the effects of introducing congestion fees in Stockholm and Gothenburg (Börjesson and Kristoffersson [42]) and studies referred to in Litman [41] and SIKA [43]. We use a price elasticity of −0.6. Based on a review of cross price elasticities for train due to changes in the prices for driving by car (Dickinson and Wretstrand [44]), a cross price elasticity of 0.25 for passenger traffic by train is used. Combined with the shares of passenger traffic by train and car, 5 percent of the new traffic by car is assumed to be transferred from train.

6.3. Differences between Price and Social Marginal Cost

A Swedish project called Samkost 2 has estimated how well external effects are priced to the producers of transportation in Sweden (The Swedish National Road and Transport Research Institute [33]). For road transport, they estimate that passenger car traffic is somewhat overpriced by the taxes on fuel, while heavy truck traffic is under-priced. Concerning transport by train, the carriers are estimated to be under-priced by rail charges for passenger trains and even more by freight trains. If all external effects are internalized in the marginal costs to the producers by Pigouvian taxes, freight transportation on the road as well as all transportation by train might be priced too high due to imperfect competition or cost structures in the transport markets.

Based on the unit costs for freight trains (The Swedish Transport Administra-

tion [31]) and an assumption of the same average speed for freight trains as for trucks, the social marginal costs for freight transportation by train are estimated. Based on the annual report from Green Cargo [45], the largest provider of freight transportation by train in Sweden, an average price for consumers of 2.3 times higher than the marginal cost for the provider and 1.8 times higher than the social marginal cost is estimated. According to the Swedish Transport Agency [46], the profit of freight train businesses is insignificant or even negative. Thus, as the price exceeds marginal cost without resulting in significant profits, the explanation is high fixed costs. Consequently, in the present study, a price for transport by train that is 80 percent over the social marginal cost is used and an adjustment post is added. Freight transportation by truck is considered a competitive business, based on the Swedish Transport Agency [47]. Overhead costs in the industry are 10 - 20 percent of total costs. Thus, we use a price in this sector that is 20 percent over the social marginal cost. Additional posts are added in the example calculation for freight accordingly, as shown by Formulas 4 and 5.

Based on the annual report from the main state-owned company for passenger traffic, SJ [48], the traffic volume (Transport Analysis [49]), the average speed, the average number of passengers per train (The Swedish Transport Administration [31]) and external costs (The Swedish National Road and Transport Research Institute [33]), the price for passenger traffic by train is estimated to be 2.5 times the social marginal cost. For traffic shifted from train to car, an adjustment post as in Formula 5, with a cost of 0.51 SEK per vehicle kilometre is added.

6.4. Results

In this section, example calculations of the net benefits of AVs are carried out and considered in relation to how much the capital costs (defined earlier) can increase without making AVs unprofitable for society. The analysis includes freight transport by truck and passenger transport by car, and considers effects on the substitute markets passenger transport and freight by train. Transportation in the substitute markets air and sea is not considered. They account for 2.8 and 0.6 percent of passenger kilometres respectively in Sweden (Transport Analysis [39] [50]).

Table 8(a) and Table 8(b) summarize the quantities and values used in the example calculations for trucks and cars.

When calculating new traffic for passenger transport by car it is, as mentioned, assumed that all external effects are internalized to the GC for the consumer. This means that the savings in GC that the traveller in an AV will perceive are somewhat higher than the savings for society in 2025 but somewhat lower in 2040. The savings from reduced fuel when the price includes all external effects will include noise that will remain unchanged, but the savings in traffic safety in 2040 will be greater than the part included in the fuel price (saved fuel

is 10% while increased traffic safety is 30%). The difference is less than five percent. The relative change in GC combined with the applied price elasticity of demand results in increases of 7.2 percent in 2025 and 7.7 percent in 2040 for private travelling by car, and 13.4 percent in 2025 and 13.9 percent in 2040 for work travelling by car. The corresponding increase in vehicle kilometres for trucks in long-distance traffic is 7.0 percent in 2025 and 15.5 percent in 2040.

Table 9(a) and Table 9(b) show the quantified and valued effects of AVs for the years 2025 and 2040 in million euro[2]. All calculations are an average of urban and long-distance traffic.

Table 8. (a) Quantities and values for trucks; (b) Quantities and values for cars.

(a)

Effect	Quantities and values
Saved driver costs for long-distance	15% of long-distance transport by AV in 2025 is driver-free, 50% in 2050
Saved driver costs for other transport by truck	10% of distribution and 20% of construction vehicles that are AVs are driver-free in 2025, 50% in 2040.
Saved fuel and environmental costs due to convoy driving	convoy = 10% of long-distance in 2025, 50% in 2040; 10% saved fuel
Increased traffic safety	10% fewer accidents in 2025 and 30% in 2040 compared with today
Net benefit new traffic and added post for difference between price and MC	Price elasticity of demand for long-distance is −0.8, other transport −0.5; price 20% over marginal cost
Adjustment post: transferred traffic from train	5% of new long-distance transport transferred from train

(b)

Effect	Quantities and values
Decreased travel time cost, private travelling	The difference between travel value in car and train
Decreased travel time cost, work travelling	30% of the travel time in a car is used to work in an AV
Saved fuel and reduced emissions	Smoother driving means 10% less fuel and emissions
Increased traffic safety	10% fewer accidents in 2025 and 30% in 2040 than today
Net benefit of new traffic	The price elasticity of demand for cars is −0.6
Adjustment post: transferred traffic from train	5% of new passenger transport transferred from train

[2]The average exchange rate 9.3562 SEK/euro for 2014 (the Riksbank [51]) is used.

Table 9. (a) Effects in example calculations for freight by truck, million euros; (b) Effects in example calculations for passenger transport by car, million euros.

(a)

	2025	2040
Saved driver costs for long-distance transport	31.4	706.8
Saved driver costs for other transport by truck	13.4	287.6
Saved fuel due to convoy driving	0.9	34.9
Saved environmental costs due to convoy driving	0.6	25.3
Increased traffic safety	1.7	44.0
New traffic	1.2	30.6
Adjustment post: difference between consumer price and MC	0.5	12.2
Added post: Transferred traffic from train	− 0.5	− 2.6

(b)

Effect	2025	2040
Decreased travel time cost, private travelling	218.3	1534.9
Decreased travel time cost, work travelling	110.2	773.2
Saved fuel	45.7	288.2
Saved environmental effects	18.1	97.6
Increased traffic safety	15.0	306.0
New traffic	19.0	137.8
Adjustment post: Transferred traffic from train	−1.6	−9.4

The net benefits of the quantified and valued effects of self-driving trucks are 49.2 million euro in 2025. Saved driver costs are the largest benefit. For total net benefits to exceed costs in 2025, capital costs cannot rise by more than 36.8 percent. The most important factor for the size of net benefits for AVs is that a sufficient proportion of travelling is actually carried out without drivers on board or that the driver performs other duties that can free up other employees. As truck drivers currently carry out other tasks than only driving the vehicle, we do not estimate that more than 50 percent of the drivers' time can be freed up by 2040. By 2040, the effects are greater than 2025, because higher shares of traffic consist of AVs, the total traffic has grown and larger shares of traffic by AV are assumed to exist without any driver on board. The net benefit of the quantified and valued effects becomes 1138.9 million euro and capital costs can increase by 127.9 percent before AVs become unprofitable to society in the example calculations.

For passenger transport, the net benefit of the quantified and valued effects is 424.7 million euro in 2025. The biggest calculated effect is the decreased travel time costs with AVs. Although work travelling only accounts for a tenth of transport, it accounts for one third of the benefits of reduced travel costs. This is because the travel time cost is higher per hour for work travelling than for pri-

vate travelling. For the year 2040, the net benefit is 3128.3 million euro. For the benefits and costs in the example calculation to be equal, with all other quantities and values equal, the capital cost for AVs may be no more than 22.3 percent higher than for MDVs in 2025 and 29.2 percent higher in 2040.

If all external effects are internalized in GC for the consumer, the effects of decreased GC that the traveller in an AV will experience are somewhat larger than the savings for society in 2025 but somewhat lower in 2040. The difference is less than five percent between what the consumers perceive and the total effects for society. For trucks, the difference is less than three percent.

6.5. Sensitivity Analysis

A sensitivity analysis means that quantities and values are varied to see the effect on the overall result. One factor at a time is varied in the example calculation for AVs. Table 10(a) shows the results for 2025 and Table 10(b) for 2040. The first row shows how much capital costs can increase to reach the point where society's net benefits are equal to the costs in the main calculation presented above, and then the percentage with some alternatives. It can be noted that transport volume and the share of AVs have no impact on whether benefits exceed costs of AVs in the example calculations, since benefits and costs will increase by the same proportion because all effects in the example calculations are per vehicle kilometre. Thus, forecasts of growth in traffic or shares of AVs will not determine whether AVs' benefits exceed costs to society, only how big the gain (or loss) is. For this to alter, one benefit or cost must change more than the others do. As the sensitivity analysis shows, altering the quantities or values related to saving driver costs has the biggest impact on the results.

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7. Conclusions

Table 11 is a summary of the shares of the net benefits for autonomous trucks and cars in the example calculations, without capital costs.

The most important factor for benefits to exceed costs for AVs for freight transport by truck is the share of the number of vehicle kilometres by AVs driven without a driver. The sensitivity analysis underlines that only a minor variation is crucial for the result for autonomous trucks. For autonomous cars, the most decisive effect is the extent to which the drivers' value of travel time changes.

Table 10. (a) Sensitivity analysis for transport by AVs in 2025; (b) Sensitivity analysis for transport by AVs in 2040.

(a)

	Maximum increase in capital cost for AVs for benefits to exceed costs	
	Truck	Car
Main example calculation	**36.8%**	**22.3%**
Halved increase in transport volume	36.8%	22.3%
Share of AVs is twice as large	36.8%	22.3%
Share of AVs is half as large	36.8%	22.3%
Driver-free 7.5% of AVs in long-distance transport	24.5%	
Driver-free 30% of AVs in long-distance transport	61.3%	
The change in travel time value is twice as large		39.5%
The change in travel time value is half as large		13.7%
Twice as large saving in fuel	38.0%	25.6%
Twice as large decrease in accidents	38.1%	23.0%
The decrease in emissions is half as large from a given reduction in fuel consumption	36.6%	21.8%
25% higher average speed	32.8%	19.6%
25% lower average speed	42.2%	28.8%
Platooning 20% instead of 10% of long-distance transport	38.0%	

(b)

	Maximum increase in capital cost for AVs for benefits to exceed costs	
	Truck	Car
Main example calculation	**127.9%**	**29.1%**
Halved increase in transport volume	127.9%	29.1%
Share of AVs is twice as large	127.9%	29.1%
Share of AVs is half as large	127.9%	29.1%
Driver-free 25% instead of 50% of AVs in long-distance transport	86.7%	29.1%
The change in travel time value is twice as large		50.6%
The change in travel time value is half as large		18.4%
Twice as large saving in fuel	135.0%	32.7%
Twice as large decrease in accidents (60% instead of 30%)	132.8%	32.0%
The decrease in emissions is half as large from a given decrease in fuel consumption	126.4%	28.7%
25% higher average speed	114.4%	24.8%
25% lower average speed	145.7%	36.3%

Table 11. Contributing shares of net benefits without capital costs in the example calculations.

	2025		2040	
	Freight	Passenger	Freight	Passenger
Driver costs	91.1%	77.3%	87.3%	73.8%
Fuel	1.8%	10.8%	3.1%	9.2%
Emissions	1.2%	4.3%	2.2%	3.1%
Safety	3.5%	3.5%	3.9%	9.8%
Net new traffic	2.4%	4.1%	3.5%	4.1%

Reduction in fuel consumption because of convoys and smoother driving and the resulting decrease in emissions on the roads are benefits. However, a shift to fossil-free fuels in the future may reduce these benefits. In the example, emission reductions represent 25 - 28 percent of the benefit of reduced fuel consumption for cars and 40 - 42 percent for trucks. As is demonstrated by the example calculations, these factors contribute to a relatively small share of the total benefits. Better safety is another effect. As the effect of freeing drivers from their duties is so dominant, alternative scenarios about fuel consumption or safety have small effects on the result. The acceptance level for autonomous vehicles is another crucial factor. We have used a modest decrease in accidents by 10 percent for 2025, but it is possible that the autonomous vehicles must be a lot safer than MDVs before they will be accepted on the roads.

As autonomous vehicles have a lower generalized cost, the total traffic will increase. More traffic is a net benefit, as long as the price to the consumer is equal to the social marginal cost. This contributes 2.4 - 4.1 percent of the total benefits, including the lost value of rail traffic.

The real gain is achieved if trucks and cars can indeed be driver-free and resources saved for other uses. For drivers of cars, this shift is unproblematic. For trucks, it means a period of structural change in the labour market. As autonomous trucks will be replacing manually driven trucks during a period that will probably last for several decades, the labour market will have time to adjust and no permanent unemployment can be expected.

No assumptions are made about how much an AV will cost. The example calculations show how much higher capital costs (including technology development for vehicles, higher capital costs due to more expensive production costs and changed maintenance costs) for AVs can be compared to MDVs without costs being larger than the benefits. In the example calculations, the costs can increase more than marginally without making AVs unprofitable to society, as presented in Table 10. The margin for increases in capital costs per vehicle kilometre for trucks is relatively higher.

The results show that nearly all benefits will come to consumers and producers of the goods. Thus, an important policy conclusion is that there is no reason for giving subsidies to the industry producing AVs or to the consumers buying

them. The market mechanisms will lead to the introduction of AVs without subsidies if it is profitable. The sole external effect in this study is part of a possible future reduction in accidents compared to MDVs, but this effect is relatively small in Sweden. However, it is important to adjust regulations so that the new technology can be implemented if safety is satisfactory.

In addition to the contribution from this study, the value of new groups being able to ride a car, the perceived safety, privacy, changed congestion and change in land use are factors that remain to be analysed.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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