sustainability

MDPI

Article

A Systemic View of Future Mobility Scenario Impacts on and Their Implications for City Organizational LCA: The Case of Autonomous Driving in Vienna

Alexander Cremer [1], Katrin Müller [2] and Matthias Finkbeiner [1,*]

[1] Institute of Environmental Technology, Technische Universität Berlin, 10623 Berlin, Germany; alexander.rt.cremer@campus.tu-berlin.de
[2] Siemens AG, 13629 Berlin, Germany; katrin.km.mueller@siemens.com
* Correspondence: Matthias.finkbeiner@tu-berlin.de

Abstract: Autonomous vehicles (AV) are expected to significantly reshape urban mobility. Whether advancements at vehicle level also translate into positive environmental outcomes at city level is still uncertain. We investigate under which conditions a city could enable low emission AV mobility and what challenges are to be expected along the way from an environmental point of view. We build upon our recent environmental performance study of Vienna and combine city organizational life cycle assessment (city-OLCA) with AV transport models from literature for three AV use cases: an own AV, a shared AV, and a shared AV ride service. Most cases lower Vienna's passenger capacity (by up to 28%) and increase motorized road traffic by a maximum of 49% (own AVs). Traffic relief is observed for shared AVs (−40%) if accompanied by a conventional car ban. This case reduces transport related GHG emissions compared to both Vienna's current baseline (−60%) and a future electrified transportation system (−4.2%). These transformations have also shifted emission responsibility to the public level. While Vienna's total GHG emissions could be reduced by 12%, the city's emission responsibility increases from 25% to 32%. Efficient mass transit, the electrification of the mobility sector and grid decarbonization are key to reducing transport emissions in Vienna. The direction of GHG emission development will be determined by the extent to which these conditions are promoted. AV mobility probably will not be a main contributor.

Keywords: autonomous vehicles; life cycle assessment; organizational LCA; future mobility; cities

check for updates

Citation: Cremer, A.; Müller, K.; Finkbeiner, M. A Systemic View of Future Mobility Scenario Impacts on and Their Implications for City Organizational LCA: The Case of Autonomous Driving in Vienna. *Sustainability* **2022**, *14*, 158. https://doi.org/10.3390/su14010158

Academic Editor: Eckard Helmers

Received: 15 November 2021
Accepted: 20 December 2021
Published: 24 December 2021

1. Introduction

While the effects of autonomous vehicles (AVs) are subject to controversial debates, most scholars agree that AVs will be an integral part of future transportation systems [1–3]. If AVs follow the deployment of previous vehicle technologies, they are expected to dominate new vehicle sales in one to three decades [4].

Self-driving vehicle technology could yield significant improvements in safety [5], time utilization [6], parking demand [7], accessibility [8], and traffic capacity [9]. The vehicle itself is expected to amplify fuel savings through smart driving practices such as dynamic ecorouting or speed harmonization. Literature reports fuel efficiency gains of, usually, between 5% and 20% [10–13].

Many of these improvements will reduce energy demand per transport service. However, some of them could lead to trade offs. Additional travel (e.g., to perform productive work while driving or due to modal shifts) could offset benefits at vehicle level [6]. The extents of these effects are still uncertain. Modeling studies estimate a wide range of travel increases, from 8% to 57%, depending on the AV use case and underlying transportation system [14–17].

How AV mobility translates into environmental benefits or drawbacks is less known. Literature reports the effect of AV transportation impacts on greenhouse gas (GHG) emissions from −25% to +50% [18–21]. Since most studies still focus on travel behavior and energy issues, GHG impacts refer to highly aggregated approximations. They often do not consider indirect emissions through, e.g., the production of vehicles or generation of fuel and electricity. In addition, while AV research is mostly focused on modeling the transportation system, it lacks consideration of the local government's role as being responsible for maintaining the city's operational needs while reducing its environmental pressures.

This makes it hard for city managers to establish the right framework for (future) AV mobility in their city. Should they facilitate a rapid uptake of AVs or implement restrictive measures to ensure high performance, low emission transportation?

The aim of this paper is to find out under which conditions a city could enable positive effects of AV mobility and help city managers make better informed decisions. We will build upon our recent development in urban environmental research to assess the impacts of future mobility scenarios incorporating AV use cases from a systemic point of view. Estimating environmental impacts of and in cities is a fairly challenging exercise on its own. With city organizational life cycle assessment (city-OLCA), we introduced a novel decision–support framework that acknowledges responsibilities and highlights which emission levels can be influenced by the local government [22]. So far, city-OLCA has only been applied as a baseline case study for Vienna [23]. We now combine the latest AV impact models from literature with the parameterized transport sector model from our Vienna case study [23] and discuss different mobility scenarios.

Vienna's city-OLCA considers all major city activities, from housing to waste management. In this analysis, we separate the transport sector model from the entire city model and investigate how different mobility scenarios would change its performance. Then, we extend the scope to the entire city and discuss emission and responsibility transformations based on the most promising candidate for emission reduction.

In this study, we consider three use cases: an own AV, a shared AV and a shared AV ride service. More differentiation, such as platooning vs. station-based, will not be subject to this work. We do not aim at predicting a most likely mobility scenario in Vienna. We, rather, formulate extreme scenarios to identify the most influencing parameters that should help identify advantageous framework conditions in a city.

Results gained from this study go beyond the scope of previous studies dealing with the environmental effects of AV mobility. Firstly, because we follow a life cycle approach in estimating environmental effects. Secondly, because we include the view point of the local government into our analysis.

Section 2 describes the methodology to assess AV induced impacts on the urban level and introduces Vienna's city-OLCA profile as basis for further discussion. Section 3 presents scenario results on the chosen performance indicators. We will then interpret these results on both the transportation system level (Section 4) and the city level (Section 5). Section 6 concludes with final remarks on the local government's responsibility in organizing and securing future mobility needs within their city.

2. Methodology

We base our analysis on Vienna's transport system as presented in [23] (Section 2.1) and apply two extreme mobility scenarios (Section 2.2). In each scenario, the three use cases—own AV, shared AV, and shared AV ride service—will have distinct effects taken from literature, as described in Section 2.3. We will consider typical transport parameters, such as motorized road traffic and passenger capacity, to represent the scenario's impacts on the transportation system. GHG emissions are calculated as described in Section 2.4 and an overall view of the entire city is given in Section 2.5. Results for each case will comprise of a changed modal split, GHG emissions, and the transport parameters mentioned. Details are given in the respective following sections.

2.1. Baselining Vienna's Passenger Transportation System

Vienna's passenger transport sector is characterized by both a strong public transport share and individual car travel alike. The baseline configuration is taken from our city-

OLCA study as reported in [23]. Freight transport is out of scope for this work. To describe Vienna's baseline transport system and track its performance throughout the analysis, we mainly rely on four key parameters: transport demand, modal split, utilized capacity, and GHG emissions. A description of each parameter is given in Table 1.

Table 1. Baseline parameters used to track Vienna's transport system performance across the mobility scenario analysis.

Parameter	Unit	Description	Reasoning
Transport demand	pkm/a	Total passenger transport demand in the city with all modes of transport per year	Main driver of how much service is to be provided in the city
Modal split	%/pkm	Share of different modes on the total passenger transport demand	Main driver how the transport service is provided
Utilized capacity	P	Utilized passenger capacity per vehicle km for all modes	Main driver of how efficient a specific transport service is
GHG emissions	kg CO_2e	GHG emissions per vehicle km including production and use phase	Key parameter of environmental performance of the transport service

Total passenger transport demand in Vienna is 19.24 bn passenger kilometer (pkm) for the 2016 baseline. Overall utilized passenger capacity is 2.2 passengers per vehicle kilometer (vkm) driven. This represents an average value over the entire passenger transportation system, taking all modes of transport into account. The relation between capacity, vkm and pkm is described in Section 2.4. GHG emissions from passenger transport demand is 2876 kt CO_2e. This equals nearly 1.6 t CO_2e per capita per year, according to population statistics from [24]. Figure 1 summarizes the main baseline performance indicators. Here, transport demand per mode is shown in total pkm.

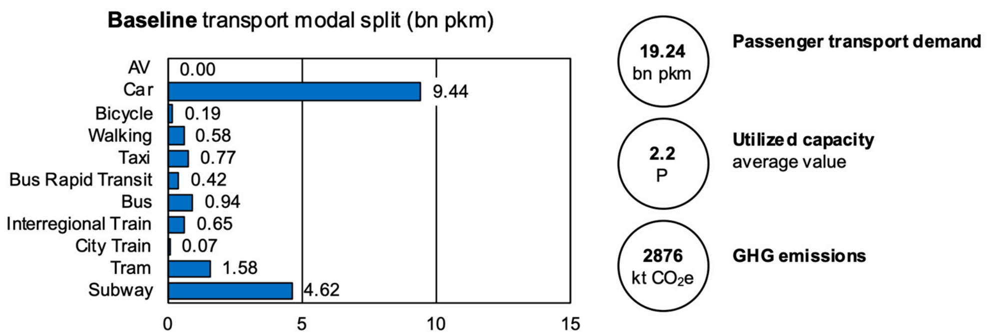

Figure 1. Summary of Vienna's baseline performance indicators according to [23].

2.2. Scenario Definition

We formulate two scenarios in which all three AV services (use cases) operate. The scenarios were chosen to reflect two extreme conditions. Scenario A restricts conventional car traffic and strengthens public transport. Scenario B keeps conventional cars in the city while prioritizing AVs over public road transport. These two extremes can be seen as counterparts of a policy agenda applying a rather high influential (Scenario A) versus a low influential (Scenario B) power, respectively. The extent to which AVs will meet transport demand in the city (modal shift) will be determined by the scenario itself and by distinct effects deducted from literature (see Section 2.3). These effects can comprise of an induced (additional) demand, changed capacity utilizations or individual modal shifts. The general shifting logic behind each scenario is described as follows:

- **Scenario A**: Conventional car ban. New AV services enter the city based on own assumptions and distinct effects deducted from literature. If, as a result, the conventional car share is > 0% (based on pkm), the remaining demand will be met by all other modes left. It will be distributed to all modes based on their new share after the AV uptake.

- **Scenario B**: Maximal individualization of transport. New AV services enter the city based on expert assumptions and distinct effects deducted from literature. If, as a result, the conventional bus share is > 0% (based on pkm), the remaining bus demand will also be met by the AV service.

2.3. AV Effect Mechanisms and Scenario Assumptions

2.3.1. Individual AV

In determining effects of owning an individual AV, we refer to the study by [6]. In their work, the authors conducted a macroeconomic study to estimate rebound effects (induced demand) of private AVs. Unlike previous studies, they not only considered a predicted fuel efficiency increase. Time benefits were also monetarized based on the user's socioeconomic situation (income group). This allows to calculate demand behavior for AVs based on price elasticities for the two factors fuel efficiency and time benefits.

The induced travel demand (δ) can be expressed as percentage of baseline travel demand with fuel elasticities $\left(\varepsilon_f\right)$ and time elasticities (ε_t) for each income group according to Equation (1) [6]:

$$\delta = \left(\frac{1}{1+x}\right)^{\varepsilon_f} (1-y)^{\varepsilon_t} - 1 \tag{1}$$

with x being a percentage increase in fuel efficiency and y being a percentage decrease in time cost. The authors assumed a fuel efficiency increase by between 5% and 20% (x = 0.05,0.2) and time benefits of maximum 60% (y = 0,0.6) based on comparisons with train rides.

Results of this model are as follows. For the lowest income group, the range of simulated price changes forecasts a minimum of 1% induced travel and a maximum of 35%. The highest income group produces a minimum of 2% and a maximum forecast of 58% induced travel. All price elasticities per income group can be found in [6].

We transferred this procedure to Vienna, assuming the reported price elasticities are applicable to the city. Equation (1) gives us only the induced demand per income group. Since different income groups drive differently, a high share of rich households (i.e., high elastic demand) does not necessarily mean proportionally high induced demand. To estimate the total induced demand in Vienna, we had to find out each income group's contribution to the baseline car travel demand. We achieved this by introducing a driving performance factor per income group as reported in [25]. We also needed to break down Vienna's 19 reported income levels from [26] into five income groups to match the US scale used in [6] and utilize its respective price elasticities. Breaking down the income levels was performed by maintaining the relative differences between the income groups of the US scale. This could easily be achieved as Vienna's data was disaggregated enough. Income group distribution, driving performance, and final travel demand share is shown in Figure S1.

With regards to the scenarios from Section 2.2, we assume a (theoretical) 1:1 shift of private conventional cars to AVs. In favor of our premise to formulate extreme scenarios, we also take the upper range of fuel efficiency increase (i.e., 20%) and time benefits (i.e., 60%) to calculate induced individual AV demand. Since the individual AV use case is by definition limited to individual transportation, Scenario B does not apply or will produce the same results as Scenario A, respectively.

In summary, we used Vienna specific data for income structure, driving performance, and baseline travel demand. Price elasticities, vehicle efficiency increase and time benefits as well as Equation (1) were taken from [6].

2.3.2. Shared AV

An autonomous car sharing fleet corresponds to a conventional taxi service—with the convenience of getting picked up anywhere, anytime. However, without a driver.

Earlier studies followed the rational of replacing conventional trips in a city with a certain shared AV fleet while meeting the same transport demand, thus significantly reducing individual car travel, increasing convenience and eliminating the need to buy an own AV. These studies show a theoretical potential but fail to take user preferences into account, i.e., behavioral parameters.

A recent study by [15] to support Zurich's transport office filled this gap. The authors introduced a simulation where a small fleet would be unattractive due to long waiting times and a large fleet would increase prices. A "sweet spot" of 3000 taxis was identified as an optimum, covering 15% of the city's total pkm demand.

For the reported case, vehicle km increased by around 24% with the introduction of an AV taxi fleet. This is mainly because of a shift from public transport to AVs and a lower capacity utilization of AVs than conventional cars (empty trips). Total pkm in the city remained constant.

Based on the reported data, we deducted the change in capacity utilization in percent for public transport modes and for the AV itself (Equations (2) and (3)). The data suggest that, while the public transport capacity decreases with an uptake of shared AVs, the capacity of the AV taxi increases. This can be explained as follows: If only 1% of the transport demand is carried out by AV taxis, very few vehicles would cover trips in each corner of the city, resulting in driving empty most of the time. With an increase in vehicle fleet, empty runs are reduced.

The passenger capacity of public transport modes (C_{P2}) and AV taxis (C_{AV}) follows

$$C_{P2} = C_{P1}(1 - X_{AV}0.64) \text{ and} \tag{2}$$

$$C_{CAV} = X_{AV}4.77 \tag{3}$$

with C_{P1} being the passenger capacity before the AV uptake and X_{AV} being the modal share of AVs in percent of total transport demand. For an AV service share of 15%, this results in 0.7 passengers per AV (while at 1% it would only be 0.05).

With regards to the scenarios from Section 2.2, we assume an initial 15% modal share of AVs that resulted in an optimal fleet in Zurich and keep the total transport demand constant. For scenario A, remaining conventional car traffic is then eliminated by increasing all other modes, including the initial AV share. This triggers an iteration of capacity calculation based on the new AV share. For scenario B, all bus travel is shifted to the AV taxi fleet by increasing its share accordingly. Again, final capacity of modes is then iterated according to Equations (2) and (3).

In summary, we used Vienna specific values for baseline travel demand, baseline passenger capacities, and baseline modal split. Initial AV uptake as well as the modal split factors 0.64 and 4.77 in Equations (2) and (3) were deducted from [15]. The Equations have been formulated by the authors of the present paper as a mathematical representation of data reported and effects explained in [15].

2.3.3. Shared AV Ride

To further increase passenger capacity of the AV, rides could be shared along the same travel route. A blueprint on how to develop a commercially viable AV ride sharing service in cities is presented in the MERGE Greenwich project [17]. Similar to Hörl's study on car sharing [15], the authors considered user preferences as well as technological and financial restrictions.

As dominating factor, the willingness to share a ride limits the overall potential uptake of an AV ride sharing fleet (although more trips might be sharable in theory). In fact, only 41% of passengers were willing to share their ride with another person regularly, based on customer research [17]. Being willing *and* able to share a ride in the modeled area resulted in a possible AV ride sharing for 28% of total trips.

By investigating the reported data, we could deduct a change in modal choice and, specifically, conclude where customers came from (shifting factors). The final modal share for public transport modes (X_{P2}) and conventional private cars (X_{C2}) can be calculated according to Equations (4) and (5):

$$X_{P2} = X_{P1} - (Y_T W_T S_P) \text{ and} \quad (4)$$

$$X_{C2} = X_{C1} - (Y_T W_T S_C) \quad (5)$$

with X_{P1} being the modal share of a public transport mode before the AV uptake and Y_T and W_T being the potential sharable trips in the city and the willingness to share, respectively. S_P denotes the specific shifting factors from public transport modes to the AV service. The modal change of conventional private cars behaves analogous.

With regards to the scenarios from Section 2.2, we assume that all trips in Vienna could be shared $(Y_T = 1)$. The willingness to share a ride is adopted from [17], assuming customer preferences in London are applicable to Vienna $(W_T = 0.41)$. With the specific shifting factors from Table S1, we can calculate a change in modal split with a resulting initial modal share of AVs in the city. For scenario A, the car ban will then increase both AVs and all remaining modes. For scenario B, bus travel is entirely attributed to the AV ride sharing service.

In summary, we used Vienna specific values for baseline modal splits and potential sharable trips. The willingness to share as well as relative mode shifting factors in Equations (4) and (5) were taken from [16]. The Equations have been formulated by the authors of the present paper as a mathematical representation of data reported and effects explained in [16].

2.4. Environmental Impact Calculation Model

All individual cases described above will feed into the LCA transport model from our recently presented city-OLCA case study for Vienna [23]. A comprehensive list of the calculation setup used for the resulting six cases is shown in Table S2. In this work, we will first have an isolated view of transportation related results and then discuss how they interact with other sectors and could change the entire city-OLCA profile.

The LCA transport model we refer to was calculated in SimaPro v8.5 using the Ecoinvent database v3.4 [27]. In this work, we focus on global warming only, measured in kg CO_2e. We consider the life cycle phases use and production. This includes direct emissions from vehicle operation as well as upstream emissions related to fuel and electricity generation. Likewise, vehicle, road and rail construction including maintenance are covered in the model. All emissions were calculated at vehicle level, i.e., per vkm driven. A detailed process overview is provided in [23]. Operational emissions are based on the vehicle's specific fuel (diesel or petrol) or electricity consumption, as displayed in Table 2. With a given passenger capacity, transport demand in pkm was broken down to vehicle level. For example, a subway in Vienna effectively carries 259 passengers per vkm. Hence, 1 vkm equals 259 pkm. The utilized passenger capacity for each mode in Vienna was taken from [28].

We assume AVs to be fully electric, as industry reference suggest. To account for grid mix impacts, we will compare the existing Austrian grid mix (327 gCO_2e/kWh) with the Swedish grid mix (44 gCO_2e/kWh), representing Europe's most decarbonized grid [31].

2.5. Vienna's GHG Profile According to City-OLCA

In full city-OLCA, the transportation system is split according to its responsibility into individual transport and public transport (Figure 2). Taking all activities into account, Vienna's city administration is responsible for 25% of citywide GHG emissions [23]. This includes any public service they provide (electricity production, community housing, public transport, etc.). In city-OLCA, these activities are considered **level 1** (own operations) and **level 2** (contracted services) activities. Vienna provides all public services with publicly owned companies (level 1), which means that their operational power (i.e., governmental control) is considered high. Public transport accounts for 8% of level 1+2 emissions or 304 kt CO_2e, respectively. Activities indirectly influenced by the local government are categorized

level 3a and account for 28% of overall emissions. Within level 3a, individual transport dominates with 60% or 2358 kt CO_2e, respectively. Activities with the government's least to no control are represented in **level 3b**, which make up the remaining 47% of total emissions. Level 3b is almost entirely led by food and goods consumption. Based on our results from mobility scenario impacts to the transportation system (Sections 3 and 4), Vienna's full city-OLCA will be revisited in Section 5. This also includes a discussion on city-OLCA's general potentials in supporting future urban environmental research studies.

Table 2. Mode specific energy consumption and utilized capacity values.

Mode	Energy Consumption Operation				Utilized Capacity in Vienna		
	Energy Carrier	Value	Unit	Source	Value	Unit	Source
Subway	Electric	56.52	MJ/vkm	[27]	259	Passengers	[28]
Tram	Electric	27.04	MJ/vkm	[27]	71	Passengers	[28]
City train	Electric	65.52	MJ/vkm	[27]	259	Passengers	[28]
Interregional train	Electric	82.08	MJ/vkm	[27]	259	Passengers	[28]
Bus	Diesel	15.78	MJ/vkm	[27]	17	Passengers	[28]
	Electric	7.81	MJ/vkm	[29]	17	Passengers	[28]
Bus rapid transit	Diesel	15.78	MJ/vkm	[27]	28	Passengers	[28]
Car	Petrol	2.71	MJ/vkm	[27]	1.3	Passengers	[28]
	Diesel	2.41	MJ/vkm	[27]	1.3	Passengers	[28]
	Electric	0.67	MJ/vkm	[29]	1.3	Passengers	[28]
Taxi	Diesel	2.41	MJ/vkm	[27]	1.7	Passengers	[28]
AV	Electric	0.53	MJ/vkm	[29]	0.9–1.3	Passengers	[6,15,17]
AV minibus	Electric	1.62	MJ/vkm	[30]	2.5	Passengers	[6,15,17]

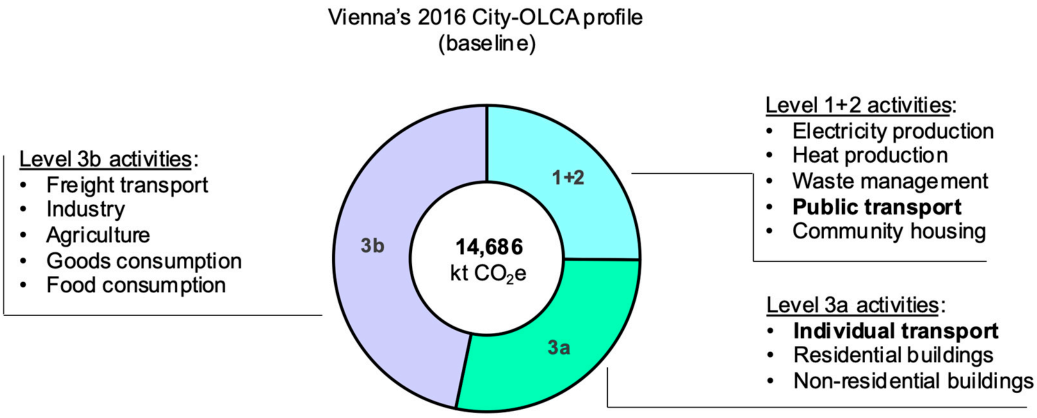

Figure 2. Vienna's city-OLCA profile for GHG emissions in kt CO_2e according to [23]. Vienna's own operations (level 1+2) account for 25% of citywide GHG emissions.

3. Results

Vienna's baseline, two scenarios and three use cases account to six individual scenario cases in this work. As described above, the individual AV case combines both scenario A and scenario B. We use the following codes to distinguish between each scenario case (Table 3).

Table 3. Scenario naming convention used throughout the course of this paper.

Scenario Case Code	Use Case	Scenario (See Section 2.2)
baseline	Not applicable	Not applicable
IA/A,B	Individual AV	A: Conventional car ban or B: Prioritized AV
SA/A	Shared AV	A: Conventional car ban
SA/B	Shared AV	B: Prioritized AV
SR/A	Shared AV ride	A: Conventional car ban
SR/B	Shared AV ride	B: Prioritized AV

3.1. Transport Demand and Modal Split

Figure 3 shows the change in modal split after applying the scenarios to Vienna's baseline for each scenario case. Values are given in absolute demand (pkm) and the scenario specific car restriction and bus replacement has been highlighted. Total baseline transport demand is 19.27 bn pkm.

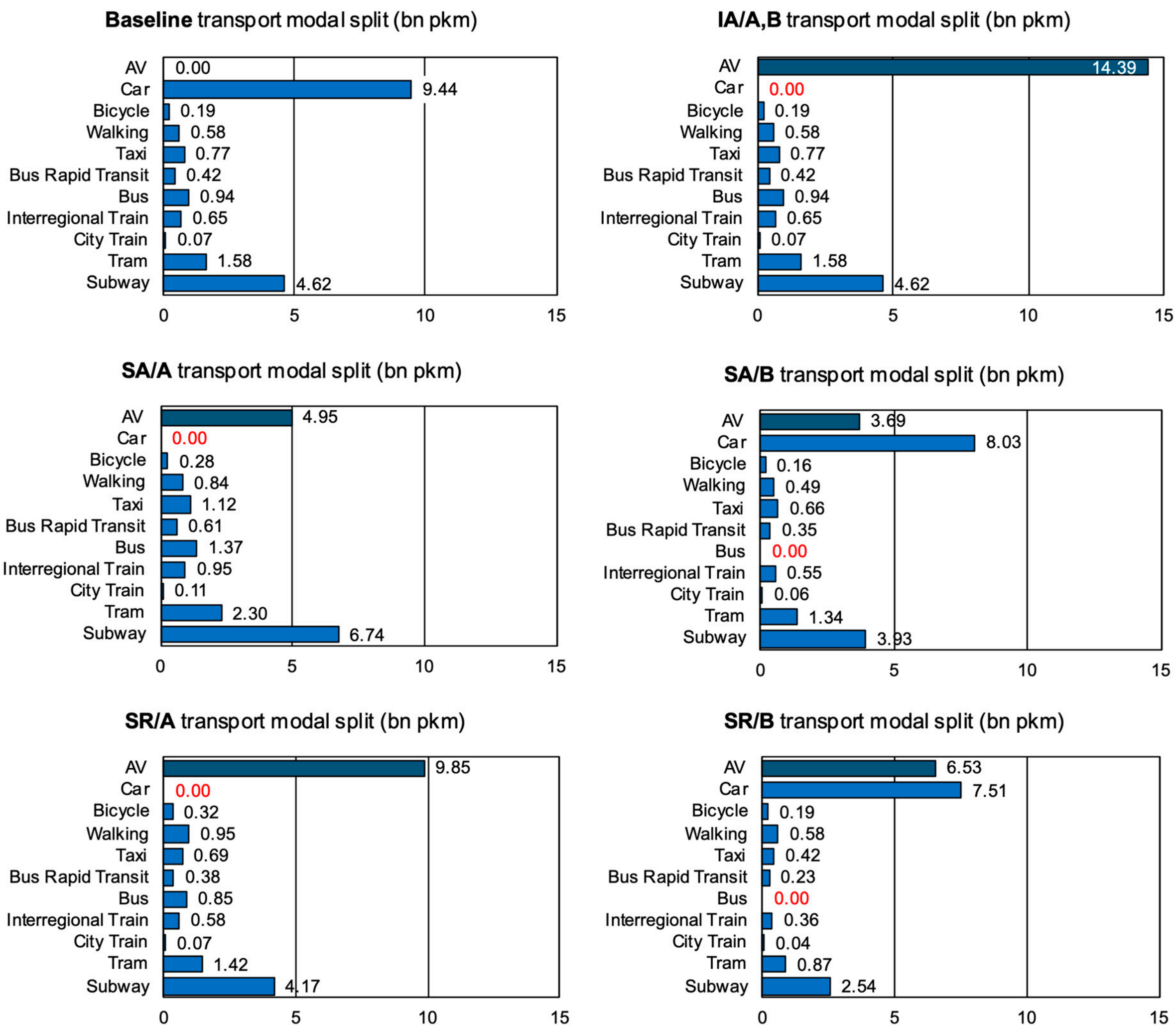

Figure 3. Transport modal split for Vienna's baseline and the impact of five future mobility scenario cases incorporating AV services. Effects considered include modal shifts based on behavioral responses, changes in utilized capacity, and induced demand due to time–cost reductions (limited to scenario case IA/A,B). Scenario specific car and bus replacements are highlighted in red. Scenario naming convention disclosed in Table 3.

With 14.39 bn. pkm, IA/A,B shows the highest AV uptake. Individual AVs entirely take over the transport demand of conventional cars while the remaining modes keep constant. IA/A,B is also the only case that adds total pkm demand to the system, resulting in a total demand of 24.21 pkm (+24%).

Under scenario A, shared AVs (SA/A) account for 4.95 bn. pkm (or 26%). The shared AV uptake is accompanied by an expansion of the public transport modes. SR/A shows almost no change in conventional mode shares. Its demand coverage is with 9.85 bn. pkm (or 51%) almost double the SA/A case.

Under scenario B, shared AVs (SA/B) meet a demand of 3.7 bn. pkm (or 19%). Part of the shared AV demand (25%) comes from bus travel that was displaced by the new service. All remaining modes decrease by 15%. With 6.5 bn pkm (or 33%), shared rides (SR/B) show a 75% higher demand coverage than SA/B. Here, 14% are coming from buses. While conventional car demand decreases by 21%, public transport drops by 41% compared to baseline demand.

3.2. Emissions, Traffic and Passenger Capacity

Figure 4 shows combined results for the remaining performance indicators transport GHG emissions, motorized road traffic, and passenger capacity. Baseline values are displayed accordingly. A detailed description is provided in the following sections.

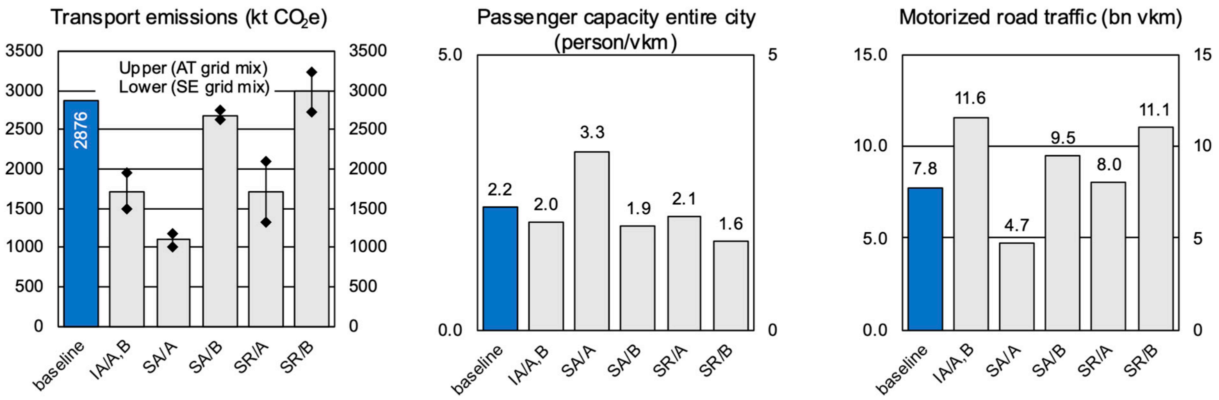

Figure 4. Vienna's combined performance indicators for all mobility scenario cases. Baseline values are displayed accordingly.

3.3. Transport Emissions

Transport emissions show a range from 1021 kt to 3246 kt CO_2e emissions, depending on scenario and electricity grid mix. In the best case, this equals −60% and in the worst case +15% compared to the baseline. The lowest possible emissions, while keeping the overall demand constant, are achieved in scenario A for the shared AV (SA/A). The highest emissions are observed in Scenario B for the shared AV ride service (SR/B). However, this scenario case shows a turning point, as a better grid mix could pull its emissions just below baseline. The sensitivity to grid mix becomes most apparent for SR/A, as this scenario case shows the second highest (electric) AV uptake accompanied by a decrease in public transport (see also Figure 3). Its average emissions are almost identical to owning an AV accompanied by a conventional car ban (IA/A,B). Although ownership induced 24% of additional demand, its emission performance is among the middle field.

3.4. Motorized Road Traffic

Motorized road traffic, measured in total vehicle km driven, shows a rather different profile. Shared AVs under scenario A (SA/A) record the only decrease in road traffic (−40%). Owning an AV (IA/A,B) peaks at 11.6 bn. vkm, which is 49% more than the baseline road traffic. The other scenario cases show an increase in road traffic of +3% (SR/A), +22% (SA/B), and +42% (SR/B). Note that the demand increase for IA/A,B (+24%)

does not correspond to the road traffic increase (+49%) of that scenario. This is because the demand increase is based on all modes, including rail.

3.5. Passenger Capacity

As the best performing scenario case, SA/A also has the highest passenger capacity (system efficiency). The other modes are more or less stable, showing an expected inverted trend towards traffic increase. Only the IA/A,B case behaves differently. It shows the largest traffic increase while its overall capacity is not the lowest. Here, the reduced (−10%) passenger capacity is only caused by a higher weighting of car travel on the modal split due to its induced demand.

4. Discussion Part I: The Transportation System

4.1. Mobility Scenario Analysis and the AV's Role in Reducing Greenhouse Gas Emissions and Reshaping Vienna's Transportation System

Based on the scenarios, emissions are only effectively reduced if a restriction of conventional cars is assumed (scenario A). All individual scenario cases under a car ban produce substantially lower GHG emission values than promoting the extensive use of AVs (either as shared AVs or shared AV rides). The latter is often referred to as cannibalization of public transport (which is not limited to AVs). That does not necessarily lead to negative consequences.

Cities and scholars have already discussed such effects with regards to conventional sharing approaches [32]. There are many uncertainties in quantifying the outcome of new mobility solutions and some argue that fleet sizes are still far too small to have a measurable effect at all. However, at a larger scale, their impact on the way we travel will increase and certainly challenge existing modes of transport. One major advantage of AVs is that they eliminate the cost of a driver. This could increase customer acceptance in the ride hailing business (autonomous taxi fleet) and strengthen the general sharing market by being more competitive and cheaper than public transport [33].

Our results indicate that a smart yet moderate integration of AV services could lead to reducing transport related GHG emissions in Vienna. However, as soon as services with lower utilization take over parts of the demand, this will be at the expense of the overall transportation system's efficiency. Lower GHG emissions can only be achieved if, at the same time, mass transit absorbs "free" demand created by shifting from high to low capacity modes. In addition, while GHG emissions might be reduced, public infrastructure is used more extensively. Four out of five cases have witnessed an increase in road traffic, peaking at 49% (Figure 4). Although our results are partly based on sensitive behavioristic effects, the observed traffic increase is within the reported range in previous studies (see e.g., [14,15]).

It does not necessarily mean that AVs also produce more congestion. They are designed to drive smarter and more predictively than conventional vehicles. This translates not only to energy efficiency, but to reduced parking pressure and safety aspects alike [7]. While AVs may increase the availability of public space, this is at the cost of driving more. How that impacts traffic flow is subject to different scientific disciplines.

However, this highlights that reasoning the decision for AVs on GHG emissions alone would not meet the diverse missions of a city administration. Cities have to weigh up which parameters they believe fit best in measuring their mobility quality and in ensuring services of general interest. This task goes beyond the scope of this research.

4.2. The E-Car Effect: Accounting for Future Mobility Trends in An Electrified Transportation System

Results suggest that a reduction in GHG emissions in the transport sector can be achieved in almost all cases. In addition to the scenario conditions (i.e., restricting conventional cars), this may either be due to efficiency gains at vehicle level or because of the advantages of the electric AV itself (lower CO_2e emissions). To find out to what extent the e-car is responsible for emission reduction and how the scenario cases would perform under future conditions, we introduce an adapted baseline for Vienna. This new baseline represents a fully electrified transportation system, indicated by "*e" in the scenario case codes. Regarding the EU's roadmap to transport electrification [34] and major OEM strategies [35], electrification is the most likely trend under which AVs enter the market at scale in future. For the new electrified baseline, individual AV uptakes and modal splits shown in Figure 3 still apply. However, all modes are now electrified (i.e., electric cars, electric buses). The changes happening in the system's GHG profile are attributed to efficiency gains and mode shifting only. Adjusted transport emissions and a qualitative comparison to our initial baseline are shown in Figure 5.

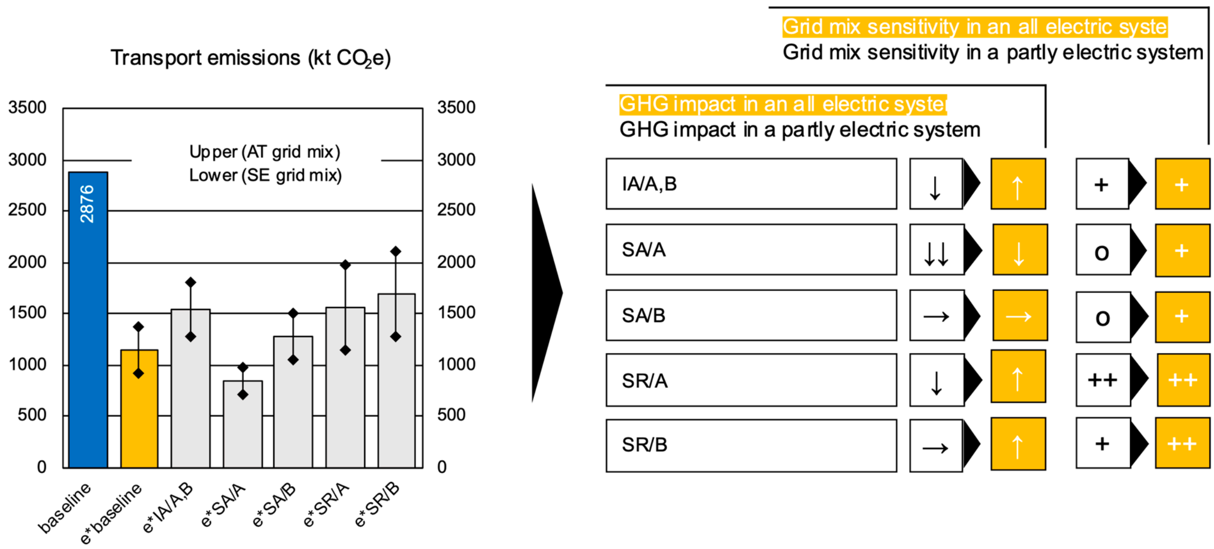

Figure 5. Scenario impacts on transport GHG emissions in a future all electric transportation system (left) and a qualitative comparison of impacts to the initial and electrified baseline (right).

Observations regarding the adjusted cases are as follows:

1. The new reference (e*baseline) performs significantly better than the old baseline. Without any intervention on modes or introduction of AV services, an electrified transportation system is 60% lower than Vienna's initial baseline from Figure 4.
2. Comparing AVs in a fully electrified transportation system shows an actual increase in emissions among most cases. For owned AVs, this means that they cannot offset their additional transportation demand with vehicle efficiency gains (e*IA/A,B). For example, switching entirely from private conventional cars to private AVs would increase emissions by 33%. In general, emission increase is observed at a range from 11% (e*SA/B) to 48% (e*SR/B). Shared AVs under scenario A (e*SA/A) is the only case that show an emission benefit (−4.2%).
3. Differences between scenario cases become smaller. The delta between lowest to highest emissions is 852 kt CO2e for the all electric cases, while it was 1890 kt CO2e for the baseline cases (on average). Especially, scenario B cases have decreased, which is mainly caused by less emissions from electric buses compared to the ones with combustion engines. In addition, that is by taking all upstream emissions, including battery production, into account.
4. Sensitivity to grid mix becomes higher. All scenario cases show a significantly higher sensitivity to grid mix choice compared to the ones from Figure 4. As a result, emission reductions could be achieved if a highly decarbonized electricity mix is used (lower range in Figure 5). However, these reductions become only effective if Vienna would keep its carbon intensive grid mix (upper range in Figure 5).

Electricity demand is worth a closer look. The increased sensitivity to grid choice is because of the higher electricity demand in all cases, as shown in Figure 6. Here, fuel savings and additional electricity required for each case is displayed in absolute terms. The electrified baseline already requires a significant amount of additional electricity of 1600 GWh (Figure 6, right). This is four times the (initial) baseline electricity needed to operate trams, subways and trains. At the same time, fuel savings of 2900 kt (diesel and petrol) indicate that the transportation system is fully electrified. It is mainly these fuel savings that translate into GHG emission reduction.

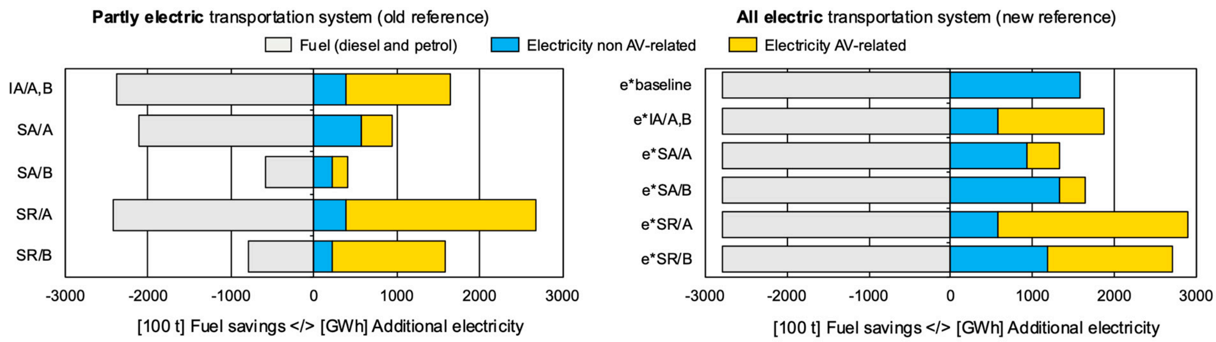

Figure 6. Absolute fuel savings and additional electricity required compared to the initial baseline in the partly electric system (**left**) and all electric system (**right**).

Although AVs induce additional electricity by their very nature, it is not the AVs that will direct the GHG emissions profile. It is, rather, the electrification of the transport system as a whole that has a more significant impact than incorporating AV mobility. A comparison between the partly electric (Figure 6, left) and the new all electric system (Figure 6, right) clearly show the increased non-AV electricity requirements. Owning where the electricity comes from will determine the GHG performance. However, without a restriction of individual car traffic and promoting efficient mass transit, the path towards clean transportation will be challenging. This matches well with [36], who argue that future emission reduction is only possible with high occupancy vehicle travel and a decarbonized energy system across the globe.

4.3. Life Cycle Stages and Emission Sources

Breaking down Vienna's GHG performance into its life cycle stages, use and production, helps understand the emission origin and reveals additional insights on reduction pathways. Figure 7 shows Vienna's transport related life cycle emissions and displays relative process contributions within each stage. Results are provided for the baseline case, the electrified baseline (e*baseline), and the best performing use case (e*SA/A).

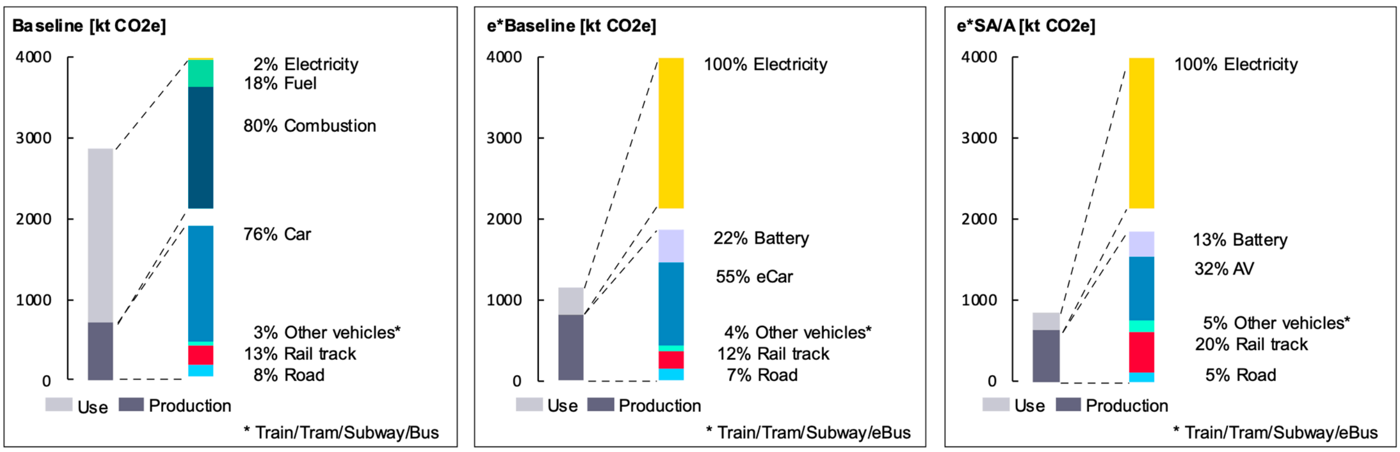

Figure 7. Contribution of processes to the life cycle stages use and production for Vienna's transport baseline, the electrified baseline, and the best performing AV mobility scenario case in kt CO_2e.

As expected, Vienna's transport baseline is dominated by the use and combustion of fuel for conventional vehicles. Production only accounts for 25%, with car production as leading process. The opposite is observed in an electrified environment (e*Baseline). Here, production dominates the emission performance. Battery manufacturing for electric cars and electric buses induce a slight increase in overall production related emissions.

A change in modal split then reduces total emissions, while public infrastructure becomes more dominant. The new emission profile of e*SA/A indicates rail tracks to be one of the emission hotspots besides vehicle manufacturing. These emissions happen to be supply chain related. Mitigating them cannot be achieved by only changing the modal split. This will later be relevant when discussing citywide scenario impacts in Section 5.1.

4.4. Harmonization of Transport Research Parameters to Ensure Consistency

Our estimations for AV induced impacts to the transportation system is based on individual reference studies for each use case. While some consider the effect of additional demand, others simulate capacity changes. To ensure that these mechanisms are not the only ones that count, we have formulated extreme scenarios in which each use case operates (Table 4). The reason that these models produce different outputs lies in their motivation, which is directly connected to the parameters used. The shared AV model, for example, is motivated for fleet optimization, while the shared AV ride model focuses on demand fulfillment. As there is already high uncertainty within each model, we did not want to combine the mechanisms. However, this consistency issue comes at a price.

Table 4. Model parameters used to calculate AV induced mobility effects in Vienna.

Model Parameters	Unit	Individual AV	Shared AV	Shared AV Ride Service
Transport demand	Pkm/a	✓	✓	✓
Modal split transport system	%/pkm	✓	✓	✓
Passenger capacity per mode	P	✓	✓	✓
Energy/fuel consumption per mode	kWh/km	✓	✓	✓
Upstream and direct emissions per mode	kg CO_2e	✓	✓	✓
Income distribution	%	✓		
Fuel elasticity	[–]	✓		
Time elasticity	[–]	✓		
Fuel cost reduction	%	✓	✓	✓
Time cost reduction	%	✓		
Changed capacity utilization AV	P		✓	✓
Changed capacity utilization PT	%		✓	
Sharable trips	%			✓
Willingness to share	%			✓
Car trips shift	%			✓
PT trips shift	%			✓

Especially, the additional demand from the first model (individual AV) is not reflected in the shared models (shared vehicle and shared AV ride). It can be expected that the shared use cases also induce some additional demand. However, we assume that the effect of voluntarily taking longer trips to carry out productive work is much higher if the AV is owned. Whereas using a taxi service where customers pay per minute (or km) might not necessarily lead to longer travel times. Although an AV driving experience might also come with some increase in comfort for the shared use cases.

In general, translating mechanisms observed in one city to another increases uncertainty. We tried to disaggregate the influencing parameters in each model and use Vienna specific values. The configuration of the transport system (transport demand and modal split) proved to be one of the main influencing factors here (more than the income distribution or the utilized capacity of a specific mode). In addition, this configuration is independent of the AV model used.

Predicting the effects of future technologies is inherently uncertain. That is why we have chosen an approach to identify trends and a potential impact range, rather than trying to make exact statements. In addition, although we include mechanisms in our scenarios that were not directly designed for Vienna, we believe this approach is justified because of the following three aspects. Firstly, all mechanisms are based on models for OECD countries with similar income and societal structures. Secondly, additional (extreme) scenario conditions were defined to reduce the sensitivity of model parameters. Thirdly, results suggest that other effects contribute significantly more to the environmental performance than AV mobility (e.g., electrification).

Nevertheless, we encourage AV transportation researchers in harmonizing impact mechanisms, or at least the parameters that are being used. This will help scholars who utilize such findings in other frameworks (such as LCA) to gain more consistent results. In addition, it will strengthen city administrations in their public communication and reasoning of strategic mobility decisions.

4.5. Different Forms of Sharing Approaches

The sharing approaches presented in this work can vary in design and type. Strategies such as free-floating or station based car sharing or platooned ride hailing all have different effects on the acceptance of new services. The degree people may forego or postpone the acquisition of an own car is probably higher the fewer restrictions a new service entails and the more convenience a driver experiences [37].

We made no distinctions between different types of sharing approaches, as our models do not allow to determine the specific effects of each type. However, our results should be interpreted on the basis of highest user acceptance. Especially, scenario B was defined to promote AV services. This rather fits to a free-floating, highly individualized sharing approach than to a stationary service. After all, many benefits from vehicle automation would be counteracted by only allowing a station-based model.

Considering different forms of AV car sharing will certainly be an interesting topic for future research. As this technology emerges, additional features could also be investigated, such as combining passenger transport with last mile delivery.

5. Discussion Part II: The City

5.1. An Illustrative Case of Mobility Scenario Impacts on Vienna's City-OLCA: Potential Emission and Responsibility Shifts Explained

So far, our analysis has covered assessment scopes from vehicle level ("what"), over the use case ("how"), to the urban transportation level ("where"). We now broaden the assessment scope further and examine impacts at city level. The basis of this assessment is Vienna's entire city-OLCA profile as introduced in Section 2.5. City-OLCA's unique approach in acknowledging emission responsibilities should support environmental performance tracking and helps city managers prioritize mitigation measures.

This study has identified transport electrification to be the key driver in GHG emissions reduction. Using city-OLCA, the transformation happening in the transport system will now be visible in the entire city profile. On the example of the best performing scenario in our analysis (e*SA/A), we will discuss how activities beyond direct governmental control can feed back into the city's own operations and how that changes Vienna's city-OLCA.

Firstly, the city as electricity producer could provide the electricity needed for AVs and other electric vehicles. The uptake of electric cars and AVs will induce electricity production in Vienna. In addition, although this transformation mainly happens in level 3a (here:

individual transport), the impact is also visible in level 1 (own operations). Hence, the city of Vienna could indirectly contribute to decarbonizing the mobility sector by providing fossil free electricity. This might incentivize Vienna's power plant operators to switch to alternative fuels. Figure 8 illustrates scenario impacts on the city-OLCA profile. For comprehensibility purposes, we have highlighted only the activities that affected electricity production, public transport and individual transport.

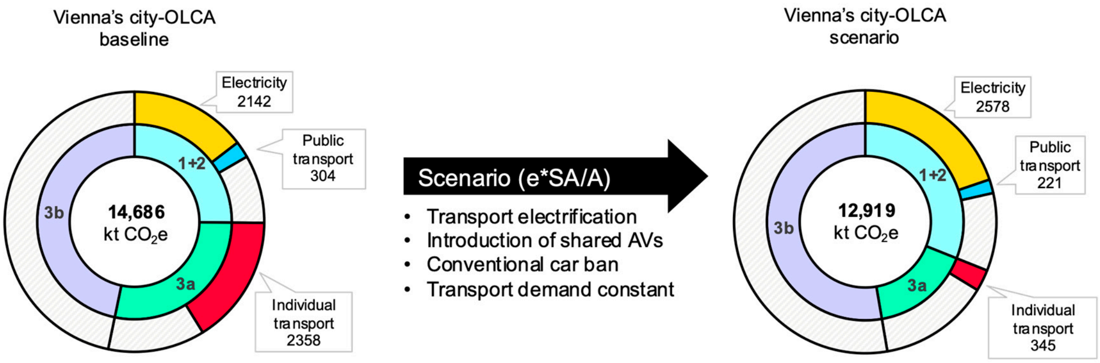

Figure 8. Scenario impacts on Vienna's city-OLCA profile. Electrification and AV mobility induce electricity demand at city level. Total GHG emissions could be reduced, yet transformations at individual transportation (level 3a) have shifted emission responsibilities to the local government (level 1+2).

Electrification of the transport system results in 0 kt CO_2e direct GHG emissions from vehicles (petrol and diesel are not burnt anymore). The remaining indirect emissions (production of vehicles, battery and road) correspond to 345 kt CO_2e for individual transportation and 221 kt CO_2e for public transportation. This scenario needs some additional 1334 GWh electricity (see Figure 6). Assuming Vienna generates all the additional electricity, overall level 1+2 emissions increase by 9% (using the Austrian grid mix factor) while level 3a emissions are reduced by 49%. In total, this scenario reduces Vienna's city-OLCA from 14,686 kt CO_2e to 12,919 kt CO_2e. At the same time, the city's responsibility increases from 25% (baseline) to 31% (scenario).

Secondly, the city is network manager. An electrified transportation system would not only induce more energy needs but also hardware to enable uninterrupted access. Besides charging infrastructure, hybrid sensor technology at vehicle level and at road side may play a crucial role to achieve full automation [38]. Additional infrastructure is not yet recognized in this study.

Thirdly, the modal split changes. If the overall transport demand should remain constant, more bus or subway travel needs to be provided, depending on the scenario. If AVs are not efficient enough to absorb the free travel caused by modal shifts, public transport is going to be extended. This will induce emissions in level 1. In our case, public transport emissions seem to decrease from 304 kt CO_2e (baseline) to 221 kt CO_2e (scenario). However, while baseline emissions are almost entirely use-phase driven, scenario emissions are based on additional rail infrastructure and electric bus production (see also Figure 7). Electrification and modal shifts have completely changed the emission origin in the city. To further reduce its emissions, Vienna would have to target the production related emissions of OEMs (e.g., through green purchasing strategies).

5.2. Environmental Impacts beyond Global Warming

Due to the focus of this work, we have chosen CO_2e as an exemplary performance indicator. However, city-OLCA has already proven to reveal valuable insights beyond global warming for Vienna's full environmental profile in [23]. These findings should be brought into perspective when discussing mobility scenario impacts.

In our former case study, the contribution of activities to Vienna's environmental performance changed with impact category [23]. While transport related activities dominated global warming, fresh water eutrophication was led by the city's heat production. Since none of the mobility scenarios in the present study changed the city's heat demand, one could argue that freshwater eutrophication might not be relevant regarding AV mobility. However, as was shown in the scenario analysis, the origin of emissions changed from operation to production. This could also change the contribution to either of the two impact categories. Additionally, in fact, a hotspot shift among life cycle stages was observed for transport emissions earlier in [23]: the operational phase dominated global warming, while the production phase dominated freshwater eutrophication. Trade offs among impact categories can be the consequence.

This example highlights that new mobility scenarios might not only change the responsibility of the city administration over emissions. It may also shift environmental hotspots from one category to another and also among life cycle stages. In addition, as the quality of urban environmental assessments increases, so does the complexity of recommendations for improvement. A more detailed study of the overall environmental profile with respect to the mobility scenarios is pending.

5.3. Limitations of City-OLCA-Related Implications

The city-OLCA framework is still in an early stage of development. Some limitations should be considered when basing strategic decisions upon city-OLCA results. The most important ones will be discussed in the following sections.

5.3.1. Accounting for Service Quality

City-OLCA does not state anything about the quality of the services provided in a city. Implementing a quality constraint into the analysis was previously discussed but found to exceed complexity at this stage of development [22]. Introducing AVs might change the quality of the system. However, there is no agreed upon definition on what parameters should be used to account for quality. The frequency of bus rounds, driving comfort, privacy, accessibility are all possible constraints but the choice is certainly somewhat arbitrary. In addition, one quality constraint might not be reasonable for all cities. Regarding services of general interest, it will be the administration's role to define a constraint that they also communicate to the general public. In the worst case, if the quality of a service reduces over time, more of that service is (theoretically) needed to meet the higher quality. Therefore, activity related emissions are better comparable over time. In a way, we have added a quality constraint by leaving the travel demand constant. Thus, car travel cuts led to an increase in other modes (e.g., public transport). However, maintaining the transport system at all should not be up for debate and is the absolute minimum requirement regarding quality.

5.3.2. Estimating the Probability of A Trend

Including trend impact analysis into city-OLCA assessments proved feasible and insightful. However, conclusions are limited to results based on scenario discussions. We have chosen extreme scenarios to avoid giving the impression of false accuracy. These scenarios do not give an indication as to whether and when an event will happen. However, they highlighted a clear shift in responsibilities within the city, which would not be possible nor visible in classic LCA practice. Identifying these shifts will be a valuable exercise for city managers and scholars to point out potential "side effects" of a technological development and trend. Translating the results into a governmental agenda will be the task of political decision makers.

5.3.3. Non-Environmental Performance Indicators

With regards to AVs and mobility services in general, indicators beyond GHG emissions (or other environmental figures) will play an important role in assessing the overall system performance. Aspects such as (local) land occupation, passenger safety, parking pressure, congestion, etc., must accompany the city-OLCA based results in order to give clear recommendations to city officials. With our approach, we have tried to utilize concepts and parameters from transportation research (e.g., passenger capacity, willingness to share, etc.). Likewise, we hope to inspire scholars from other disciplines consider city-OLCA findings in their own scientific work.

5.3.4. Transferability to Other Cities

The scenario results and recommendations identified in this study appear to apply exclusively to Vienna. AV mobility scenarios will probably have different impacts in cities with other baseline travel patterns and framework conditions. In cities whose sustainable modes already dominate the mobility landscape, AVs would not necessarily bring additional benefit. In car centric cities, however, the administration could have a greater lever in cutting emissions and traffic by incentivizing the use of different forms of AVs (owned and shared). As fleet operator, they could even take an active role in transforming the way we travel.

As more experience with city-OLCA is gained, similarities among cities could be found that make predictions on trend impacts easier. Identifying these "Vienna-like" cities as well as other archetypal characteristics will be an interesting topic for future research.

6. Conclusions

Efficient mass transit, the electrification of the mobility sector and grid decarbonization are key to reduced transport emissions in Vienna. The direction of GHG emission development will be determined by the extent to which these conditions are promoted. AV mobility probably will not be a main contributor to either radical emission cuts or missing GHG emission targets. AVs have, however, the potential to significantly impact urban traffic. That is, by lowering overall capacity utilization if introduced to a system which is not already car dominated. For Vienna, it appears that effects such as congestion or safety appropriately lead current debates on AV induced impacts. This does not necessarily apply to other cities with different travel patterns.

Based on city-OLCA, Vienna faces greater challenges with electrification per se than with AV transportation. Electrifying Vienna's transportation system would already require four times the baseline energy demand. This not only comes with additional infrastructure to be installed. It also shifts emissions from individual transport into the responsibility of the city, who acts as energy provider. In addition, while former public transport emissions were use-phase dominated, the focus now lies at bus and rail production. Influencing these types of emissions is much more difficult for city officials.

City-OLCA proved to be a valuable tool to consider transformational change in urban environmental research. We could show that the city as transport and infrastructure provider has a key role in reducing emissions beyond direct governmental control. This increased responsibility emphasizes the potentials city managers can have in accelerating emission reduction. Cities should be seen as enablers for future mobility by setting framework conditions that support both environmental and operational benefits.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14010158/s1, Figure S1: Procedure to calculate each of the five income group's (I to V) share of final car travel in Vienna (based on pkm). The distribution of income groups on car travel share is used to estimate induced AV demand in the city based on a macro-economic approach. Table S1: Specific shifting factors (S-values) from public transport and conventional cars to the AV ride sharing service according to Equations (4) and (5). Table S2: Key transport model parameters per scenario and case.

Author Contributions: Conceptualization, A.C. and M.F.; methodology, A.C.; software, A.C.; validation, K.M. and M.F.; formal analysis, A.C.; investigation, A.C.; data curation, A.C.; writing—original draft preparation, A.C.; writing—review and editing, K.M. and M.F.; visualization, A.C.; supervision,

K.M.; project administration, A.C. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge support by the German Research Foundation and the Open Access Publication fund of the TU Berlin.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Manyika, J.; Chui, M.; Bughin, J.; Dobbs, R.; Bisson, P.; Marrs, A. *Disruptive Technologies: Advances That Will Transform Life, Business, and the Global Economy*; McKinsey Global Institute: New York City, NY, USA, 2013.
2. Massar, M.; Reza, I.; Rahman, S.M.; Abdullah, S.M.H.; Jamal, A.; Al-Ismail, F.S. Impacts of Autonomous Vehicles on Greenhouse Gas Emissions—Positive or Negative? *Int. J. Environ. Res. Public Health* **2021**, *18*, 5567. [CrossRef] [PubMed]
3. Williams, E.; Das, V.; Fisher, A. Assessing the Sustainability Implications of Autonomous Vehicles: Recommendations for Research Community Practice. *Sustainability* **2020**, *12*, 1902. [CrossRef]
4. Litman, T. *Autonomous Vehicle Implementation Predictions- Implications for Transport Planning*; Victoria Transport Policy Institute: Victoria, BC, Canada, 2021.
5. U.S. DOT. *Automated Vehicles 3.0 Preparing for the Future of Transportation*; U.S. Department of Transportation: Washington, DC, USA, 2018.
6. Taiebat, M.; Stolper, S.; Xu, M. Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound. *Appl. Energy* **2019**, *247*, 297–308. [CrossRef]
7. Kondor, D.; Zhang, H.; Tachet, R.; Santi, P.; Ratti, C. Estimating Savings in Parking Demand Using Shared Vehicles for Home-Work Commuting. *IEEE trans. Intell. Transp. Syst.* **2019**, *20*, 2903–2912. [CrossRef]
8. Harper, C.D.; Hendrickson, C.T.; Mangones, S.; Samaras, C. Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions. *Transp. Res. Part C Emerg. Technol.* **2016**, *72*, 1–9. [CrossRef]
9. Yao, Z.; Jiang, H.; Cheng, Y.; Jiang, Y.; Ran, B. Integrated Schedule and Trajectory Optimization for Connected Automated Vehicles in a Conflict Zone. *IEEE Trans. Intell. Transport. Syst.* **2020**, 1–11. [CrossRef]
10. Barth, M.; Boriboonsomsin, K.; Wu, G. Vehicle Automation and Its Potential Impacts on Energy and Emissions. In *Road Vehicle Automation*; Meyer, G., Beiker, S., Eds.; Springer: Heidelberg, Germany, 2014; pp. 103–112.
11. Barth, M.; Boriboonsomsin, K. Energy and Emissions Impacts of a Freeway-Based Dynamic Eco-Driving System. *Transp. Res. Part D Transp. Environ.* **2009**, *14*, 400–410. [CrossRef]
12. Prakash, N.; Cimini, G.; Stefanopoulou, A.G.; Brusstar, M.J. Assessing Fuel Economy from Automated Driving: Influence of Preview and Velocity Constraints. In Proceedings of the ASME 2016 Dynamic Systems and Control Conference (DSCC), Minneapolis, MN, USA, 12–14 October 2016; Volume 2. [CrossRef]
13. Wu, G.; Boriboonsomsin, K.; Xia, H.; Barth, M. Supplementary Benefits from Partial Vehicle Automation in an Ecoapproach and Departure Application at Signalized Intersections. *Tranp. Res. Rec.* **2014**, *2424*, 66–75. [CrossRef]
14. Fagnant, D.J.; Kockelman, K.M. Dynamic Ride-Sharing and Fleet Sizing for a System of Shared Autonomous Vehicles in Austin, Texas. *Transportation* **2018**, *45*, 143–158. [CrossRef]
15. Hörl, S.; Becker, F.; Dubernet, T.; Axhausen, K.W. *Induzierter Verkehr Durch Autonome Fahrzeuge: Eine Abschätzung*; Institut für Verkehrsplanung und Transportsysteme, ETH Zürich: Zurich, Switzerland, 2019.
16. Kaltenhäuser, B.; Werdich, K.; Dandl, F.; Bogenberger, K. Market Development of Autonomous Driving in Germany. *Transp. Res. Part A Policy Pract.* **2020**, *132*, 882–910. [CrossRef]
17. McCabe, P.; Hutt, C.; Petralia, A.; Skipp, D.; Karagiorgis, S.; Witt, D.; Jones, M.; Voukas, Y.; Lodge, C.; Ballis, H.; et al. *Autonomous Vehicle Ride-Sharing Services: Will They Make Cities Greener, More Efficient and More Accessible?* MERGE Greenwich: London, UK, 2018.
18. Brown, A.; Gonder, J.; Repac, B. An Analysis of Possible Energy Impacts of Automated Vehicles. In *Road Vehicle Automation*; Meyer, G., Beiker, S., Eds.; Lecture Notes in Mobility; Springer International Publishing: Cham, Switzerland, 2014; pp. 137–153. ISBN 978-3-319-05990-7.
19. Li, J.-M.; Gao, Z. Exploring the Impact of Speed Synchronization through Connected Vehicle Technology on Fleet-Level Fuel Economy. *SAE Int. J. Passeng. Cars–Electron. Electr. Syst.* **2013**, *6*, 213–221. [CrossRef]
20. Schito, P.; Braghin, F. Numerical and Experimental Investigation on Vehicles in Platoon. *SAE Int. J. Commer. Veh.* **2012**, *5*, 63–71. [CrossRef]
21. Wadud, Z.; MacKenzie, D.; Leiby, P. Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles. *Transp. Res. Part A Policy and Pract.* **2016**, *86*, 1–18. [CrossRef]

22. Cremer, A.; Müller, K.; Berger, M.; Finkbeiner, M. A Framework for Environmental Decision Support in Cities Incorporating Organizational LCA. *Int. J. Life Cycle Assess.* **2020**, *25*, 2204–2216. [CrossRef]
23. Cremer, A.; Berger, M.; Müller, K.; Finkbeiner, M. The First City Organizational LCA Case Study: Feasibility and Lessons Learned from Vienna. *Sustainability* **2021**, *13*, 5062. [CrossRef]
24. Vienna Population Statistics. Available online: https://www.wien.gv.at/statistik/bevoelkerung/bevoelkerungsstand/ (accessed on 15 December 2021).
25. Behrends, S.; Engel, W.; Kott, K.; Neuhäuser, J. *Private Haushalte—Einkommen, Konsum, Wohnen*; Statistisches Bundesamt: Wiesbaden, Germany, 2018.
26. Lukacsy, M.; Fendt, C. *Statistisches Jahrbuch Der Stadt Wien 2020*; Magistrat der Stadt Wien: Vienna, Austria, 2020.
27. Ecoinvent 3.4. Available online: https://www.ecoinvent.org/database/older-versions/ecoinvent-34/ecoinvent-34.html (accessed on 25 October 2021).
28. Heidinger, K.; Verdis, S.; Wandaller, P. *Vienna 2025—Comparing the Benefits of Vienna's Infrastructure Choices*; Siemens: London, UK, 2014.
29. Weiss, M.; Cloos, K.C.; Helmers, E. Energy Efficiency Trade-Offs in Small to Large Electric Vehicles. *Environ. Sci. Eur.* **2020**, *32*, 46. [CrossRef]
30. Cignini, F.; Genovese, A.; Ortenzi, F.; Alessandrini, A.; Berzi, L.; Pugi, L.; Barbieri, R. Experimental Data Comparison of an Electric Minibus Equipped with Different Energy Storage Systems. *Batteries* **2020**, *6*, 26. [CrossRef]
31. Sweden Is a Leader in the Energy Transition, According to Latest IEA Country Review (International Energy Agency). Available online: https://www.iea.org/news/sweden-is-a-leader-in-the-energy-transition-according-to-latest-iea-country-review (accessed on 25 October 2021).
32. Giesel, F.; Nobis, C. The Impact of Carsharing on Car Ownership in German Cities. *Transp. Res. Proc.* **2016**, *19*, 215–224. [CrossRef]
33. Mo, B.; Cao, Z.; Zhang, H.; Shen, Y.; Zhao, J. Competition between Shared Autonomous Vehicles and Public Transit: A Case Study in Singapore. *Transp. Res. Part C Emerg. Technol.* **2021**, *127*, 103058. [CrossRef]
34. Krukowska, E.; Patel, T. EU Aims to Have 30 Million Electric Cars on the Road by 2030. Available online: https://www.bloomberg.com/news/articles/2020-12-03/eu-aims-to-have-30-million-electric-cars-on-the-road-by-2030 (accessed on 26 September 2021).
35. How Volkswagen Is Becoming a Climate-Neutral Company. Available online: https://www.volkswagen-newsroom.com/en/stories/how-volkswagen-is-becoming-a-climate-neutral-company-6823 (accessed on 26 September 2021).
36. Fulton, L.; Mason, J.; Meroux, D. *Three Revolutions in Urban Transportation: How to Achieve the Full Potential of Vehicle Electrification, Automation and Shared Mobility in Urban Transportation Systems around the World by 2050*; University of California: Davis, CA, USA, 2017.
37. Fromm, H.; Ewald, L.; Frankenhauser, D.; Ensslen, A.; Jochem, P. *A Study on Free-Floaring Carsharing in Europe*; Karlsruhe Institute of Technology: Karlsruhe, Germany, 2019.
38. Bezai, N.E.; Medjdoub, B.; Al-Habaibeh, A.; Chalal, M.L.; Fadli, F. Future Cities and Autonomous Vehicles: Analysis of the Barriers to Full Adoption. *Energy Built Environ.* **2021**, *2*, 65–81. [CrossRef]