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Cost-based analysis of autonomous mobility services

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A B S T R A C T

Fast advances in autonomous driving technology trigger the question of suitable operational models for future autonomous vehicles. A key determinant of such operational models' viability is the competitiveness of their cost structures. Using a comprehensive analysis of the respective cost structures, this research shows that public transportation (in its current form) will only remain economically competitive where demand can be bundled to larger units. In particular, this applies to dense urban areas, where public transportation can be offered at lower prices than autonomous taxis (even if pooled) and private cars. Wherever substantial bundling is not possible, shared and pooled vehicles serve travel demand more efficiently. Yet, in contrast to current wisdom, shared fleets may not be the most efficient alternative. Higher costs and more effort for vehicle cleaning could change the equation. Moreover, the results suggest that a substantial share of vehicles may remain in private possession and use due to their low variable costs. Even more than today, high fixed costs of private vehicles will continue to be accepted, given the various benefits of a private mobility robot.

1. Introduction

Autonomous vehicles (AVs) are expected to revolutionize mobility by turning cars into mobility robots and allowing more dynamic and intelligent forms of public transportation. A multitude of transport services are conceivable with AVs, yet it is largely unclear which ones will prevail. Besides travel time, reliability and comfort, price is the key attribute of a transport service. Therefore, predicting level of acceptance and resulting competitiveness of future AV operational models requires knowledge about their cost structures. The validity of scenarios, simulations and conclusions of such studies relies heavily on accuracy of assumptions about the absolute and relative competitiveness of new transport services compared to current offerings. Better estimates of absolute competitiveness thus allow better estimates of mode choice, induced demand and spatial distribution of travel demand - in short: future travel behavior.

First cost estimates of future transport services with AVs were proposed by Burns et al. (2013). For three different cases (small to medium town, suburban and urban), they calculated the cost, per trip, of a centrally organized system of shared AVs (medium sedans with AV technology), which would replace existing transport services. Their estimates are based on different cost categories, which capture fixed and variable costs. They concluded that such systems could provide "better mobility experiences at radically [up to ten times] lower cost". In the case of a shared AV system for a small to medium town, they found the cost of driverless, purpose-built vehicles to be 0.15 US$ per trip-mile.

In a second approach, Fagnant and Kockelman (2014) considered the external costs (e.g. crash or congestion cost) of today's private transport system to calculate AVs' potential benefits, which they found to be substantial. In a following paper, Fagnant and Kockelman (2015) focused on possible prices for users of a centrally organized, shared AV system. By assuming an investment cost of 70000 US$ and operating costs of 0.50 US$ per mile for AVs only, they found that a fare of 1.00 US$ per trip-mile for an AV taxi could still produce a profit for the operator. This is a higher price level than in Burns et al. (2013), but still very competitive compared to today's transport options.

Litman (2015) introduced additional factors into the discussion, like cleaning costs of shared vehicles. He estimates costs based on different categories. For some values, however, the paper remains unclear about sources, or uses ballpark estimates. For example, it assumes shared autonomous vehicles cost more than car-sharing (0.60 US$ - 1.00 US$ per mile), but less than driver-operated taxis (2.00 US$ - 3.00 US$ per mile).

Building on the work above, Johnson (2015) estimated the price of shared AVs to be 0.44 US$ per trip-mile (operating cost plus 30% profit margin). For purpose-built shared AVs used as pooled taxis, they estimate the price per trip-mile as only 0.16 US$. They use detailed cost categories to estimate the total cost, but do not fully specify the sources of the numbers. It is, therefore, difficult to reproduce and understand their estimates. In contrast to earlier studies, however, they compare and validate their calculations against today's private cars.

Less rigorous and detailed, but more transparent estimates are provided by Stephens et al. (2016) and Friedrich and Hartl (2016). Stephens et al. (2016) find the lower-bound cost of fully autonomous vehicles used

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with ride-sharing to be less than 0.20 US$ per passenger-mile and the upper bound to be 0.30 US$ per passenger-mile. This encompasses a range similar to Friedrich and Hartl (2016), who assume 0.15 € per passenger-km for a ride-sharing scheme in an urban area in Germany. Stephens et al. (2016), however, do not differentiate between private and commercially offered vehicles and Friedrich and Hartl (2016) focus their cost analysis on the ride-sharing service only. Costs of US$0.30 per passenger-mile are also estimated by Johnson and Walker (2016) in a less rigorous, but more detailed approach. With a less detailed approach for the Netherlands, Hazan et al. (2016) estimate that fully-autonomous vehicles in a ride-sharing scheme can be operated at costs as low as 0.09 € per passenger-km - i.e. at lower cost than rail services.[1]

Overhead costs of shared services were neglected in all cases, which is a major limitation given the new service market in the transport sector; for example, Lyft or Uber, which - in their definitions of their services - provide only the overhead of shared transport services, but no actual transport service.

As outlined above, earlier approaches to determining the cost structures of operational models for AVs were incomplete for both the diversity of possible operational models and cost components. This research addresses this gap by conducting a comprehensive, bottom-up calculation of the respective cost structures of fully autonomous (level 5 (SAE International, 2014)) vehicles for various operational models, such as dynamic ride-sharing, taxi, shared vehicle fleets or line-based mass transit. The chosen methodology allows determination of different cost components' importance and differentiation of vehicle automation effect on individual cost components. This research focuses on passenger transportation. Freight transport, where AVs will undoubtedly also cause major disruptions, cannot be investigated in this paper.

The remainder of this paper is structured as follows: Section 2 presents a bottom-up determination of operating cost for a variety of vehicle systems in various situations, while Section 3 studies their respective utilization for different use-cases. Based on this, the cost structures of different operational models are calculated. The results, including a robustness analysis against different assumptions of key variables, as well as the impact of autonomous vehicle technology on future transport systems are presented in Section 5. Section 6 then goes one step further by assuming a future with autonomous-electric vehicles and studying the prospects of different modes under these circumstances. Finally, in Sections 7 and 8, insights gained through this research are discussed and suggestions for further research are given.

2. Cost structures

This research covers three generic operational models:

- line-based mass transit (public transport),
- taxi (pooled or individual),
- private car.

In this context, line-based mass transit uses full-size buses or trains running along predefined lines on a fixed schedule. Taxi represents a taxi or ride-hailing scheme, as it is known today, where transport may be offered as individual service providing private ride, or pooled services in which multiple travelers may be bundled into one vehicle.[2] Private cars are owned by private persons and are solely used by themselves, or their family and friends. As detailed below, for the generic operational models taxi and private cars, different vehicle types were considered. Although many further variations of operational models can be hypothesized, their cost structures are assumed to be close to one of those three generic models.

Various indicators can be used to represent the competitiveness of a service. The most important dimensions are:

- cost of production vs. prices,
- vehicle kilometers vs. passenger kilometers,
- full cost of a trip vs. direct cost only.

While the cost of production is relevant for fleet operators to meet demand most efficiently, prices can be assumed to be a key attribute of customer mode choice. The two indicators can be converted into each other by considering taxes, payment fees and profit margins. Similarly, vehicle kilometers can be planned by the operator, whereas passenger kilometers take demand reaction to the service (i.e. occupancy, empty travel, etc.) into account. Finally, the direct cost of a trip is the operating cost for a ride from point B to point C, while the full cost of a trip also includes a possible empty access trip from point A to B. While the first measure determines the customer's willingness to pay, an operator must cover the full cost of the trip. Pursuing a bottom-up approach; in this research, first, individual cost components are determined for different vehicle types, then operating costs are determined from an operator's perspective and after that, travel behavior impact is estimated using prices.

The respective cost components (overview in Appendix B) are obtained in two steps: First, based on manufacturer data and additional sources, fixed and variable vehicle costs are determined for the case of private ownership and use of the vehicle. In a second step, variations are introduced into the calculation to cover the case of commercial ownership and shared use of vehicles. Then, using a separate approach, the cost components of today's line-based mass transit are established. Eventually, the effects of vehicle electrification and automation are estimated for individual cost components, allowing calculation of overall operating costs and required minimum charges.

2.1. Cars

2.1.1. Fixed cost

Fixed vehicle costs depend substantially on the vehicle type. In this research, four general vehicle categories are considered:

- **Solo**: One-seat urban vehicle (Example: Renault Twizy [3]),
- **Midsize**: Standard four-seat all-purpose car (Example: VW Golf [4]),
- **Van**: Large eight-seat all-purpose car (Example: VW Multivan [5]),
- **Minibus**: Minibus with 20-seats with small trunk (Example: Mercedes-Benz Sprinter [6]).

For each of these categories, example vehicle acquisition cost was obtained from the car manufacturer's website for a model with a medium level of optional equipment. It should be noted that the costs mentioned in this and the next section include Swiss VAT of 8%. Depreciation is split into a fixed part, attributable to aging of the vehicle and a variable part from its usage. For the fixed part, it is assumed that the vehicle depreciates one tenth of its acquisition cost every year, independent of mileage. The variable part is explained at the beginning of the next section. It should be noted, however, that the calculations do not reflect costs for private owners who prefer to drive relatively new cars. Furthermore, as it is the purpose of the paper to derive an internal cost

[1] 2016 exchange rates (ER) (Organisation for Economic Co-operation and Development (OECD), 2017a) and purchasing power parities (PPP) (Organisation for Economic Co-operation and Development (OECD), 2017b): CHF/US$: ER 1.0, PPP 1.2; €/US$: ER 0.9, PPP 0.7.

[2] In this research, shared and pooled use are differentiated. Shared use of vehicles refers to sequential sharing of a vehicle (e.g. taxi), while pooled use describes simultaneous sharing of a vehicle, where different customers travel in the same vehicle at the same time (e.g. UberPool).

[3] Webpage: http://www.renault.ch/, last accessed 01.02.2017.

[4] Webpage: http://www.volkswagen.ch/, last accessed 01.02.2017.

[5] Webpage: http://www.volkswagen-nutzfahrzeuge.ch/, last accessed 01.02.2017.

[6] Webpage: http://www.mercedes-benz.ch/, last accessed 01.02.2017.

calculation, cash flow calculations, such as the repayments of the necessary loans, are not explicitly considered.

The interest amount was determined based on an annuity loan with an interest rate of 7.9% and a five-year credit period (Migrosbank, 2017). Processing fees for the borrower are ignored. Insurance rates were determined using the cheapest fully comprehensive insurance according to the internet comparison service Comparis (Comparis AG, 2016) for vehicles registered in the Canton of Zurich. The rates reflect the cheapest offer for non-business customers with 25 years of driving experience without accidents and 30000 driven kilometers per year. It should be noted that the policy with 15000 km per year is only 10 CHF cheaper. Taxes were obtained using a web-tool provided by the Canton of Zurich (Strassenverkehrsamt Kanton Zürich, 2017). For parking costs, the average for private cars in Switzerland was used (TCS, 2016). For tolls, the price of the Swiss motorway permit sticker was used for solo, midsize and van vehicles (Eidgenössische Zollverwaltung, 2017b). Minibuses are subject to a lump-sum heavy vehicle charge (Eidgenössische Zollverwaltung, 2017a). The resulting monetary values are presented in Table 1.

2.1.2. Variable cost

Variable costs of private vehicles were estimated for the four vehicle types. For depreciation and maintenance cost, the average for the Swiss car fleet was used and scaled by price of the car (TCS, 2016). For a midsized car, this results in a fixed depreciation of 3500 CHF per year and an additional 11.67 CHF for every 100 km driven. It is clear that this procedure underestimates value losses in the first years and overestimates them in later years. As this paper compares average cost figures, this nonlinear nature of value losses is ignored. It is further assumed that a private car is cleaned eight times a year, based on a median value between 6 and 10 in Germany (abh Market Research, 2007). The associated cost was estimated based on the price list of a self-service car-wash facility in Zurich (Autop, 2016). Concerning tires, it was assumed that two sets of tires (each 300 CHF) and two annual tire changes (each 100 CHF) would allow for 50000 km of driving. Fuel costs were given by urban fuel consumption as reported by the manufacturer at a fuel price of 1.40 CHF per liter (Shell, 2016). Given that there are no distance-based tolls for passenger cars in Switzerland at this time, a zero toll has been used here. The resulting monetary values are presented in Table 2.

2.1.3. Fleet effects

Commercial fleet operators benefit from various discounts on fixed and variable vehicle costs due to scale effects. By reviewing their platform transactions, Blens (2015) assessed the average discount granted to commercial customers for thirty popular company cars. The discounts range between 8.5% and 30.5%, with a median of 21%. As the number of vehicles bought by fleet operators should be substantially larger than for an average company, a general discount on the vehicle price of 30% is assumed. Due to more intense use, commercially used vehicles are further assumed to be written off over 300000 km (Klose, 2012), rather than ten years. Moreover, it is assumed that insurance rates for fleet operators are 20% lower, reflecting discounts typically available for group insurances (Helvetia, 2016). Given that the German car rental company Sixt SE issues bonds at 1.125% p.a. with six years duration (Sixt SE, 2016), the corporate interest rate is set at 1.5%; credit period is

Table 1
Fixed vehicle costs.

	Solo	Midsize	Van	Minibus
Capacity	1	4	8	20
Acquisition [CHF]	13000	35000	66000	70000
Interest [CHF/a]	260	700	1320	1400
Insurance [CHF/a]	500	1000	1200	1400
Tax [CHF/a]	120	250	700	1100
Parking [CHF/a]	1500	1500	1500	1500
Toll [CHF/a]	40	40	40	2200

Table 2
Variable vehicle costs.

	Solo	Midsize	Van	Minibus
Depreciation [CHF/100 km]	2.60	7.00	13.20	14.00
Maintenance [CHF/100 km]	2.38	6.40	12.07	12.80
Cleaning [CHF/100 km]	2.00	3.00	4.00	5.00
Tires [CHF/100 km]	2.00	2.00	2.00	2.00
Fuel [CHF/100 km]	5.60	7.98	12.88	20.30
Toll [CHF/100 km]	0.00	0.00	0.00	0.00

assumed to be three years. In addition, maintenance and tire costs are assumed to be 25% lower due to better conditions for bulk buyers. For fuel costs, a 5% reduction is assumed based on typical group discounts (Migrol, 2016). Based on Schlesiger (2014), parking costs for fleet operators are assumed to be 133% higher than for private drivers. In addition, VAT is deducted where appropriate, as costs in the previous section are based on gross prices of products and services.

It is assumed that customers pay less attention to third parties' property (tragedy of the commons), leading to substantially higher cleaning costs. Based on experiences of a car-sharing operator,[7] it was assumed that vehicles need to be cleaned after every 40th trip. If a car is not automated, the costs per driver hour are estimated at 35 CHF, based on the average yearly salary of Swiss taxi-drivers (Lohnanalyse, 2016) and the calculation tool of Braendle (2013), which helps determine labor costs for a company based on gross income.

Further cost components include overhead costs (consisting of management, human resources, fleet-coordination, advertising, etc.) and vehicle operations costs per vehicle and day for commercially operated on-demand services. These figures are assumed to depend on the fleet size and composition. An analysis based on US data (Federal Transit Administration, 2016) is presented in Appendix A. It suggests that, for a case in Switzerland, approximately 14 CHF per vehicle-day can be assumed for overhead and 10 CHF per vehicle-day for operations costs.

In addition to operating costs, user prices take into account a profit margin of 3%, the Swiss VAT of 8%, and a payment transaction fee of 0.44% (Wettbewerbskommission WEKO, 2014). The profit margin estimation is based on the study of SCI Verkehr (2016) that reports that the median profit margin for German logistic companies is between 2% and 4%.

2.2. Public (mass) transportation

For a fair comparison of different modes, the full production costs of today's public transportation services were estimated before direct subsidies. Given the large fleet sizes of most public transportation operators, it was assumed that administrative overhead share in the full costs is independent of fleet size. Therefore, overhead costs are assumed to be already incorporated in the full production cost per kilometer, not treated separately.

Operating costs for passenger rail are based on the annual report of the SBB (Swiss national railway company), for the year 2015 (SBB AG, 2016). The cost per train kilometer is stated as 31.40 CHF/km. This number should serve as a ballpark estimate, given that it only reflects the average across various train types and routes. Although the figure includes track fees, it should be highlighted that track fees in Switzerland are subsidized.

Among local public transportation providers, tight competition hinders transparency in reported business results. To attempt an accurate an estimate as possible, the framework introduced by Frank et al. (2008) was adapted, using Swiss salaries (Verkehrsbetriebe Zürich, 2016); this was then applied to an urban and a regional transit provider. The results were cross-validated, with data on average kilometer costs of 98 urban and 787 regional public transport lines across Switzerland from 2012

[7] Private communication.

(Bundesamt für Verkehr, 2011). It should be noted that trams are not part of the current analysis.

For bus and rail transportation, no scale effects are assumed because such effects are already incorporated in public transport providers' reported cost structures.

2.3. Cost effects of new technologies

In this research, two technological advances are expected to have a substantial impact on the cost structures of vehicles and transport services: electric propulsion technology and vehicle automation.

2.3.1. Electric propulsion

The battery is one of the main cost drivers of electric vehicles. As multiple batteries may be needed during the lifetime of a vehicle, it was decided to add the depreciation of the battery to the maintenance costs. It is thus assumed that the purchase price of an electric vehicle is similar to its conventional counterpart. Saxton (2013) analyzed the battery capacity of used Tesla Roadsters in line with their age, mileage and climate conditions. He found that only mileage would have a significant correlation and that most Tesla Roadsters would have a battery capacity of 80–85% after 160000 km. As fleet vehicles are written off over 300000 km, it is assumed that a battery needs to be replaced every 150000 km. Furthermore, a McKinsey (2017) analysis concludes that average production costs of an electric car battery are 227 US$ (227 CHF) per kwh. Including a profit margin of 3% and taking into account the Swiss VAT of 8%, this amounts to 252 CHF/kwh per customer. Taking the Volkswagen E-Golf[8] with a battery of 24.2 kwh as a reference, additional maintenance costs of 0.04 CHF/km are calculated. However, Diez (2016) report that the remaining maintenance costs for electric vehicles were found to be 35% less than for conventional vehicles. In total, maintenance costs therefore increase by 28%. Given that maintenance costs are adjusted to the different vehicle types, it is assumed that this increase covers the different battery capacities. Nevertheless, it needs to be emphasized that prices for batteries are likely to decline in the future. In fact, Nykvist and Nilsson (2015) even highlight that past predictions about today's costs of battery packs have been too pessimistic.

Furthermore, according to an internet comparison service (Comparis AG, 2016), insurance fees are 35% lower for the e-Golf than for a comparable gasoline Golf. This ratio has thus been assumed for all vehicle categories. In addition, electric vehicles are exempted from road tax in the Canton of Zurich (100% reduction). The fuel costs are 50% lower based on a comparison of the Golf and e-Golf energy consumption at current fuel/electricity prices.

2.3.2. Vehicle automation

Impacts of AV technology are less clear. It was assumed that the necessary technology would increase vehicle price by an average of 20% (IHS, 2014), leading to higher acquisition cost, interest cost and depreciation. Due to more balanced driving, it is further assumed that automation lowers fuel costs by 10% (Stephens et al., 2016). Due to more considerate automatic driving, it is expected that autonomous vehicles will need less maintenance for traditional car components. However, since it can be expected that the new sensors themselves need periodic maintenance, we do not assume different cost figures for the total maintenance costs. Based on earlier research, it was assumed that safer driving would lower insurance rates by 50%. This is regarded as conservative, as today's Tesla Autopilot is reported to have already decreased accident rates by 40% (NHTSA, 2017). The authors acknowledge, however, that this estimate is highly uncertain, given the profound changes ahead for the insurance industry (Morgan Stanley and Boston Consulting Group, 2016), which are beyond the scope of this research.

2.3.3. Automation and electrification of public transportation

To estimate the effect of vehicle automation on trains, the number of full time equivalents of active train drivers in passenger rail (2485 (SBB AG, 2016),) was multiplied by the average personnel cost of train drivers (87,946 CHF, including the average salary (Lohnanalyse, 2017) and employer outlay (Braendle, 2013)). The resulting total salary sum was then divided by the total annual operating cost of SBB passenger rail in 2015 (SBB AG, 2016). Assuming train drivers will not be needed any longer, this corresponds to a 4.7% decrease in cost per kilometer. Given that in Switzerland, railway lines already operate on electrified tracks, no further impact through electric propulsion is assumed.

To estimate the impact of electric propulsion and automated vehicle systems on bus operations, the framework by Frank et al. (2008) was used. Following assumptions on private and taxi operations, it was assumed that electric propulsion halves the fuel cost (5.5% decrease in total kilometer cost). Based on information by the Swiss Federal Office for Transport (Bundesamt für Verkehr, 2011) a bus driver's salary amounts to 55% of the total cost. As with trains, it is assumed that costs decrease by this share through automation.

Automation technology and electric propulsion are not expected to have substantial impacts on the fixed and variable cost of public bus and train services because automation technology is already pre-installed (in trains) or would not represent a substantial increase in the purchase price of a vehicle (for buses). Moreover, it is assumed that systems will continue to be operated in the same manner as today, so that impact on administration costs will be minimal.

2.4. Cost and price calculation

Based on cost factors provided above, comparable costs and prices of vehicles and transport services are calculated. The primary results are costs per vehicle-kilometer, cost per seat-kilometer, cost per passenger-kilometer, and price per passenger-kilometer. Cost thus represents the production costs for the fleet operator, while price also includes a profit margin for the provider, the VAT, and a payment transaction fee.

The cost-calculation framework allows for specification of the vehicle fleet, expected usage of this fleet and the operation model, including expected revenue.

- **Vehicle fleet:** The vehicle fleet is specified by type of vehicles, number of those vehicles and their features (electrified, automated).
- **Expected usage:** Usage is differentiated between peak, non-peak and night usage. For all three cases, average number of operating hours, relative active time (share of operating hours during which passengers are on board), average occupancy, average speed, average passenger trip length, relative empty rides, relative maintenance rides and relative maintenance hours are required. Expected usage is further specified in Section 3.
- **Operational model:** Besides private vehicle ownership, two forms of public transport are differentiated here: dynamic shared fleet operation and line-based mass transit.

Expected usage parameters (Section 3) result in an average number of kilometers travelled per day, plus number of passengers, including passenger kilometers and passenger hours per day.

From the fleet, usage, and operation specifications, different cost and price estimates are calculated:

- The **price per passenger-kilometer** P_{pkm} is the production cost per passenger-kilometer C_{pkm}, plus expected profit margin r, payment transaction fee p, and VAT:

$$P_{pkm} = \frac{C_{pkm}}{(1-r)(1-p)} \cdot (1 + \text{VAT})$$

[8] Webpage: http://www.volkswagen.ch/, last accessed 14.08.2017.

- The **cost per passenger-kilometer** C_{pkm} is calculated as the average total cost per vehicle and day C_{vd} divided by average passenger kilometers per vehicle and day.
- Similarly, the **cost per vehicle-kilometer** C_{vkm} is calculated as the average total cost per vehicle and day C_{vd} divided by average total kilometers per vehicle and day $vkm_{tot/d}$.
- **Average total kilometers per vehicle and day** $vkm_{tot/d}$ is the sum of average service kilometers skm and average empty kilometers driven ekm.
- **Average total cost per vehicle and day** C_{vd} is the sum of fixed costs per vehicle and day (fix cost of the vehicle FC_{vd}, plus service provider overhead costs OHC_{vd}), plus total variable cost per vehicle and day (variable cost of the vehicle per kilometer VC_{vkm}, plus variable service costs per hour VSC_{vh} (e.g. the driver)):

$$C_{vd} = (FC_{vd} + OHC_{vd}) + \left(\left(VC_{vkm} \cdot vkm_{tot/d}\right) + \left(VSC_{vh} \cdot DT_{h/d}\right)\right)$$

With $DT_{h/d}$ being the total time the vehicle is on duty per day and with vehicle costs, FC_{vd} and VC_{vd}, being sums of respective cost factors adjusted by scaling factors representing technologies and applicable fleet discounts.

- The **cost per seat-kilometer** C_{skm} is calculated by dividing the cost per vehicle-kilometer C_{vkm} by the number of seats per vehicle $seats_v$.

The cost calculation framework is implemented in the programming language R with an input interface in Microsoft Excel.[9] The cost calculation software framework is available from the authors on request. Fellow researchers are encouraged to reproduce the cost estimates presented in this paper, but also to estimate costs for different situations, use cases and other possible future transport services with AVs.

3. Utilization parameters

Average cost per user depends not only on vehicle characteristics, but also on service efficiency, i.e. vehicle utilization, empty travel and overhead. To approximate these values, this section first presents the utilization cases differentiated in this paper and then describes their average usage as assumed for the Zurich, Switzerland region. A summary of the complete parameter set can be found in Appendix C.

In this paper, three spatial and three temporal cases were differentiated for private and shared services including taxis. The three spatial cases are:

- Urban: Trips starting and ending in an urban area and which are shorter than 10 km.
- Regional: Trips starting and ending outside of an urban area and which are shorter than 50 km.
- Overall: Any trips shorter than 200 km, independent of the area.

For each of these spatial cases, the following three temporal cases were defined:

- Peak: Trips beginning or ending between 7am and 8am or 5pm and 6pm.
- Off-peak: Not peak-trips, which begin or end between 8am and 5pm.
- Night: Neither peak, nor off-peak trips.

For each of the above use cases, the following parameters were assumed for the Zurich, Switzerland region:

- *Average operation hours:* The time a taxi or a service is available.
  For private vehicles in Switzerland, the average usage time was determined for each of the above cases based on the Swiss transportation microcensus (Swiss Federal Statistical Office (BFS) and Swiss Federal Office for Spatial Development (ARE), 2012). This suggests 0.32 h during peak, 0.7 h during off-peak, and 0.3 h during night.
  Conventional mobility services were assumed to stay online for 20 h per day (minus maintenance). The live time would span the peak hours, the off-peak hours and a part of the night. To account for maintenance issues, 5% of the live time was subtracted during peak and off-peak times and 20% during the night. In contrast, professional AV services would be operated throughout the day, except for maintenance (as above).

- *Relative active time:* The share of operation hours, during which the vehicle serves customers.
  For private vehicles, this is 100% of the operation time.
  For commercial services, these numbers were calculated from Bösch et al. (2016). This represents relative active time if a substantial part of the population were using the service for all of their trips. According to their results, relative active time for taxis and shared services is 57% during peak, 59% during off-peak, and 30% during night. The lower relative active time during peak hours than during off-peak is due to the more uni-directional demand in peak hours (commuters). No spatial differentiation was made here.

- *Average occupancy:* Average number of passengers in the vehicle when on duty.
  For private cars in Switzerland, average occupancy was calculated from the Swiss transportation microcensus (Swiss Federal Statistical Office (BFS) and Swiss Federal Office for Spatial Development (ARE), 2012). It was found to be 1.34 for peak, 1.46 for offpeak, and 1.43 for night. For commercial services, taxi and ride sharing (pooled) was differentiated. For taxi services, the same occupancy values as found for private cars were assumed. For ride sharing (pooled) services, occupancy values found by the International Transport Forum (2015) were used; 2.6 for peak, 2.4 for off-peak, and 2.3 for night. The same values were used for urban and regional settings.

- *Average speed:* The overall average speed of the vehicle (service and passenger trips).
  Average speed of cars in Switzerland was calculated for each spatio-temporal case, as found in the Swiss transportation microcensus (Swiss Federal Statistical Office (BFS) and Swiss Federal Office for Spatial Development (ARE), 2012); overall peak 32.4 km/h, overall off-peak 34.0 km/h, overall night 36.2 km/h, urban peak 20.6 km/h, urban off-peak 21.9 km/h, urban night 23.7, regional peak 31.3 km/h, regional off-peak 32.2 km/h and regional night 34.0 km/h.

- *Average passenger trip length:* The average in-vehicle trip length of passengers using the service.
  Average Swiss car trip length was calculated based on the Swiss transportation microcensus (Swiss Federal Statistical Office (BFS) and Swiss Federal Office for Spatial Development (ARE), 2012) for each spatio-temporal case; overall peak 15.0 km, overall off-peak 10.5 km, overall night 12.6 km, urban peak 3.4 km, urban off-peak 3.0 km, urban night 3.4 km, regional peak 8.0 km, regional off-peak 5.9 km and regional night 7.1 km.

- *Relative empty rides:* Percentage of empty vehicle trips due to, for example, relocation, pick-up drives, or return-to-base drives.
  As empty kilometers for private vehicles would be the result of a substantially different user behavior than today (e.g. several people privately coordinating for a vehicle), assumptions here would imply many far-reaching assumptions about user behavior. As this is beyond

[9] The detailed input values, as well as the resulting cost structures and prices of different services, are presented in the appendix of this publication.

the scope of this publication, empty rides for private vehicles are excluded here. For commercial services, based on (Fagnant et al., 2015), number of empty rides was assumed to be 8% for urban settings, and based on (Bösch et al., 2016), 15% for regional settings.

- *Relative maintenance rides:* Share of vehicle trips due to maintenance, cleaning and repair.
  For private vehicles, no maintenance rides were assumed (given the dense network of gas stations in the Zurich area, additional distance through refilling and/or cleaning is negligible). For commercial services, 5% was assumed, based on experience with traditional car sharing services.

Given the limited information available about public transportation, average daily values were determined without a temporal differentiation. In average, 19 h of operation were assumed for bus and rail services to account for the official public transport night break from 00:30 to 05:30 in the Zurich, Switzerland region. This probably overestimates vehicle operation hours, as each individual vehicle is not operated for the full 19 h. It is thus a conservative estimate for public transportation. Relative active time was estimated at 85%, based on the official schedule (Zürcher Verkehrsverbund, 2017). Average occupancy and speed of public transport vehicles was derived from Bundesamt für Verkehr (2011); for urban buses an average occupancy of 22.42% and a speed of 21.31 km/h were reported, for regional buses 12.6% and 20.89 km/h, and for regional trains a speed of 37.82 km/h. Average regional train occupancy was 22.7% according to the SBB annual report (SBB AG, 2016). Empty rides and maintenance rides were assumed to be already accounted for in the average occupancies and thus set to 0% (SBB AG, 2016).

A full table presenting the various cases and corresponding values is included in Appendix C. Current usage values as presented here are average values based on current market situation and price structure. If lower costs were assumed, these values would probably be too high for occupancies and too low for trip lengths.

4. Validation with current services

Combining the cost structures (Section 2) with utilization parameters (Section 3) allows for the calculation of average cost values for each use case (Section 2.4). In a first step, results were validated against data on current transportation services.

4.1. Private car

An average private car in Switzerland costs 0.71 CHF per kilometer (TCS, 2016). Our own cost calculations resulted in a cost of 0.69 CHF per kilometer for a conventional private midsize car with average usage as in (TCS, 2016). Also considering that shares of different cost components show only minimal differences, the framework is considered to correctly calculate cost structures for private vehicles.

4.2. Taxi

In Zurich, taxi prices are regulated, with a base price of 8.00 CHF plus 5.00 CHF per kilometer. (Stadt Zürich, 2014). UberPop fares consist of a base price of 3.00 CHF plus 0.30 CHF per minute and 1.35 CHF per kilometer (Uber, 2017). For a conventional midsize car used as taxi in an urban setting (usage as defined in Section 2), the framework returns costs of 3.38 CHF per kilometer, which can be assumed to be in the correct range, given taxi and UberPop charges cited above.

4.3. Public transport

Calculation of cost values for city and regional buses was calibrated to the full cost per vehicle kilometer, as stated in (Bundesamt für Verkehr, 2011). Original reference values are 7.14 CHF per kilometer for city buses and 6.70 CHF per kilometer for regional buses (Bundesamt für Verkehr, 2011). Cost of rail services was derived from SBB AG (2016) as 31.40 CHF per kilometer for trains. In both cases, given the lack of an additional, independent source of information, no actual validation is possible.

5. Results

After validation in Section 4, the framework presented above was used to estimate the cost of future transport services. Given the large number of operational model combinations, vehicle types, and spatial classifications, only a selection is presented below, representing the use cases offering the most important insights. A more complete list with other combinations can be found in Appendix D.

In a first step, the framework was used to analyze the impact of vehicle automation on the cost structures of various mobility services.

5.1. Cost structures

To better understand the impact of autonomous vehicle technology, the cost structures of different operational models were compared. First, conventional private vehicles (*Private Car*) and conventional taxi fleet vehicles without pooling (*Ind. Taxi*) were studied. Fig. 1 presents the cost components for the case of conventional midsize vehicles in an urban setting with (*Autonomous*) and without (*Conv*) vehicle automation (for the complete list of values see Table 3).

As shown in Fig. 1, there is a general difference between the two operational models. While the operating cost of a private vehicle is mostly determined by its fixed costs related to the car (such as depreciation, insurance or interest), the operating cost of current taxi fleets is mostly determined by the driver's salary. Administration cost, as well as car related costs, play a minor role.

Vehicle automation drastically changes cost structures of the different services. In general, three effects are at work; on one hand, autonomous vehicle technologies raise the vehicle purchase price, but on the other hand, reduce operating cost through lower insurance fees, maintenance and fuel costs. In addition, they allow taxi fleets to operate without drivers, thus cutting their main cost component.

It is interesting to note that for privately used cars, the first two effects cancel out, so that running costs remain largely unchanged (around 0.49 CHF/km, see Table 3). The third effect does not apply for private vehicles, because there is no direct monetary gain through their automation.

Due to substantially higher utilization, reductions in variable and labor costs more than outweigh the increases in fixed costs for ride-hailing or taxi vehicles. In particular, driverless technology is the key factor in substantially lower production costs for such fleets. It is assumed that the operating costs of a ride-hailing or taxi vehicle would plummet from 2.73 CHF/km to 0.41 CHF/km (see Table 3). Given the absence of a driver and fellow passengers, however, customers of such taxi services are expected to show more irresponsible behavior in the vehicle (e.g. by eating) resulting in a faster soiling of the vehicle. To estimate this effect, minimum cleaning efforts of current car-sharing schemes were used. As shown in Fig. 1, even minimum assumptions result in substantial cleaning efforts, which would rapidly account for almost one-third of automated taxi's operating costs. Combined with an estimated share of 20% due to overhead cost, this means that more than half of autonomous vehicle fleets' operating costs will be service and management costs. Hence, by optimizing their operations processes, providers may realize substantial efficiency gains, allowing them to increase their respective market share. However, even without such additional measures, autonomous vehicle technologies would allow fleets to operate at lower costs than private vehicles.

5.2. Impact of vehicle automation

As outlined above, the effect of vehicle automation on the cost

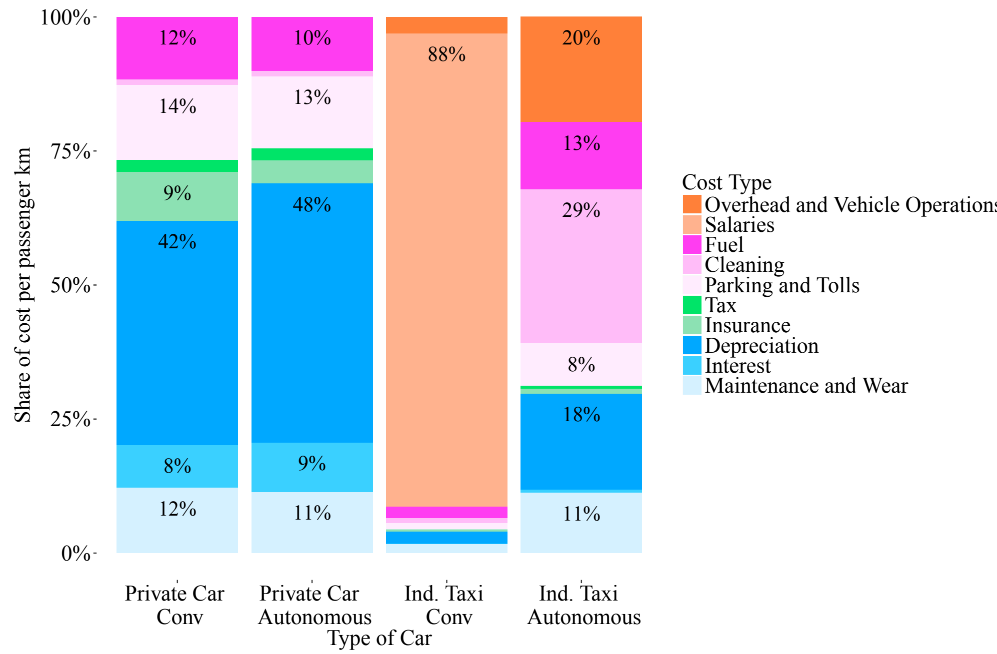

Fig. 1. Cost structure comparison with (*Autonomous*) and without (*Conv*) vehicle automation for private vehicles (*Private Car*) and taxi fleet vehicles without pooling (*Ind. Taxi*).

Table 3
Cost structure comparison with (*Autonomous*) and without (*Conv*) vehicle automation for private vehicles (*Private Car*) and taxi fleet vehicles without pooling (*Ind. Taxi*).

	Private Car Conv		Private Car Autonomous		Ind. Taxi Conv		Ind. Taxi Autonomous	
	CPKM [CHF]	Share of CPKM	CPKM [CHF]	Share of CPKM	CPKM [CHF]	Share of CPKM	CPKM [CHF]	Share of CPKM
Overhead and Vehicle Operations					0.083	3.0%	0.08	19.6%
Salaries					2.409	88.3%		
Fuel	0.056	11.6%	0.051	10.0%	0.057	2.1%	0.051	12.5%
Cleaning	0.005	1.1%	0.005	1.0%	0.026	0.9%	0.117	28.8%
Parking and Tolls	0.068	13.9%	0.068	13.4%	0.033	1.2%	0.032	7.9%
Tax	0.011	2.3%	0.011	2.2%	0.002	0.1%	0.002	0.6%
Insurance	0.044	9.1%	0.022	4.4%	0.008	0.3%	0.004	0.9%
Depreciation	0.203	41.9%	0.243	48.3%	0.061	2.2%	0.073	18.0%
Interest	0.039	8.0%	0.046	9.2%	0.002	0.1%	0.002	0.5%
Maintenance and Wear	0.059	12.2%	0.058	11.4%	0.047	1.7%	0.046	11.3%
Sum	0.485	100%	0.504	100%	2.728	100%	0.407	100%

CPKM: Costs per passenger-kilometer.

structure of future transport services is substantial. Fig. 2 shows the effect of automation on today's main operational modes for the urban and the regional (suburban and exurban) case. Given the dominant role of midsize cars in today's transport system, private and taxi operational models are assumed to be conducted using midsize vehicles. Up to this point, no electrification of vehicles is considered (except for trains which are already electrified today) to isolate the effect of automation.

Fig. 2 shows that, without automation, the private car has the lowest

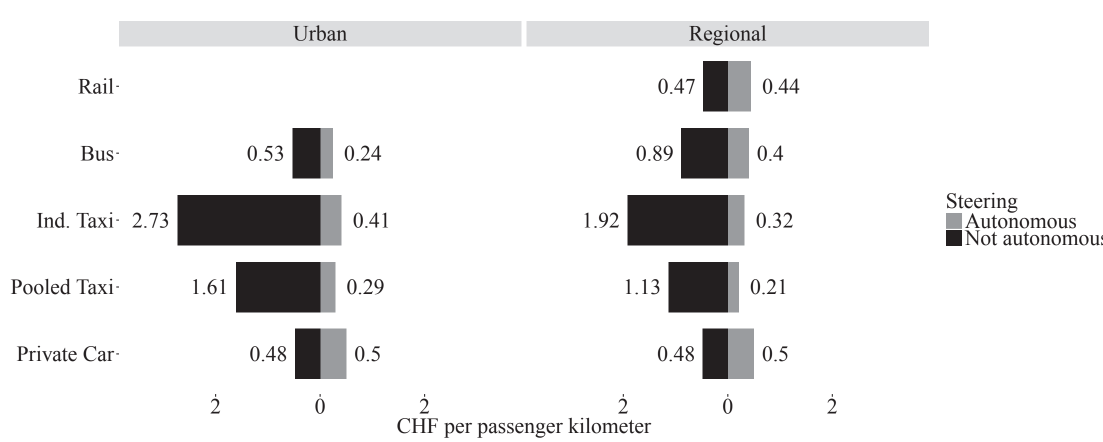

Fig. 2. Cost comparison of different modes with and without autonomous vehicle technology.

operating cost per passenger kilometer (except regional rail services). Because of the paid driver, taxi services are substantially more expensive. In the current transportation system, they are used for convenience or in situations without alternatives, not because of their cost competitiveness. Non-automated urban buses and regional rail lines operate at similar costs per passenger kilometer as private cars.

The picture changes substantially with the automation of vehicles. While the cost of private cars and rail services changes only marginally, autonomous driving technology allows taxi services and buses to be operated at substantially lower cost, even more cheaply than private cars.

In an urban setting, taxis become cheaper than conventional buses, yet they remain more expensive than automated buses. The absolute cost difference between buses and taxis, however, is reduced substantially through automation from 2.20 CHF/pkm to 0.17 CHF/pkm for individual taxis. Even in relative terms, automated taxis will be only 71% more expensive for individual and 21% more expensive for pooled use than automated buses (compared to 415% and 204% before automation).

In regional settings, defined as suburban and exurban trips, automated taxis and buses become cheaper than private vehicles and rail services. Here, pooled taxis are the cheapest mode (0.21 CHF/pkm), followed by individual taxis (0.32 CHF/pkm). In a regional setting, based on operating cost, automated buses and trains no longer seem to be competitive (0.40 and 0.44 CHF/pkm).

5.3. *Robustness of the estimates*

Calculation of the presented cost structures relies on a number of assumptions, which - given the limited state of knowledge today - have different degrees of certainty. To analyze how robust the results are to changes in assumed cost components, three of the variables with highest uncertainty were varied in the calculation. The selected variables are: vehicle sticker price, overhead costs for fleet operators and relative active time of the vehicles.

To reduce the complexity of the problem, changes in each of the three variables were analyzed uni-dimensionally only. The resulting elasticities for a 10% increase in the three variables are presented in Table 4. They are in line with Fig. 1 in that salaries are the key cost driver for conventional services, whereas for autonomous vehicles, hardware is also important (because vehicle price relative effect is substantially higher). As shown in the table, changes in sticker price of a vehicle have a substantial impact only for privately used vehicles. For fleet vehicles, in contrast, neither the vehicle price nor changes in the overhead cost show a substantial impact. Increases in the relative active time of a vehicle show a substantial effect on the operating cost. Although actual effect of changes in the relative active time are non-linear because fixed costs are distributed over relative active time (hence an inverse relation), the linear approximation can be assumed valid between values of 30% and 90% active time. It is therefore argued that for this range, combined changes in the three variables can be approximated by adding up the individual effects.

When comparing the different modes, results show that autonomous buses and solo vehicles benefit most from increased active times and reduced overhead costs, whereas in the conventional scheme, all systems benefit comparably. Yet, when compared to Fig. 2, substantial disruptions in the three variables would be required to actually change the ratios of the costs of the different vehicle types. It can thus be assumed that cost structures presented above also robustly represent the different vehicle types' relative order.

6. The new competitive situation

Based on the cost structures described above, suitable market niches are studied for different operational models with automated vehicles. Besides private vehicle ownership (midsize, *Private aCar*), midsize taxis (individual *aTaxi*) and line-based public transport (*aCityBus* in urban settings and *aRegBus* for regional settings), a fleet of shared solo vehicles (*Shared aSolo*) is considered. Taking into account ongoing developments, it is assumed that by the time autonomous driving technology is introduced, all vehicles will be equipped with electric propulsion.

Here, as opposed to the previous two sections Section 4 and Section 5, the perspective changes from supplier to user, represented by a change from cost analysis to price analysis. The price consists of the operator cost plus the expected profit margin, VAT and fees (see Section 2.4). Obviously, this does not apply to private vehicles, as there the user is also the operator.

6.1. *The global view*

Fig. 3 summarizes the prices per passenger kilometer for the above modes in an urban and a regional (sub- and exurban) setting with average usages as described in Section 3. It indicates the future competitive situation. The cost of private vehicles is differentiated between fixed and variable cost, as private users often consider only immediate out-of-pocket cost in their short-term mode choice.

In both settings, it can be observed that a service with shared aSolo vehicles is not substantially cheaper than aTaxis, because in Switzerland today, the average occupancy of a midsize vehicle ranges between 1.34 and 1.46 persons per ride (see Section 3). This is enough to make - per passenger-kilometer - aTaxis competitive with shared aSolos. It can also be observed that, while city buses remain substantially cheaper than aTaxis (see Fig. 3(a)), aTaxis can provide services for around 80% of the regional bus service price (see Fig. 3(b)). In summary, aTaxis are very competitive, especially for regional settings, if the full cost of private vehicles is considered. Together with aSolos, they are the cheapest mode

Table 4
Robustness of estimated cost structures (cost per passenger kilometer) to a 10% increase in selected variables.

		Private	Urban			Regional				
			Pooled Taxi			Line-based	Pooled Taxi			Line-based
		Midsize	Solo	Midsize	Van	Bus	Solo	Midsize	Van	Bus
Vehicle price	Conventional	0.024	0.003	0.004	0.007	0.010	0.004	0.004	0.008	0.018
		5.0%	0.1%	0.2%	0.4%	1.9%	0.3%	0.8%	0.8%	2.0%
	Autonomous	0.029	0.004	0.004	0.008	0.010	0.004	0.005	0.009	0.018
		5.8%	1.0%	1.5%	2.3%	4.2%	2.3%	3.6%	4.2%	4.4%
Overhead	Conventional	–	0.006	0.003	0.003	0.004	0.002	0.001	0.001	0.005
		–	0.2%	0.2%	0.2%	0.7%	0.2%	0.1%	0.1%	0.6%
	Autonomous	–	0.007	0.003	0.003	0.004	0.002	0.001	0.001	0.005
		–	1.6%	1.0%	0.7%	1.7%	0.9%	0.5%	0.3%	1.3%
Active time	Conventional	–	−0.331	−0.137	−0.137	−0.038	−0.088	−0.036	−0.036	−0.065
		–	−8.8%	−8.5%	−8.2%	−7.2%	−7.9%	−7.2%	−6.2%	−7.3%
	Autonomous	–	−0.015	−0.006	−0.007	−0.012	−0.004	−0.002	−0.002	−0.017
		–	−3.6%	−2.2%	−1.8%	−4.9%	−2.1%	−2.0%	−1.3%	−4.3%

The upper line shows the absolute change in the cost [CHF] per passenger kilometer, the lower line shows relative change.

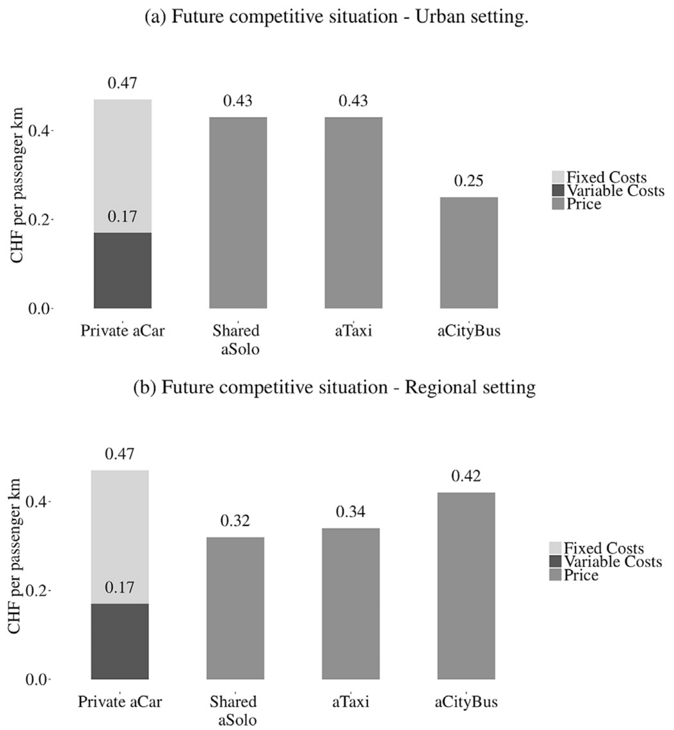

Fig. 3. Future competitive situation with autonomous vehicle technology in an urban and a regional setting.

in a regional setting, ranking among the cheapest individual service options in an urban setting.

Quite like today, private vehicles represent the cheapest option if only immediate out-of-pocket costs (0.17 CHF) are considered. In particular, in an urban setting (Fig. 3(a)), they incur about two thirds of what has to be charged for line-based city-bus services and about 40% of autonomous taxis.

It should be mentioned here that the above refers to relative differences in prices. Even if these differences could be substantial, in absolute terms they are still small (see Fig. 2), which makes the value of travel time savings a substantially more important factor in mode choice.

6.2. Demand-based view

Having shown that fleet vehicles can be offered at competitive prices, in a next step, different vehicle sizes are compared. To that end, minimum prices per passenger kilometer were calculated for different vehicle types and demand levels. In this context, demand levels are defined as passengers per vehicle per main load direction. It is further assumed that the vehicles operate as part of larger fleets. Therefore, no additional scale effects arise when adding more vehicles to a specific route and the operational model from above is used (see Section 3).

The results are presented in Fig. 4. It becomes immediately clear that electric propulsion and self-driving technologies allow a substantial decrease in prices for all modes. This decrease, however, does not affect all modes in the same way as shown in Section 5. In fact, the most substantial gains are achieved for shared midsize vehicles, for which the price per passenger kilometer falls precipitously by 78% to 0.24 CHF/Pkm at full load. This way, the price gap between a city bus and a midsize taxi at full load decreases from 0.95 CHF/pkm to 0.18 CHF/pkm. Interestingly, autonomous-electric vans (0.21 CHF/pkm) and minibuses (0.17 CHF/pkm) are not substantially less expensive than midsize vehicles when operated at full load. The detailed cost values can predict viability of different autonomous vehicle operational models at different levels of demand. For example, the data shows that autonomous solo vehicles are the cheapest mode only for low-demand origin-destination relations. With an average occupancy of two on this route, a midsize car would already be more efficient. On the high-demand side of the spectrum, for demand levels of more than fifteen simultaneous passengers per main load direction, a city-bus is more economical than a midsize car. The threshold between a minibus and a city bus is at 21 passengers. The average occupancy of a city bus today is 22.42 passengers (Bundesamt für Verkehr (2011)).

7. Discussion

7.1. A new world?

The results of this research help to understand the roles that the various modes may play in a future transport system, encouraging future research on AVs and the study of possible implementations in a more efficient way.

In particular, this research shows that private cars still represent an attractive option in the era of autonomous vehicles, as out-of-pocket costs for the user (0.17 CHF/km, c.f. Fig. 3) are lower than for most other modes (and could be even lower if the user e.g. produced its own electricity). This is in the range of the $0.15/mile Burns et al. (2013) found for shared AVs and the $0.16/mile Johnson (2015) found for purpose-built pooled aTaxis, but they neglected important cost factors - for example cleaning. Compared to the assumption by Fagnant and Kockelman (2015) of a $1.00/mile price for a shared AVs, even the full cost of private vehicle ownership might be competitive.

In fact, buying an autonomous vehicle could be regarded as an investment in a private mobility robot, which can be used both for chauffeur services and for errands; this venture will therefore be even more

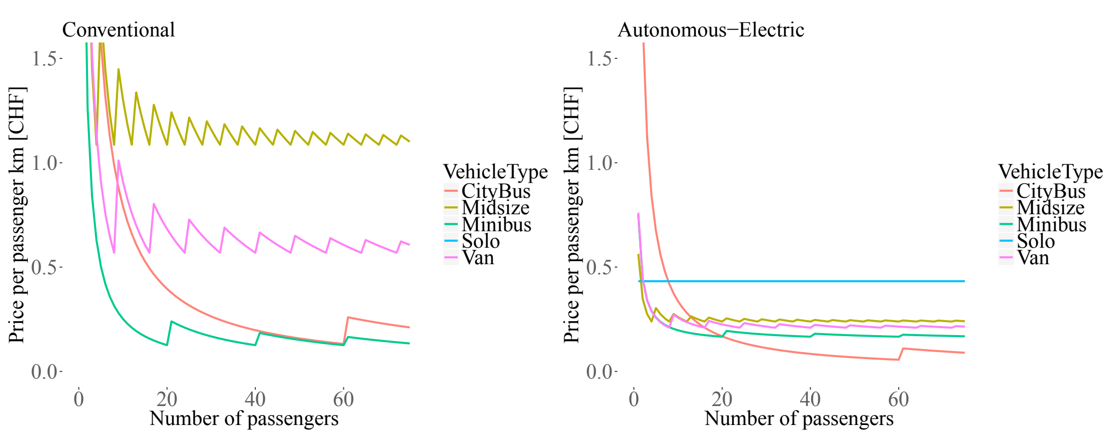

Fig. 4. Prices per passenger km versus number of passengers.

attractive than a conventional vehicle. Hence, it can be expected that a substantial number of people would value the private use of a mobility robot and will agree to pay the associated premium. Additionally, traditional car manufacturers are strongly motivated to maintain the current emotional connection many people have to their cars. In conclusion, even as low costs for shared AVs, as estimated by Burns et al. (2013) and Johnson (2015), might not be low enough to end the reign of the private car.

In contrast to private vehicle ownership, results of this research suggest that current line-based public (mass) transportation will probably be subject to adjustments beyond its automation. Although its operation will become cheaper, pooled taxi schemes and other new forms of public transportation will emerge as new and serious competition. The results of this paper (see Figs. 3 and 4) suggest, however, that the situation is not as clear as suggested by for example Hazan et al. (2016). If full cost of shared vehicles is considered, combined with the low average occupancy achievable with pooling even in an urban setting (International Transport Forum, 2015), mass transit public transport is still competitive - especially for urban settings and high-demand relationships - and even more, if unprofitable low-demand relationships can be served with more flexible services, thus increasing average occupancy. The situation gets even more interesting if one considers that today's form of public transportation in Switzerland receives subsidies for approximately 50% of its operating costs (Laesser and Reinhold, 2013). In principle, with autonomous driving technologies and constant levels of subsidies and demand, operators would be able to offer line-based mass-transit public transportation for free. However, public money - if available - would be much more wisely spent on new forms of public transportation promising not only lower operating costs, but also higher customer value by offering more comfort, faster travel times and fewer transfers. Hence, it is likely that particularly rural or tangential relations will be served by new forms of AV-based public transportation.

Shared solo vehicles are seen by some researchers as an ideal first-and-last-mile complement of mass transit public transportation. Offering direct point-to-point service for single travelers, they promise short access and travel times. However, they may not be designed to carry baggage and are not much less expensive to operate than shared midsize vehicles (see Fig. 3). Policies aside, it is therefore more likely that fleet operators opt for a homogeneous midsize or van fleet to serve individual travelers, as well as smaller groups. One vehicle size functions well, particularly because - assuming acceptably low waiting times - few relations see a demand as low as only one traveler per time interval.

Fleets of (pooled) aTaxis are another mode often proposed as the new 'jack of all trades' in transport: offered at such low prices that they will replace every known mode. As this study shows, however, this picture changes if full costs, including overhead, parking, maintenance and cleaning, are considered. Just these factors, neglected in most studies on the topic so far (see Section 1), contribute two thirds of the total cost of aTaxis (see Section 5). It is thus no surprise that the costs of shared services determined here are substantially higher than those in previous work (e.g. Burns et al. (2013); Johnson (2015); Stephens et al. (2016); Hazan et al. (2016)). Because shared AVs are still very economical to operate and OEMs might also have an interest in shared services (Abhishek et al., 2016), these business models might still have a bright future. Shared fleets of aTaxis also have the advantage that the usage can be controlled and (geographically) restricted - especially compared to privately owned vehicles. This minimizes the liability risk for OEMs and mobility providers as long as AVs are not yet an established and proven technology.

Car-pooling might lower prices if high average occupancies can be achieved. High occupancies, however, come with more detours, longer individual travel times and more strangers in the same intimate environment of a car. Especially the latter factor might be an obstacle to the success of pooled midsize or van fleets. Although people usually prefer the privacy of their own vehicle to the anonymity of a bus ride, many find sharing a vehicle with strangers burdensome (Schmid et al., 2016). In this respect, more research is required to better understand customer preferences and design pooled vehicles accordingly, because, if successful, ride-sharing with AVs will definitely have a number of benefits (Friedrich and Hartl, 2016; International Transport Forum, 2015).

A further challenge for shared services will be to find a solution to maintain vehicle cleanliness. The analysis above revealed that even with low cleaning frequencies and costs, cleaning is the single largest contribution to the operating cost of autonomous (individual) taxi schemes. Any higher level of soiling may even endanger their competitiveness through high costs or low service standards.

7.2. Limitations

The analysis presented in this paper is - to date - the most comprehensive approach to estimating operating costs of future autonomous transportation services. It includes several aspects previous studies have overlooked, or assumed negligible (e.g. overhead costs or cleaning) and it draws a clearer and/or different picture of the future transportation system than earlier works (Burns, 2013; Fagnant and Kockelman, 2015; Litman, 2015; Johnson, 2015; Stephens et al., 2016; Hazan et al., 2016). While this detailed approach reveals new insights, it is also comes with various limitations.

First, it is likely that vehicle automation will change the demand for certain kinds of infrastructure, like parking, which could also have an effect on assumed prices. It is also possible that automated vehicle introduction induces changes in overall mobility behavior, which will require the government to take measures to counterbalance negative effects. The impact of governmental policy measures (e.g. road pricing), external subsidies, company-internal cross-subsidies and special pricing strategies, however, have been ignored in this paper; attention to policies was restricted to those already implemented today. Extended services, such as for example non-driving personnel in the vehicles or premium vehicles have been ignored too. Such extras might be part of an improved customer experience (with a matching price adjustment), or due to legal requirements (e.g. personnel assisting users with disabilities).

While such measures, policies, and extra services are expected to substantially influence price structure and thus the competitive situation, their cost will probably be passed along to the user. It follows that they would not substantially influence the basic cost structure of different services for the provider. Given their unpredictable nature and that they are often designed based on analyses like the one presented in this paper, it was decided to leave these questions open for future research. Scenario-based analyses of possible measures, e.g. to achieve socially optimal prices, or to incorporate externalities in the prices, as well as to investigate different price vs. service combinations, could further be a topic for future work.

It should be mentioned that bus and train capacities are likely to be adjusted after automation. While the influence of different occupancy rates has been analyzed in Section 6.2, that study does not account for different vehicle purchase prices and increased vehicle management costs for growing fleets. It is anticipated that increased resource scheduling flexibility in a system without drivers will lead to financial savings. As extensive analysis would be required to quantify these savings, these effects would exceed the scope of this paper.

While the cost structures of cars, whether private or as shared vehicles, could be analyzed with a high degree of detail (Section 2.1), the overhead costs of shared mobility services are well-kept secrets within the respective companies. Furthermore (Federal Transit Administration, 2016), data suggests that these figures vary substantially among companies of similar size, indicating that further factors like internal organisation and detailed business case play an important role. Accordingly, estimates of the overhead cost of shared services and total costs of public transport services must be treated with caution.

The same applies for the cost effects of new technologies. Electric cars are already on the market and thus estimates of the cost effects are reliable and well grounded. The effects of automation, however, are uncertain. Admitting this, the approach presented in this paper identifies different factors resulting in the observed total cost. Then, the effect of autonomy is estimated for each cost factor separately, resulting in more precise and reliable estimates. Where available, these estimates were based on values reported in literature. The authors are aware, however, that even such detailed estimates' accuracy is questionable. Correspondingly, usage values in this study are based on current market situation and price structures. If radically lower costs are assumed, these values are likely to change substantially (e.g. lower occupancy or longer trips). Once travel behavior impacts and usage patterns of such schemes become clearer, the framework introduced in this research can be used for a scenario-based analysis of their cost structures and will probably yield more accurate results. Until then, the reader should be aware of these limitations when interpreting the results presented in this paper.

8. Conclusion

This paper presents a detailed cost estimation for current and future transport modes, with special consideration of automated vehicles. It is based on a detailed cost structure reconstruction of different transport services as far as available and best knowledge estimates otherwise. This analysis goes beyond earlier assessments of future modes' cost structures in both its level of detail and its rigor.

The framework was validated and delivers new insights into automation's impacts on different transport services and vehicle categories. For example, it is clear that fleets of shared autonomous vehicles may become cheaper than other modes in relative terms, but in absolute numbers, the difference will be small. Thus, there will still be competition by other modes and even by private car ownership, which may well persist beyond the dawn of autonomous vehicle technologies by offering the luxury and convenience of a personal mobility robot. On the other hand, this research was able to confirm expectations (e.g Meyer et al. (2017)) that conventional forms of public transportation may face fierce competition in the new era.

Importantly, this research also revealed that the success of shared AV fleets may well depend on a factor which has been previously ignored - cleaning efforts. According to our findings, developing viable business models for shared AV fleets will entail solutions to require that customers behave appropriately while on board (e.g. video observation of passengers, or a confirmation check by the next user on the condition of the car to identify irresponsible passengers) and/or to clean and repair vehicles efficiently and at low costs.

Based on an exclusively cost-based approach, this research was able to clarify use cases of future modes of transportation, although many open questions remain and require further research. For example, the actual mode choice is determined not only by cost, but also substantially by travel time and comfort (value of time), as well as other factors like the perception of transfers, waiting times, etc. - all of which were not investigated in this paper. Therefore, actual implementations of the proposed schemes need to be implemented in a field trial or simulation approach to better understand the size of the respective market segments in a realistic environment. Moreover, due to its complexity, long-distance travel could not be covered in this research, but it is known to play an important role in mobility tool choices (Canzler and Knie, 1994).

Another future research area is the investigation of a re-sized, line-based transit resulting from the automation of buses. If driver wage is no longer part of the cost structure, it might be worthwhile to operate buses with smaller capacities and higher frequencies. Not only is demand bundling, when possible, more economic than point-to-point service (see Section 5), there is also a user preference for high-frequency, line-based service over dynamic services (for a recent review, see (White, 2016)). Current passenger statistics of the City of Zurich (Verkehrsbetriebe Zürich, 2014) make a first approximation of the utilization possible. Nonetheless, cost ramifications of legal requirements, as well as infrastructure necessary for mass transit need further consideration that would exceed the scope of this paper.

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A. Determination of Overhead Costs

Given their competitive environment, ride-hailing and car sharing services treat any information on their overhead and vehicle management cost as confidential. One source, however, provides data on the financial, operating, and asset condition of 660 transit providers in the US (Federal Transit Administration, 2016). Overhead costs are denoted as General Administration and include: Transit service development, injuries and damages, safety, personnel administration, legal services, insurance, data processing, finance and accounting, purchasing and stores, engineering, real estate management, office management and services, customer services, promotion, market research, and planning. Vehicle management is denoted as vehicle operations and includes: Transportation administration and support, revenue vehicle movement control, scheduling of transportation operations, revenue vehicle operation, ticketing and fare collection, and system security. Detailed information is only available for a subset of all agencies (so called "full reporters"). In order to derive cost figures for on-demand fleet services, the analysis focused only on full reporters offering van pooling and demand responsive transport services, with the latter being defined as transit services with a flexible route and schedule. The resulting sample consists of 527 services of 430 agencies. Fleet size (number of revenue vehicles operated in the annual maximum service) ranges from 1 to 1840.

The analysis started by plotting overhead costs per vehicle and day versus the fleet size. It was observed that these costs per vehicle and day vary substantially (between 0.60 US$ and 311.44 US$) below and equal to the fleet size of 150. Focusing on this data and regressing fleet size on overhead costs per vehicle and day reveals that fleet size does not have a significant effect in that range (p-value equals 0.14). Above a threshold of 150 vehicles, overhead costs per vehicle and day range between 1.39 US$ and 15.47 US$, except for two agencies, and data show neither a positive nor a negative trend (p-value of fleet size equals 0.53). It was therefore hypothesized that fleet composition plays a key role in explaining these variations. When, however, regressing average vehicle capacity and fleet size on overhead costs per vehicle and day using the whole dataset, the average vehicle capacity does not have a significant effect (p-value equals 0.62). Interestingly, a similar picture emerges when analyzing dependence of vehicle operations cost per vehicle and day on the fleet size, as well as average vehicle seat capacity. Again, vehicle operations cost per vehicle and day vary substantially (between 4.70 US$ and 623.06 US$) below and equal to the fleet size of 150. With the exception of two agencies, this figure is between 1.79 US$ and

23.97 US$ for fleets with a size above 150.

To conclude, results indicate that either: important data is missing needed to determine the relationship between fleet composition and overhead and operations cost, or that agencies operate with very different cost structures. As mentioned previously, however, companies with fleet sizes of 150 vehicles and more show stable figures for both cost structures. Therefore, corresponding median values are used as estimates for overhead (10.24 US$ per vehicle-day) and vehicle operation costs per vehicle and day (8.39 US$ per vehicle-day). Adjusting these figures to unit labor costs in Switzerland (Neff et al., 2015) results in approximately 14 CHF per vehicle-day for overhead and 10 CHF per vehicle-day for operations costs.

B. Cost parameters

B.1
Costs vehicles

Car Type	Solo	Midsize	Van	Minibus
Capacity [Seats for Pass.]	1	4	8	20
Acquisition [CHF]	13000 [a]	35000 [b]	66000 [c]	70000 [d]
Yearly insurance [CHF/a]	500 [e]	1000 [e]	1200 [e]	1400 [e]
Yearly tax [CHF/a]	120 [f]	250 [f]	700 [f]	1100 [f]
Yearly parking [CHF/a]	1500 [g]	1500 [g]	1500 [g]	1500 [g]
Yearly toll [CHF/a]	40 [h]	40 [h]	40 [h]	2200 [i]
Maintenance [CHF/km]	0.02 [j]	0.06 [j]	0.12 [j]	0.13 [j]
Cleaning [CHF/km]	0.02 [k]	0.03 [k]	0.04 [k]	0.05 [k]
Tires [CHF/km]	0.02 [l]	0.02 [l]	0.02 [l]	0.02 [l]
Fuel [CHF/km]	0.06 [m]	0.08 [m]	0.13 [m]	0.2 [m]

[a] Data: http://www.renault.ch/, last accessed 01.02.2017.
[b] Data: http://www.volkswagen.ch/, last accessed 01.02.2017.
[c] Data: http://www.volkswagen-nutzfahrzeuge.ch/, last accessed 01.02.2017.
[d] Data: http://www.mercedes-benz.ch/, last accessed 01.02.2017.
[e] Source: Comparis AG (2016).
[f] Source: Strassenverkehrsamt Kanton Zürich (2017).
[g] Source: TCS (2016).
[h] Source: Eidgenössische Zollverwaltung (2017b).
[i] Source: Eidgenössische Zollverwaltung (2017a).
[j] Data: TCS (2016).
[k] Data: Autop (2016).
[l] Assumption: Two sets of tires (each 300 CHF) and two annual tire changes (each 100 CHF) would allow for 50000 km of driving.
[m] Sources: Fuel price - (Shell, 2016); Consumption - Respective manufacturers website - Solo: 4.3 l/100 km; Midsize 5.7 l/100 km, Van 9.3 l/100 km, Minibus 14.2 l/100 km.

B.2
Cost adjustments

Position	Electric	Automated	Fleet	VAT deductible
Acquisition	–	+20% [a]	−30% [b]	Yes
Yearly insurance	−35% [c]	−50% [d]	−20% [e]	Yes
Yearly tax	−100% [f]	–	–	No
Yearly parking	–	–	+133% [g]	Yes
Yearly toll	–	–	–	Yes
Maintenance	+28% [h]	–	−25% [i]	Yes
Cleaning	–	See *Cost parameters*		No
Tires	–	−10% [j]	−25% [i]	Yes
Fuel	−50% [k]	−10% [d]	−5% [l]	Yes

[a] Source: IHS (2014).
[b] Data: Blens (2015).
[c] Data: Comparis AG (2016).
[d] Source: Stephens et al. (2016).
[e] Source: Helvetia (2016).
[f] Source: http://www.stva.zh.ch/internet/sicherheitsdirektion/stva/de/StVAgeb/GEBva14.html, last accessed 01.02.2017.
[g] Data: Schlesiger (2014).
[h] Data: Diez (2016), Saxton (2013), McKinsey (2017).
[i] Assumption: In-house maintenance.
[j] Assumption: Similar effect as fuel consumption.
[k] Data: Fuel price - (Shell, 2016); Electricity price - https://www.ewz.ch/de/private.html, last accessed 01.02.2017; Consumption - http://www.volkswagen.ch/, last accessed 01.02.2017.
[l] Source: Migrol (2016).

B.3
Costs mass transit

Transportation Type	CityBus	RegBus	Rail
Capacity	60 [a]	60 [a]	297 [b]
Costs per vehicle-kilometer [CHF/km]	7.14 [c]	6.7 [c]	31.4 [d]
Effect electric	−5.5% [e]	−5.5% [e]	–
Effect automated	−55% [e]	−55% [e]	−2.5% [d]

[a] Data: https://www.stadt-zuerich.ch/vbz/de/index/die_vbz/fahrzeuge/autobusse.html, last accessed 01.02.2017.
[b] Source: SBB AG (2016).
[c] Data: Frank et al. (2008), Verkehrsbetriebe Zürich (2016), Bundesamt für Verkehr (2011).
[d] Data: SBB AG (2016).
[e] Data: Frank et al. (2008).

B.4
General cost parameters

Cost parameter	Value
Vehicle lifetime professional	300000 km [a]
Vehicle lifetime private	10 a
Cleaning price	15 CHF[b]
Yearly cleaning frequency private	8 [c]
Yearly cleaning frequency professional conventional	183 [d]
Cleaning frequency commercial AV per trip	0.025 [e]
Driver's hourly wage	35 CHF [f]
Daily overhead costs per vehicle	14 CHF/d [g]
Daily vehicle management costs per vehicle	10 CHF/d [g]
Annual interest private customer	0.079 [h]
Annual interest commercial customers	0.015 [i]
Credit period private customers	5 a [h]
Credit period commercial customers	3 a
VAT in Switzerland	0.08 [j]
Profit margin	0.03 [k]
Payment transaction fee	0.0044 [l]

[a] Data: Klose (2012).
[b] Source: Autop (2016).
[c] Data: abh Market Research (2007).
[d] Assumption: Cleaned every second day.
[e] Source: Private communication with car sharing operator.
[f] Data: Lohnanalyse (2016); Braendle (2013).
[g] Data: Federal Transit Administration (2016).
[h] Source: Migrosbank (2017).
[i] Data: Sixt SE (2016).
[j] Source: https://www.ch.ch/en/vat-rates-switzerland/, last accessed 01.02.2017.
[k] Data: SCI Verkehr (2016).
[l] Source: Wettbewerbskommission WEKO (2014).

C. Usage parameters

C.1
Average usages private ownership and dynamic fleet public transport

Transport Type											
Area	*	*	*	Urban	Urban	Urban	Urban	Regional	Regional	Regional	Regional
VehicleType	Solo	Midsize	Van	Solo	Midsize	Midsize	Van	Solo	Midsize	Midsize	Van
Operation	Priv	Priv	Priv	PT-NP	PT-NP	PT-P	PT-P	PT-NP	PT-NP	PT-P	PT-P
Peak Hours											
operationHours_AV [h]	0.32 [a]	0.32 [a]	0.32 [a]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]
operationHours [h]	0.32 [a]	0.32 [a]	0.32 [a]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]	3.80 [b]
relActiveTime [%]	100.00	100.00	100.00	57.00 [c]	57.00 [c]	57.00 [c]	57.00 [c]	57.00 [c]	57.00 [c]	57.00 [c]	57.00 [c]
avOccupancy [%]	100.00	33.50 [a]	16.75 [a]	100.00	33.50 [a]	65.00 [d]	32.50 [d]	100.00	33.50 [a]	65.00 [d]	32.50 [d]
avSpeed [km/h]	32.40 [a]	32.40 [a]	32.40 [a]	20.60 [a]	20.60 [a]	20.60 [a]	20.60 [a]	31.30 [a]	31.30 [a]	31.30 [a]	31.30 [a]
avTripLengthPass [km]	15.00 [a]	15.00 [a]	15.00 [a]	3.40 [a]	3.40 [a]	3.40 [a]	3.40 [a]	8.00 [a]	8.00 [a]	8.00 [a]	8.00 [a]
relEmptyRides [%]	0.00	0.00	0.00	8.00 [e]	8.00 [e]	8.00 [e]	8.00 [e]	15.00 [c]	15.00 [c]	15.00 [c]	15.00 [c]
relMaintenanceRides [%]	0.00	0.00	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Off-Peak Hours											
operationHours_Av [h]	0.67 [a]	0.67 [a]	0.67 [a]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]
operationHours [h]	0.67 [a]	0.67 [a]	0.67 [a]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]	7.60 [b]
relActiveTime [%]	100.00	100.00	100.00	59.00 [c]	59.00 [c]	59.00 [c]	59.00 [c]	59.00 [c]	59.00 [c]	59.00 [c]	59.00 [c]
avOccupancy [%]	100.00	36.50 [a]	18.25 [a]	100.00	36.50 [a]	60.00 [d]	30.00 [d]	100.00	36.50 [a]	60.00 [d]	30.00 [d]
avSpeed [km/h]	34.00 [a]	34.00 [a]	34.00 [a]	21.90 [a]	21.90 [a]	21.90 [a]	21.90 [a]	32.20 [a]	32.20 [a]	32.20 [a]	32.20 [a]
avTripLengthPass [km]	10.50 [a]	10.50 [a]	10.50 [a]	3.00 [a]	3.00 [a]	3.00 [a]	3.00 [a]	5.90 [a]	5.90 [a]	5.90 [a]	5.90 [a]
relEmptyRides [%]	0.00	0.00	0.00	8.00 [e]	8.00 [e]	8.00 [a]	8.00 [e]	15.00 [c]	15.00 [c]	15.00 [c]	15.00 [c]
relMaintenanceRides [%]	0.00	0.00	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

C.1 (*continued*)

Night Hours											
operationHours_AV [h]	0.30 [a]	0.30 [a]	0.30 [a]	9.60 [b]	9.60 [b]	9.60 [b]	9.60 [b]	9.60 [b]	9.60 [b]	9.60 [b]	9.60 [b]
operationHours [h]	0.30 [a]	0.30 [a]	0.30 [a]	8.60 [b]	8.60 [b]	8.60 [b]	8.60 [b]	8.60 [b]	8.60 [b]	8.60 [b]	8.60 [b]
relActiveTime [%]	100.00	100.00	100.00	30.00 [c]	30.00 [c]	30.00 [c]	30.00 [c]	30.00 [c]	30.00 [c]	30.00 [c]	30.00 [c]
avOccupancy [%]	100.00	35.75 [a]	17.88 [a]	100.00	35.75 [a]	57.50 [d]	28.75 [d]	100.00	35.75 [a]	57.50 [d]	28.75 [d]
avSpeed [km/h]	36.20 [a]	36.20 [a]	36.20 [a]	23.70 [a]	23.70 [a]	23.70 [a]	23.70 [a]	34.00 [a]	34.00 [a]	34.00 [a]	34.00 [a]
avTripLengthPass [km]	12.60 [a]	12.60 [a]	12.60 [a]	3.40 [a]	3.40 [a]	3.40 [a]	3.40 [a]	7.10 [a]	7.10 [a]	7.10 [a]	7.10 [a]
relEmptyRides [%]	0.00	0.00	0.00	8.00 [e]	8.00 [e]	8.00 [e]	8.00 [e]	15.00 [c]	15.00 [c]	15.00 [c]	15.00 [c]
relMaintenanceRides [%]	0.00	0.00	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Abbreviations.
*: Overall.
Priv: Private ownership.
PT-P: PT with Pooling.
PT-NP: PT Non-Pooling, especially relevant for midsize taxis.

[a] Data: Swiss Federal Statistical Office (BFS) and Swiss Federal Office for Spatial Development (ARE) (2012).
[b] Assumption: Defined duration minus maintenance.
[c] Data: Bösch et al. (2016).
[d] Data: International Transport Forum (2015).
[e] Source: Fagnant et al. (2015).

C.2
Average usages line-based mass transit

Transport Type			
Area	Urban	Regional	Regional
VehicleType	CityBus	RegBus	Rail
Operation	PT	PT	PT
operationHours_AV [h]	19 [a]	19 [a]	19 [a]
operationHours [h]	19 [a]	19 [a]	19 [a]
relActiveTime [%]	85 [b]	85 [b]	85 [b]
avOccupancy [%]	22.42 [c]	12.6 [c]	22.7 [d]
avSpeed [km/h]	21.31 [c]	20.89 [c]	37.82 [c]
avTripLengthPass [km]	–	–	–
relEmptyRides [%]	0	0	0
relMaintenanceRides [%]	5	5	5

[a] Assumption: 24 h minus night break.
[b] Data: Zürcher Verkehrsverbund (2017).
[c] Data: Bundesamt für Verkehr (2011).
[d] Source: SBB AG (2016).

D. Detailed cost figures for different modes

VehicleType	Area	Operation	Steering	Propulsion	CostVehKM [CHF]	CostSeatKM [CHF]	CostPassKM [CHF]
Bus	Reg	PT-P	Aut	Elec	–	0.05	0.38
Bus	Reg	PT-P	N. aut	Elec	–	0.11	0.84
Bus	Reg	PT-P	Aut	N. elec	–	0.05	0.40
Bus	Reg	PT-P	N. aut	N. elec	–	0.11	0.89
Bus	Urb	PT-P	Aut	Elec	–	0.05	0.23
Bus	Urb	PT-P	N. aut	Elec	–	0.11	0.50
Bus	Urb	PT-P	Aut	N. elec	–	0.05	0.24
Bus	Urb	PT-P	N. aut	N. elec	–	0.12	0.53
Midsize	*	Priv	Aut	Elec	0.67	0.17	0.47
Midsize	*	Priv	N. aut	Elec	0.63	0.16	0.44
Midsize	*	Priv	Aut	N. elec	0.72	0.18	0.50
Midsize	*	Priv	N. aut	N. elec	0.69	0.17	0.48
Midsize	Reg	PT-NP	Aut	Elec	0.35	0.09	0.31
Midsize	Reg	PT-NP	N. aut	Elec	2.16	0.54	1.90
Midsize	Reg	PT-NP	Aut	N. elec	0.37	0.09	0.32
Midsize	Reg	PT-NP	N. aut	N. elec	2.19	0.55	1.92
Midsize	Reg	PT-P	Aut	Elec	0.39	0.10	0.20
Midsize	Reg	PT-P	N. aut	Elec	2.16	0.54	1.12
Midsize	Reg	PT-P	Aut	N. elec	0.41	0.10	0.21
Midsize	Reg	PT-P	N. aut	N. elec	2.19	0.55	1.13
Midsize	Urb	PT-NP	Aut	Elec	0.48	0.12	0.39
Midsize	Urb	PT-NP	N. aut	Elec	3.35	0.84	2.70
Midsize	Urb	PT-NP	Aut	N. elec	0.51	0.13	0.41
Midsize	Urb	PT-NP	N. aut	N. elec	3.38	0.85	2.73
Midsize	Urb	PT-P	Aut	Elec	0.58	0.15	0.28
Midsize	Urb	PT-P	N. aut	Elec	3.35	0.84	1.60
Midsize	Urb	PT-P	Aut	N. elec	0.61	0.15	0.29
Midsize	Urb	PT-P	N. aut	N. elec	3.38	0.85	1.61
Minibus	Reg	PT-P	Aut	Elec	0.61	0.03	0.31
Minibus	Reg	PT-P	N. aut	Elec	2.37	0.12	1.23
Minibus	Reg	PT-P	Aut	N. elec	0.67	0.03	0.35
Minibus	Reg	PT-P	N. aut	N. elec	2.44	0.12	1.26
Minibus	Urb	PT-P	Aut	Elec	0.98	0.05	0.24

(*continued*)

VehicleType	Area	Operation	Steering	Propulsion	CostVehKM [CHF]	CostSeatKM [CHF]	CostPassKM [CHF]
Minibus	Urb	PT-P	N. aut	Elec	1.89	0.09	0.46
Minibus	Urb	PT-P	Aut	N. elec	1.04	0.05	0.25
Minibus	Urb	PT-P	N. aut	N. elec	1.96	0.10	0.47
Rail	Reg	PT-P	Aut	Elec	–	0.10	0.44
Rail	Reg	PT-P	N. aut	Elec	–	0.11	0.47
Rail	Reg	PT-P	Aut	N. elec	–	0.10	0.44
Rail	Reg	PT-P	N. aut	N. elec	–	0.11	0.47
Solo	*	Priv	Aut	Elec	0.35	0.35	0.35
Solo	*	Priv	N. aut	Elec	0.33	0.33	0.33
Solo	*	Priv	Aut	N. elec	0.38	0.38	0.38
Solo	*	Priv	N. aut	N. elec	0.38	0.38	0.38
Solo	Reg	PT-NP	Aut	Elec	0.23	0.23	0.28
Solo	Reg	PT-NP	N. aut	Elec	2.07	2.07	2.59
Solo	Reg	PT-NP	Aut	N. elec	0.25	0.25	0.31
Solo	Reg	PT-NP	N. aut	N. elec	2.09	2.09	2.62
Solo	Urb	PT-NP	Aut	Elec	0.34	0.34	0.39
Solo	Urb	PT-NP	N. aut	Elec	3.26	3.26	3.74
Solo	Urb	PT-NP	Aut	N. elec	0.36	0.36	0.41
Solo	Urb	PT-NP	N. aut	N. elec	3.28	3.28	3.77
Van	*	Priv	Aut	Elec	1.14	0.14	0.80
Van	*	Priv	N. aut	Elec	1.04	0.13	0.73
Van	*	Priv	Aut	N. elec	1.22	0.15	0.86
Van	*	Priv	N. aut	N. elec	1.14	0.14	0.80
Van	Reg	PT-P	Aut	Elec	0.55	0.07	0.28
Van	Reg	PT-P	N. aut	Elec	2.31	0.29	1.19
Van	Reg	PT-P	Aut	N. elec	0.58	0.07	0.30
Van	Reg	PT-P	N. aut	N. elec	2.35	0.29	1.21
Van	Urb	PT-P	Aut	Elec	0.74	0.09	0.35
Van	Urb	PT-P	N. aut	Elec	3.49	0.44	1.66
Van	Urb	PT-P	Aut	N. elec	0.77	0.10	0.37
Van	Urb	PT-P	N. aut	N. elec	3.54	0.44	1.69

Abbreviations.
Reg: Regional (suburban and exurban).
Urb: Urban.
*: Overall.
Priv: Private ownership (for private ownership the area was not differentiated (see *Averageusages*) resulting in the same values for both regions).
PT-P: PT with Pooling.
PT-NP: PT Non-Pooling, especially relevant for midsize taxis.
Aut: Autonomous.
N. aut: Not autonomous.
Elec: Electrified.
N. elec: Not electrified.

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