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Cost-based analysis of autonomous mobility services

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ABSTRACT

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

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[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.