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Abstract

Autonomous taxis seem closer than ever before. Scholars agree that they have a disruptive potential for today's transportation systems, especially for the taxi industry, as costs will significantly drop. Whether this will be beneficial to society or not, remains ambiguous.

Economics shows that market structure and regulation matter for social welfare. Little research, however, has been conducted on markets of autonomous taxis, leaving policy-makers in doubt whether and how to regulate this emerging market. This question becomes urgent as the first larger publicly accessible services have been announced for 2019.

This paper applies the economics of industrial organization and regulation theory to markets of autonomous taxis. As they do not yet exist, we describe our expectations, on which we base our analysis of market imperfections and potential regulation, building on lessons learnt from taxi regulation as the closest existing proxy. Our main policy-related findings are:

- We expect the market of autonomous taxi services to be significantly different from today's taxi industry, mainly in terms of economies of scale, relevance of locality and information asymmetries.
- Therefore, regulating it similar to today's taxicabs might do more harm than good, especially concerning regulation of entry and price.
- Subsidies for ride sharing/pooling at peak hours might prove necessary to reduce congestion and increase accessibility and equity.

Being descriptive and qualitative in its nature, this paper seeks to stimulate the academic exchange on this important topic by contributing propositions to discuss and build upon.

Keywords

Autonomous Taxi; Regulation; Industrial Organization; Welfare

1. Introduction

The autonomous taxi (AT) has recently gained a lot of attention both by researchers and the public. Significant technological progress during the last decade, especially under the influential DARPA challenges (DARPA, 2014), has propelled research on the impact of ATs on cities. This research, however, still remains theoretical in nature due to a lack of sizeable pilots for evaluation. Mainly by means of simulations, it paints a mixed image of the future with ATs (for recent overviews, see Fagnant and Kockelman, 2015a; Litman, 2017; Milakis *et al.*, 2017; Boesch *et al.*, 2018a):

- Upside potentials include a reduction of the total car fleet and traffic accidents, resulting increases of road capacity, less GHG emissions and noise, increased accessibility especially for low-income households, the elderly, young and in general people without a driver's license, higher comfort of travelling at lower prices and the possibility to pursue useful activities while travelling.
- Downside potentials include increasing overall vehicle kilometres travelled, a modal shift from mass transit to smaller vehicles, higher levels of congestion and increasing GHG emissions.

Although the various scenario simulations and their implications sometimes appear contradictory in their outcome, researchers agree that ATs have a disruptive potential and will significantly impact our transport system as we know it. The question is when and how, not if. In the last couple of years, several companies have begun first AT pilots on public roads. This recent advance, coupled with the disruptions in the taxi industry caused by ride-sourcing companies such as Uber, raises the question whether and how to regulate AT markets.

Traditional microeconomics states that in a perfectly competitive market, forces of supply and demand will produce an efficient allocation of resources. Its subdiscipline industrial organization accounts for market imperfections and establishes the relationship between market structure and firm performance. Regulation theory builds upon that same understanding and uses market imperfections as a justification for regulation 'in the public interest'. The field of transportation provides a long history of examples of justified (and unjustified) regulation based on this line of argument.

Up to now, only little research exists on (not yet existing) markets of autonomous taxis and none to our knowledge about the economic regulation of these markets. Yet, recent disruptions of the taxi industry caused by ride-sourcing companies such as Uber, and excessive ridesharing bike 'piles' in Chinese cities (Dittli, 2018) tell strong stories about the importance of thinking regulation ahead.

With this paper, we aim to stimulate academic exchange on which characteristics markets of ATs might exhibit, whether these warrant regulation, and which type of regulation might be suitable. This paper is structured as follows. First, we summarize key insights from industrial organization and regulation theory, focusing on the regulation of transportation. Second, we review the (scarce) literature on AT markets and build upon these findings to describe the AT market as we expect it. We continue to analyse market characteristics and potential market failures of the AT market as a main source of justification for regulation and relate them to corresponding regulation and lessons learnt in the taxi market. In addition to the line of argument in industrial organization and regulation theory, where market failures are the main motivation for regulation, we conduct an analysis on socially beneficial aspects of the AT market that regulation could encourage. We conclude with a discussion and directions for future work.

2. Industrial organization and regulation theory

Industrial organization, often described to be a subfield of microeconomics, emerged in the late 1930s (Grether, 1970). It builds on the theory of the firm and examines the structure of markets, giving due emphasis to market failures challenging two basic concepts of microeconomic theory: perfect competition and monopoly (Waldman and Jensen, 2001). In its origins, Mason and Bain found that the competitive environment of the firm, described as the market structure, influences its conduct, which in turn influences its performance (Mason, 1939 and 1949; Bain, 1956). The resulting structure-conduct-performance (SCP) paradigm evolved to be one of the field's basic (empirical) frameworks.

Regulatory theory can roughly be divided into two main branches:

- the normative (prescriptive) branch, which focuses on identifying conditions when regulation 'should' be introduced and the development of 'optimal' regulation, and

- the positive (descriptive) branch, which focuses on explaining why regulation emerges (Joskow and Rose, 1989).

The main theories of the latter branch are the 'public interest' theory of regulation and 'capture theory' (or 'economic theory of regulation'). As our endeavour is prescriptive in nature (how to regulate AT markets if this is necessary), we will focus on the normative branch, although it should be noted that the positive branch (esp. the economic theory of regulation[1]) offers interesting explanations - especially within transportation - of the reasons why some regulations (e.g., in the trucking, busing and airline industry), which benefit incumbent firms instead of the public interest, exist (Waldman and Jensen, 2001).

Normative regulatory theory connects to industrial organization in that it analyses market structure as an important determinant of firm (and market) performance. According to normative theory, market failures (or imperfections) leading unregulated markets to perform suboptimal according to some welfare function, justify regulation in the 'public interest' if the incurred costs can be offset by the welfare gained. Welfare, in economic terms, is usually measured as the sum of consumer and producer surplus.

The question which conditions perfectly competitive markets exhibit that need to be violated to cause regulatory action is obvious. Waldman and Jensen (2001, p. 27) describe the following five:

1. *Large number of buyers and sellers (A perfectly competitive market contains many buyers and sellers, each small relative to total purchases or sales.)*
2. *Homogeneous product (Firms in a perfectly competitive market produce a homogeneous, or identical, product. Because consumers cannot distinguish one firm's product from another's, they are indifferent about their supplier.)*
3. *Perfect information (All economic agents (firms and consumers) have all of the information they need to make economic decisions. Consumers know the price and quality of the product produced by each firm, and firms know their production functions and the prices of all inputs and outputs.)*
4. *No transaction costs (Transaction costs are the costs of using the market, such as the costs of negotiating and monitoring a contract. In a perfectly competitive market, transaction costs are zero for both buyers and sellers.)*
5. *Free exit and entry (Adjustments to changing market conditions require that the resources enter or leave the industry. In a perfectly competitive market these adjustments occur without firms having to incur any special costs, there are no barriers to entry or exit.)*

[1] See Stigler (1971) and Peltzman (1976) for the original work on this theory.

In addition, one could consider the following two additional characteristics:

6. Absence of externalities (In a perfectly competitive market, there are no costs or benefits to third parties that are not involved in the transaction)
7. Perfect elasticity of demand with regard to price (In a perfectly competitive market, even small adjustments of price lead to equal adjustments of demand)

In the transportation sector, these conditions are frequently violated (Joskow and Rose, 1989; OECD, 2007; Cetin and Deakin, 2017). Classic examples include natural monopolies and associated large barriers of entry of infrastructure providers (railways), limited number of sellers (airlines), imperfect information about price and quality (taxicabs) and externalities such as pollution and noise (road travel). This, in conjunction with the public interest to provide equitable and safe transportation, has led to a long history of regulation (and deregulation) in the transportation sector grounded in the theory of industrial organization, that improving the environment a transport provider operates in by regulation will improve the outcome for society.

In this paper, we will follow the outlined approach of identifying (potential) market imperfections to inform the analysis of suitable regulatory measures. As the market for autonomous taxis does not yet exist, we continue to describe the market of autonomous taxis as we expect it.

3. The market for autonomous taxis services

Most research on aspects of AT markets has focused on exploring singular demand and supply side characteristics, including user groups and behaviour (e.g., Becker and Axhausen, 2016), user's willingness to pay (Bansal *et al.*, 2016), perceived value of travel time (Becker and Axhausen, 2017), cost structures and price targets (e.g., Fagnant and Kockelman, 2015b; Burns *et al.*, 2016; Litman, 2017; Loeb and Kockelman, 2017; Boesch *et al.*, 2018b).

Little additional research has been conducted on business models and the organization of AT markets. Stocker and Shaheen (2017) present a first view on possible future AT business models, focusing on vehicle ownership and network operations. Axhausen (2017) presents basic scenarios for AT services on seven dimensions: market structure (monopoly, oligopoly, dispersed), role and extent of transit, system target (system optimum, user equilibrium), type of traffic system manager, road space allocation, share of autonomous vehicles and share of electric vehicles. Boesch *et al*. (2018a) are one of the first to analyse the impact of different organizational forms of the market (monopoly, oligopoly of three) finding that policies targeting market organization are the most important determinant for future performance of the system when compared to other potential policies.

Building upon these findings, we describe the market for autonomous taxis as we expect it. First, assume an unregulated and perfectly competitive market.

Prices, considering marginal cost pricing at rates comparable to the cost of privately owned vehicles (Boesch *et al*., 2018b), are likely to lead to several changes in the taxi industry as we know it today. First, human-driven taxis are likely to disappear due to a significant cost disadvantage. Second, lower prices might lead to a higher demand for autonomous taxis compared to the demand for today's 'traditional' taxis. This would lead to an increase in supply, resulting in a higher number of vehicles. This could, in turn, lead to a decrease in personal vehicle ownership as more people switch to using Mobility as a Service (MaaS), defined by Kamargianni *et al.* (2016) as follows: *The term "Mobility as a Service" stands for buying mobility services as packages based on consumers' needs instead of buying the means of transport.*

In line with recent developments in MaaS, the majority of ATs is likely to be hired digitally (e.g., via a smartphone app). As the human interaction of hiring a cruising taxicab falls away in the absence of a driver, the cruising taxicab 'mode' is like to dissolve accordingly. Stands of taxicabs might revive, as they are essentially parking places for autonomous taxis, which will be of significant importance to the efficiency of the entire system considering that moving empty vehicles causes congestion. Stands are likely to be continued at places of high demand (e.g., airports).

A large change compared to today's taxi industry is likely to occur in industry structure. Acknowledging local differences, today's taxi markets often exhibit a fairly simple industry structure shaped by an oligopoly or monopoly of a few, typically local taxi fleet operators and, in some areas, self-employed taxi drivers. In AT markets, this 'locality paradigm' is likely change due to the digitized and scalable business model as the involvement of automobile manufacturers and information and telecommunications companies (e.g., Waymo and Uber) suggests. We expect national or international, not local companies, to dominate the AT market, selectively outsourcing services, especially where locality matters.

In line with Stocker and Shaheens' (2017) B2B2C business model, we expect the majority of vehicles to be owned by large companies receiving a rent in return for their capital investment. This can be compared to the rent received by automobile manufacturers for leasing cars to car rental firms. Car-rental firms in our case would be the AT operators. A C2B2C model, in which private owners of autonomous vehicles 'check in' their car into a larger fleet of an operator (e.g., Tesla seems to pursue this direction) is also possible amongst many other alternatives, however is not in line with our expectation of decreasing personal car ownership.

A main operational task is matching supply and demand. For ATs, this entails operating a customer front-end, dispatching ATs to the customers and relocating empty vehicles so that they serve future predicted demand efficiently (Hoerl *et al.*, 2018).

In contrast to today's popularity of taxi or ride-sourcing apps operating the customer front-end as an asset-light business model, an integrated operator seems likely as synergies between the three services exist. Effective relocation and dispatching needs detailed, real-time information on demand and supply, which is held by the operator responsible for the customer front-end and the operator responsible for fleet relocation, respectively.

An alternative scenario closer to today's reality would be a (or several) companies operating (competing) taxi apps to match supply and demand. These apps could be operated by a private or public stakeholder and might provide synergies if there is a sole dispatcher for an entire municipality (Baumol *et al.*, 1982; Haeckner and Nyberg, 1995). The latter would be comparable to the (existing) single taxi app for Washington DC. Vehicle allocation could be based on price, proximity and customer preference for (potential) different fleet operators. Fleet operators would need to integrate information about their fleets into these apps and dispatch an AT whenever a customer books a ride. Inefficiencies in fleet relocation might, however, offset potential synergies of this scenario.

Further operational tasks, such as include vehicle service (e.g., cleaning, repairing), customer service (e.g., hotline, complaints handling) and payment handling might be outsourced to local (in the case of vehicle service) or international (in the case of payment handling and customer service) providers.

We continue with an analysis of market characteristics and potential failures to evaluate whether a rationale for the regulation of the AT market exists. We draw upon the long history of taxi regulation to present theoretical and empirical insights into how regulators have dealt with these imperfections and what has been achieved in a (seemingly) similar industry.

4. Market imperfections and lessons learnt from taxi regulation

We examine each of the established conditions for perfect competition for the described AT market as a way to identify market imperfections.

1. Large number of buyers and sellers

We expect the AT market to exhibit economies of scale in various areas. First, buying and insuring in large numbers is likely to be cheaper than in small numbers, which leads to economies of scale for vehicle owners. Second, matching demand and supply as a single dispatcher with access to the entire demand and supply is more efficient than several dispatchers each coordinating only parts of demand and supply. Third, operators of large fleets can use their bargaining power to receive better outsourcing conditions for activities such as cleaning and repairing vehicles or customer service than operators of smaller fleets. These economies of scale are likely to lead to a small number of sellers confronting a large number of buyers (individuals engaging taxi services).

2. Homogeneous product

Assuming an unregulated market, firms are likely to engage in price and / or quality competition (Fagnant and Kockelman, 2018). Quality competition might lead to different types of autonomous taxis being offered, i.e. luxury types offering amenities such as WiFi, television and food, and basic types. Companies are also likely to increase recognizability via advertisements emphasizing their specific difference. Thus, we cannot assume homogeneous products to develop in the unregulated market.

3. Perfect information

We can assume firms to know their production functions and the prices of all inputs and outputs. For consumers, we can also assume knowledge about the price as today's taxi and ride-sourcing apps already contain this information. Quality, however, is more difficult. In traditional taxi markets, the inability of consumers to assess quality *before the ride* in terms of price and duration, the driver's knowledge of the area and general conduct, taxicab safety, insurance and cleanliness has been a justification for regulation. Some authors have therefore described taxicabs to be a credence good (Balafoutas *et al.*, 2013; Harding *et al.*, 2016). For the AT market, some quality attributes may be easier to assess, as vehicle safety and insurance can be assumed to be the same for all vehicles of a given operator, apps such as today's car-sharing apps already provide information on expected duration, price, vehicle cleanliness and insurance options, and others such as driver conduct and knowledge are not applicable.

4. No transaction costs

Transaction costs in the AT market can be monetary (i.e., payment surcharge for using a credit card) or concern the perceived value of waiting time. While the earlier may prevail, the latter is likely to be smaller than in today's radio-dispatching taxicab market (and significantly smaller than in the cruising taxicab market), as the supply available for matching with demand is likely to be larger, leading to an increased likelihood of a free vehicle close by thus reducing spent time waiting for a vehicle.

5. Free exit and entry

Significant barriers to entry are to expect due to economies of scale. Smaller players entering the industry face higher costs. Due to the capital employed for vehicle owners and long-term service contracts with insurance companies, renting companies and outsourcing companies for operations, barriers to exit are also expected.

6. Absence of externalities

AT markets will have congestion externalities on other road users which are likely to increase with an increasing number of vehicles and vehicle kilometres travelled. Noise and air pollution externalities may be lower than for current taxis depending on which type of propulsion technology used.

7. Perfect elasticity of demand with regard to price

Due to lower generalized prices, we expect a higher number of customers using autonomous taxis than current taxis. These customers are also likely to exhibit a higher elasticity of demand with regard to price, as they have chosen different transport modes before. However, for the remaining customers, elasticity of demand is not likely to change compared to the traditional taxi case. Though dated, Frankena and Pautler (1984) estimate the elasticity of demand for taxi services between -0.8 and -1.0.

In summary, we face a number of market imperfections, though (partially) less pronounced than in today’s taxi industry. They include significant economies of scale leading to an expected small number of suppliers and barriers of entry and exit, heterogeneous products due to quality and price competition, limited transaction costs, (at least) congestion externalities and some limitations on the elasticity of demand. In comparison to today’s taxi industry, the most important differences are the significantly higher economies of scale and significantly lower information asymmetries.

How might a profit-maximizing firm exploit these market imperfections in an unregulated market?

Monopoly or oligopoly providers may exploit their market power to set the price above their marginal cost given the barriers of entry and economies of scale. This might be especially valid for monopolistic competition, which might evolve through product differentiation. Industrial organization theory supports this line of thought (Waldman and Jensen, 2001) and early empirical studies of industrial organization found industries with oligopolies to be associated with higher industry profits (Bain, 1956 and 1959; Caves, 1964; Mueller, 1970), stemming from collusion, as SCP economists would argue, or from higher efficiency, as later Chicago School economists would argue.

Considering price regulation as a potential remedy to keep prices near the marginal costs, the taxi industry offers valuable insight. In the cruising taxicab segment, fare regulation seems to be most relevant, as information asymmetry and transaction costs are greatest. Experience with deregulating prior regulated fare structures often lead to short-term price increases, while in the long turn economists do not reach a conclusion on whether prices in deregulated or regulated markets would be lower (Moore and Balaker, 2006). Regulated maximal prices may have even been used as a medium for collusion, as few examples show (Frankena and Pautler, 1984). In the radio-dispatching taxicab segment, which is structurally closer to the AT market, price regulation seems to be less relevant due to lower information asymmetries and transaction costs (Frankena and Pautler, 1984; OECD, 2007; Harding *et al*., 2016).

Given that we find no uniform agreement for or against fare regulation in the cruising taxicab segment and many critics of fare regulation in the dispatching market, expect significantly lower information asymmetry and transaction cost and some degree of product differentiation in the AT market, we are sceptical about the merits of general[2] fare regulation justified on the fare argument alone.

5. Success factors for social welfare

Up to now, we described the AV market as we expect it, examined potential market *imperfections* and how a profit-maximizing monopolist or oligopoly might exploit these. While this approach is sound with industrial organization and regulation theory, we think it is viable to analyse *positively* how autonomous taxis could improve urban transport and how the regulator might support this change.

One of the main hopes developed from simulations of large autonomous taxi fleets serving urban transport is the reduction of number of cars in cities opening spaces for recreation (i.e., Fagnant *et al*., 2015b; Spieser *et al*., 2015, Boesch *et al*., 2015; Bischoff and Maciejewski, 2016). This crucially depends upon the implementation and acceptance of ride-sharing and low substitution rates for public transport where it is more efficient.

Ride-sharing is important during peak times, when road congestion is severest. In a world with dynamic pricing (Chen and Kockelman, 2016), ATs are likely to be most expensive during rush-hour, as realizable profit per hour is low and demand is high. This provides incentives for ride-sharing, however user acceptance depends on the trade-off between incentive height and flexibility sacrifices when compared to a single ride, a personal car ride or public transportation.

[2] One exception may be airports, where price competition may lead to significant inefficiencies (Frankena and Pautler, 1984)

It is questionable whether the profit-maximizing firm would offer attractive ride-sharing options, or whether this needs additional incentives by the regulator. While there are disadvantages to potential regulatory measures such as imposing a minimum of two people per AT during peak times, subsidies might be worthwhile to investigate in future research.

Externalities such as air pollution and noise are closely linked to congestion. Although these are likely to be lower than today given the efficiency of electric propulsion for the taxi industry (Loeb *et al.*, 2018), they are tied to the number of vehicle kilometres travelled. Some simulations observe an increase in vehicle kilometres travelled mainly due to frequent relocation of empty vehicles (e.g., Fagnant *et al.*, 2015b; Bischoff and Maciejewski, 2016; Merlin, 2017; Boesch *et al.*, 2018a; Fagnant and Kockelman, 2018). This raises the importance of efficient parking (which, essentially, would be future taxi stands), specifically in terms of space devoted and pricing strategies, for further investigation.

Also related to congestion is the concept of 'deadheading'. *A cab picks up a passenger in jurisdiction B, but must then return empty* (Frankena and Pautler, 1984, p. 91). Deadheading is likely to arise when taxi licenses are bound to separate geographical areas within a single city or region. In the AV market, this is likely to lead to inefficiencies due to empty rides and may lead to fare surcharges and / or higher waiting times and should thus be avoided.

ATs are likely to have a significant effect on public transportation, which might cease to operate on unprofitable routes (Manser, 2017). While this is not necessarily problematic as ATs may provide service more efficiently in some settings – sometimes even as a substitute of all public transportation, which may be particularly true for small and medium-sized cities – it becomes problematic if these substitution effects lead to a downward spiral of decreasing service times and quality of the necessary mass-transportation backbone of large urban cores.

While the discussion on some quality attributes, mainly security, of autonomous vehicles in general has already started and does not need further impetus, ATs have the potential to improve accessibility for elderly, young, and in general people without a driver's license (Meyer *et al.*, 2017). Though dated, Frankena and Pautler (1984) find that US households with low income not only spend a higher percentage of their income on taxicabs, but also the consumption of taxi rides *per capita* seems to be higher in many markets, suggesting that ATs also have an equity potential. Considering higher utilization rates in dense city centres, it is questionable whether AT operators would follow car-sharing operators in restricting their service to these areas. A fundamental difference is that car-sharing operators face high relocation costs (manual labour), while the marginal cost for an AT to be parked in an area of low utilization is small. Whether utilization outside of city centres can be profitable and whether regulation is necessary to provide service guarantees as has been done for the taxicab industry[3], is yet another area for future research.

6. Discussion and conclusion

This paper contributes to research and practice in many ways. Drawing upon the economics of industrial organization, regulatory theory and current research on autonomous vehicles, we describe a possible AT market as we expect it. We analyse potential market imperfections and success factors for social welfare and discuss potential regulatory measures drawing upon lessons learnt from the long history of regulation and deregulation of the taxi market as we know it. Our main findings are:

- We expect the market of autonomous taxi services to be significantly different from today's taxi industry, mainly in terms of economies of scale, relevance of locality and information asymmetries.
- Therefore, regulating it similar to today's taxicabs might do more harm than good, especially concerning regulation of entry and price.
- Subsidies for ride sharing at peak hours might prove necessary to reduce congestion and increase accessibility and equity.

While we showed some possibilities for future work in the preceding chapters, plenty further opportunities exist:

- We expect ride-sharing to be necessary to reap the full potential of autonomous taxis in terms of easing traffic congestion and externalities. While research on pricing is

[3] Dempsey (1996, p. 96) in Schaller (2007) notes that *dense markets cross-subsidize low-density and impoverished areas; peak traffic cross-subsidizes off-peak service*, while Liston-Heyes and Heyes (2007) find that universal service provision is unenforceable without regulation.

plentiful, we are not aware of qualitative studies analysing barriers to ride-sharing that need to be overcome to motivate more users to switch.

- As theoretical evidence on the non-existence of an equilibrium price for an unregulated cruising taxicab market is used to justify price (and some form of entry) regulation (Cairns and Liston-Heyes, 1996), similar research would be helpful for the AT market. This could inform quantitative assessments of possible welfare effects of price regulation building upon the work of Beesley and Glaister (1983).
- While many researchers have analysed regulation and deregulation of the taxi market, we find results concerning fare and entry regulation to be ambiguous. While this might be due to the high degree of politics involved in this question, a rigorous review of the lessons learnt from almost 90 years of taxi regulation (in the case of the US) focusing on the radio-dispatch market, being structurally closest to the AT market, would be useful to inform AT market research and policy development.
- Quantitative research on the profitability of ATs as a function of population density and / or trips seems useful to inform the question, whether regulation might be necessary to guarantee certain levels of service.
- Last but not least, it might be helpful to employ oligopoly theory and game theory to understand possible behaviour of firms within an AT oligopoly.

Finally, a few words of caution. While there is plenty of theoretical evidence that monopolies or oligopolies price above marginal cost, regulation does not come free and should always be a consideration between expected benefits and costs (including possible cause of further market distortions). The economic theory of regulation and plenty of examples within the transportation sector have shown that regulation can be operationalized by incumbent firms to extend their market power, impeding innovation. Finally, in line with the basic assumptions of industrial organization, the larger environment in which a firm operates impacts its performance. This may be one of the reasons why economists do not reach a conclusion on the impact of price and entry regulation. Urban characteristics, such as sprawl and density, public opinion and many further factors are also likely to impact the performance of AT markets. Regulation, thus, should always be tailored to local conditions, there might not be a 'one-size-fits-all' solution.

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