Less workplace parking with fully autonomous vehicles?

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Abstract

Purpose – Recent studies on commuter parking in an age of fully autonomous vehicles (FAVs) suggest, that the number of parking spaces close to the workplace demanded by commuters will decline because of the capability of FAVs to return home, to seek out (free) parking elsewhere or just cruise. This would be good news because, as of today, parking is one of the largest consumers of urban land and is associated with substantial costs to society. None of the studies, however, is concerned with the special case of employer-provided parking, although workplace parking is a widespread phenomenon and, in many instances, the dominant form of commuter parking. The purpose of this paper is to analyze whether commuter parking will decline with the advent of self-driving cars when parking is provided by the employer.

Design/methodology/approach – This study looks at commuter parking from the perspective of both the employer and the employee because in the case of employer-provided parking, the firm's decision to offer a parking space and the incentive of employees to accept that offer are closely interrelated because of the fringe benefit character of workplace parking. This study develops an economic equilibrium model that explicitly maps the employer–employee relationship, considering the treatment of parking provision and parking policy in the income tax code and accounting for adverse effects from commuting, parking and public transit. This study determines the market level of employer-provided parking in the absence and presence of FAVs and identifies the factors that drive the difference. This study then approximates the magnitude of each factor, relying on recent (first) empirical evidence on the impacts of FAVs.

Findings – This paper's analysis suggests that as long as distortive (tax) policy favors employer-provided parking, FAVs are no guarantee to end up with less commuter parking.

Originality/value – This study's findings imply that in a world of self-driving cars, policy intervention related to work commuting (e.g. fringe benefit taxation or transport pricing) might be even more warranted than today.

Keywords Autonomous vehicles, Employer-provided parking, Fringe benefit, Self-driving cars, Transport policy

Paper type Research paper

1. Introduction

The advent of fully autonomous vehicles (FAVs) – also referred to as self-driving car or driverless car – is projected to revolutionize the world's transportation system (Harb *et al.*, 2021; Milakis *et al.*, 2017; Xu *et al.*, 2022). In particular safety improvements are undisputed. As driver-related errors are suggested to be the main reason behind the overwhelming majority of all crashes, these sources of accidents may disappear as vehicles become increasingly automated (Fagnant and Kockelman, 2015). Autonomous vehicles also have the potential to improve traffic throughput. Because vehicles can react to the environment much faster than humans, they will be able to maintain smaller headways with the vehicle in front, thereby, other things equal, increasing the capacity of roads (Subraveti *et al.*, 2021). Moreover, FAVs open up new mobility options to those who currently cannot drive, e.g. children, adults without driver license, elderly and disabled people (Harper *et al.*, 2016). It is also anticipated that FAVs will allow their users to engage in a wider range of pleasant or productive on-board activities, such as sleeping, watching movies, working, thereby reducing the generalized cost of driving (Pudāne *et al.*, 2018, 2021). Last but not least, FAVs are suggested to have a disruptive impact on parking demand and supply, with a wide range of consequences for traffic conditions, land use, urban form and the internal structure of cities. FAVs can self-park in less-expensive areas or even have no need to park at all, freeing city centers from parking lots and, as a result, relieving downtown land for other (more valuable) purposes such as housing, production,

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recreation (Duarte and Ratti, 2018; Guerra and Morris, 2018; Zakharenko, 2016).

The potential of FAVs to reduce the demand for and the supply of parking – the latter point just mentioned – should be a major issue of concern. As of today, parking is one of the largest consumers of urban land (Guerra and Morris, 2018). Even in relatively dense cities, substantial space is given away to park private vehicles [1]. Much of this space sits unused at any given moment in time and in many cities the number of parking spaces exceeds the number of vehicles by a multiple (Chester *et al.*, 2010; Inci, 2015; Manville and Shoup, 2005). The pure availability of parking spaces leads to a stronger car-orientation of individuals and, as a consequence, creates several further adverse side-effects associated with car traveling, e.g. road traffic congestion, pollution, noise (Shoup, 1997, 2017). Also, when parking demand is high and supply un(der)priced, cruising-for-parking may cause substantial cost to society (Inci *et al.*, 2017).

There is mostly suggestive evidence that self-driving cars will ultimately reduce parking requirements, especially in inner cities. We are aware of a few exceptions. Zhang *et al.* (2015) use an agent-based simulation model to show that FAV may be able to eliminate up to 90% of urban parking demand. Okeke (2020) adopts a simulation model too and gets similar results using a university campus as a case study. Both studies, however, focus on a system of shared autonomous vehicles. When account is taken of the fact that each shared autonomous vehicle has the potential to replace around ten privately owned vehicles (Fagnant and Kockelman, 2015), it comes not as a surprise that this eventually translates into reduction in car parking spaces. In contrast, Zakharenko (2016), Liu (2018), Millard-Ball (2019), Zhang *et al.* (2019a), Su and Wang (2020), Levin *et al.* (2020) and Bahrami *et al.* (2021) deal explicitly with the case of privately owned FAVs. They show that it could be a cost-effective option – for travelers and/or the society as a whole – not to park close to their destination, instead letting the FAV return home, seek out (free) on- or off-street parking elsewhere or just cruise (circle around). Clearly, once returning home or cruising are adopted by some travelers, parking requirements would decrease, albeit to the detriment of, e.g. more severe congestion because of increased vehicle distance traveled. Another strand of research looks at the supply side. Nourinejad *et al.* (2018), Bahrami and Roorda (2020) and Siddique *et al.* (2021) show that parking requirements can be reduced even when parking demand remains unchanged because FAVs enable car-parks to be designed more efficiently in terms of the total amount of land allocated to parking.

Interestingly, a crucial observation is that none of these studies – even though all are to a large extent concerned with commuter parking – discuss the case of employer-provided parking, although workplace parking is a widespread phenomenon and in many instances the dominant form of commuter parking. Brueckner and Franco (2018) report that more than 80% of all firms in the US provide parking for their workers. In San Diego and Los Angeles, around 90% of employees receive employer-provided parking (Greenberg *et al.*, 2017) [2]. In the sample used by van Ommeren and Wentink (2012), 45% of Dutch workers use employer-provided parking which, on average, corresponds to 26 parking spaces per firm. Moreover, about 80% of car commuters are reported to make use of parking at the workplace in the Netherlands, suggesting that workplace parking is much more important than curbside parking. Pons-Rigat *et al.* (2020) and Watters *et al.* (2006) report similar orders of magnitude for Barcelona (Spain) and Dublin (Ireland), respectively.

The principal aim of this paper is to fill this gap by explicitly focusing on employer-provided parking. We ask whether the finding of the existing literature – the advent of fully autonomous vehicle technology will likely reduce the number of commuters who park their vehicle in a traditional way (nearby workplaces) – carries over to the case of employer-provided parking. Answering that question calls for an approach that balances the incentives of the employer and the employees because in the case of employer-provided parking, the firm's decision to offer its employees a parking space and the incentive of employees to accept the offer are closely interrelated because of the fringe benefit character of workplace parking. The fringe benefit parking, along with wages, form a work package, which in turn constitutes the basis for the employer–employee negotiation process (Brueckner and Franco, 2018; Zax, 1988).

One of the most important features of workplace parking is that it is usually either provided for free or at meager direct cost to the employee. For example, in the USA, only a few percent of the parking resource costs are paid by commuters (Shoup, 2017; Small and Verhoef, 2007; van Ommeren and Wentink, 2012) [3]. In Barcelona, about 80% of those employees who use an employer-provided parking space, get it for free (Pons-Rigat *et al.*, 2020).

There is overwhelming consensus that in many cases employer-paid parking [4] can be regarded as excessive and the literature has identified three main reasons. The first reason is related to the distortive preferential tax treatment of the fringe benefit parking. Workers considerably benefit from free parking at first glance, but after all pay for it almost invisibly through lower wages (Brueckner and Franco, 2018). As wage income is taxed, whereas workplace parking as a fringe benefit in kind is usually not, firms can save labor cost for each parking space they offer at the expense of government tax revenue (Shoup, 2005; Zax, 1988). The second reason relates to parking standards. In the absence of minimum parking requirements, parking is unbundled from other transactions (e.g. the rent of the property), implying that the parking cost faced by firms is a marginal cost. In the presence of a binding minimum parking requirement, however, a firm incurs no extra cost, as the regulation turns the marginal cost of parking into a fixed cost through bundling the cost of parking spaces into the total cost of development (Cutter and Franco, 2012; Shoup, 1999). Both types of disincentives distort an employer's parking supply decisions and, as a consequence, create a deadweight loss owing to excess supply of parking (van Ommeren and Wentink, 2012). The third reason is un(der)priced road transport externalities. Inefficiently low pricing of road transport stimulates car commuting and so an overconsumption of parking (Eliasson, 2021; Shoup, 1997, 2017). Excessive workplace parking, in turn, is accompanied by several further negative effects. The group of car commuters suffers from more severe road congestion because workers with access to workplace parking are usually more car-oriented (Greenberg *et al.*, 2017; Willson and Shoup, 1990). Similarly, the society as a whole gets worse through pollution and further adverse impacts of car commuting (Shoup, 2017; Verhoef *et al.*, 1995). Further, it worsens competitiveness and urban vitality by reducing the land area available for production, housing, parks and other purposes (Shoup, 2020; Pons-Rigat *et al.*, 2020; Brueckner and Franco, 2018; Perini and Magliocco, 2014; Onishi *et al.*, 2010).

The various weaknesses associated with employer-provided parking and the observation that governments seem to be reluctant to enforce policies to reduce the level of workplace parking (Tscharaktschiew and Reimann, 2021) make it worthwhile to place the focus on self-driving cars and their auspicious capability to reduce parking requirements. In this paper, we argue that given the specific employer–employee relationship in terms of providing and demanding parking at the workplace, self-driving cars will be no guarantee to end up with less workplace parking, given the projections on the costs and benefits of fully autonomous vehicle technology. As a consequence, the imperative for policy interventions remains even in a world of self-driving cars [5].

The first part of the paper reconsiders employer-provided parking as we know it today, i.e. all car commuters are forced to park at the workplace or close to the workplace. To shed light on workplace parking provision and usage, an employer's decision to offer (free) parking must be treated together with the decision of employees to accept a firm's offer. In line with the literature on fringe benefit provision [6], we do this by modeling workplace parking, a fringe benefit, as an implicit negotiation process between employer and employee in the tradition of Katz and Mankiw (1985). The economic equilibrium model explicitly maps an employee's demand for work packages (the combination of wage and fringe benefit) together with an employer's incentive to offer a work package in favor of parking provision, taking into account the treatment of parking provision and parking policy in the income tax code established by the federal government and accounting for the feedback effects of private decisions on others and the economy as a whole. Parking choices are endogenous and depend on generalized commuting/parking costs, parking preferences, the treatment of parking in the tax code, etc. All these factors determine whether employer and employees agree on workplace parking or not. If not, employees are forced to park elsewhere or to use other travel modes. In a first step, we determine the market level of employer-provided parking, accounting for generalized commuting costs faced by employees parking at the workplace and those who park close to the workplace (non-employer parkers), the extra benefit derived from a parking space at the workplace, the resource cost of the parking spots and the characteristics of the income tax code. The latter is important because, as will see, the treatment of workplace parking in the income tax code affects our findings in various ways. We show that some of these aspects affect parking provision directly, while others influence it indirectly through the negotiation process between employer and employee. Comparative statics results will uncover how all these factors – which in sum shape a firm's generalized net cost of parking provision – influence the market level of employer-provided parking.

In the second part of the paper, we add self-driving cars to the approach. We focus on a number of FAV features which can be thought of as particularly relevant for the case of employer-provided parking: in-vehicle time use adjustments, empty driving or vehicle repositioning, adjustments in parking infrastructure design. Again, we start by determining the market level of employer-provided parking. It is shown that when both types of employees have systematic and idiosyncratic preferences – the workplace parker for the employer-provided parking spot and the non-employer parker for the opportunity of repositioning the self-driving car (e.g. returning home, parking elsewhere for free) – the market level of workplace parking in the presence of FAVs is affected by three determinants:

1. the level of workplace parking in the absence of FAVs;
2. the FAV-induced generalized cost saving to the employer; and
3. the overall generalized net cost of parking provision in the presence of FAVs.

The latter is shown to moderately reduce or increase workplace parking owing to self-driving cars, depending on whether workplace parking was initially (in the absence of self-driving cars) high or low. However, the main channel through which self-driving cars will affect workplace parking is whether FAVs induce a generalized cost saving to the employer. We decompose this cost saving channel into three components: a 'parking design cost' component, a 'labor productivity' component and a 'comparative labor cost' component. One component, the latter, leads to less workplace parking, *ceteris paribus*, as one would expect when car driving and parking at the commuter ¨ s destination are no longer perfect complements. Its mechanism, however, is less obvious. When employers provide parking spaces to their employees in a world of self-driving cars, they will no longer be able to negotiate a large wage discount for these workers in comparison to employees not receiving a parking space, because the latter may now derive extra utility from vehicle repositioning. So, offering parking becomes relatively less attractive from the employer ¨ s perspective. Other things equal, this component reduces workplace parking. The first two components, in contrast, are found to induce cost savings to the firm providing parking, thus leading to more workplace parking, *ceteris paribus*. We then approximate the magnitude of each component, relying on recent (first) empirical evidence on the impacts of FAV on car park design and, most importantly, the willingness-to-pay potential autonomous vehicle adopters attach to certain features of those cars. Our finding suggests that the first two components are likely to outweigh the latter, in other words, employer-provided parking does not necessarily decrease because of the emergence of self-driving cars. An implication of this finding is that fringe benefit taxation may be even more warranted than today.

The remainder of the paper is structured as follows: Section 2 describes the basic model, leaving self-driving cars aside. Section 3 determines the corresponding market level of employer-provided parking. Section 4 works out the potential role of self-driving cars in affecting workplace parking. Section 5 then elaborates how the advent of self-driving cars may affect workplace parking. Our approach does not enable us to make firm-sensitive predictions about the concrete future use of self-driving cars when vehicles are not parked at a particular workplace (e.g. whether vehicles will cruise or return home). So, our conclusions remain at an aggregate level, thus not referring to particular firms, locations etc. This and some further caveats are discussed in the final conclusions in Section 6.

2. Modeling employer-provided parking in the absence of self-driving cars

In this section, we set the scene for our analysis of employer-provided parking focusing on todays transport market without

FAVs. We start with some introductory comments, then continue with the description of the behavior of employees and finally explain the program of the employer/firm.

2.1 Stakeholders

Employer-provided parking naturally affects different stakeholders. To make the analysis not overly cumbersome, we focus on the impacts of work-related parking decisions among employees, but abstract from considering the impacts on non-workers. It is clear that to the extent non-workers do also travel during commuting peak hours, they will be affected by the employees parking decisions too.

Following Hashimoto and Zhao (2000), Katz and Mankiw (1985), van Ommeren *et al.* (2006) and others, we assume that, in the presence of a fringe benefit, a firm wanting to hire a worker, respectively wanting to retain a qualified workforce, offers a compensation package (wage, fringe benefit) as part of a negotiation between employee and employer [7]. The compensation package needs to generate a utility level for the employee that is at least as high as an exogenous reservation utility level which is also realized by workers not receiving an employer-provided parking space. If not, workers would not accept the offer (see also De Borger and Wuyts, 2011). In line with Zax (1991), Brueckner and Franco (2018) and Tscharaktschiew and Reimann (2021), this implies that employees will receive different wages, particularly depending on whether they make use of workplace parking and, if so, on their idiosyncratic preference for an employer-provided parking space and on generalized transportation costs. Apart from their heterogenous attitude toward the fringe benefit workplace parking, employees have identical preferences and work in a homogeneous type of job. Therefore, in the absence of workplace parking and differences in generalized transportation costs, all workers in this job would earn the same wage.

2.1.1 Employees

2.1.1.1 Worker having no access to employer parking. First, we consider a worker having no access to workplace parking. Here, we use superscript w to indicate that this employee parks his car close to the workplace but not directly at the employer who offers parking on specifically dedicated (off-street) parking spaces. Public transport and car are available as travel options. Because we are averaging over a large number of employees in the economy, the representative worker can be viewed as using both travel modes over a certain period of time.

The worker derives utility from general consumption goods (X^w), commuting trips by car (A^w), commuting trips by public transport (P^w) and leisure (L^w). The corresponding utility function is:

$$U^w = X^w + u^w(A^w, P^w) + u_L^w(L^w) - q^w\left(t_i^w\right) - y^w\left(\mu t_j^w\right), \quad (1)$$

where u_T and u_L are quasi-concave and continuous. Disutility from in-vehicle travel time (Gimenez-Nadal and Molina, 2019; Kahneman and Krueger, 2006; Stutzer and Frey, 2008) is denoted q^w and y^w for car and public transport, respectively, where t_i^w and t_j^w are in-vehicle car and public transit travel time, respectively. In the case of public transport, the travel time disutility stems from crowding discomfort, where μ is the level of crowding a public transit passenger experiences during a trip (thus, μ is expressed as a time multiplier as in Tirachini *et al.*, 2013). The level of crowding μ is zero on an empty public transit vehicle and positive and linear increasing in μ above a threshold load factor or passenger density (de Palma *et al.*, 2017), i.e. $\mu = 0$ up to a threshold passenger density above which the transit user perceives the vehicle as crowded and $\mu = 1$ refers to a predetermined reference level of crowding [8].

The worker is further subject to a time constraint:

$$\begin{aligned} & L^w + (1+\psi+\eta)A^w + (1+\phi)P^w \\ & = L^w + \underbrace{(A^w + P^w)}_{\text{time spent working}} + \underbrace{\underbrace{(\psi+\eta)A^w}_{\text{in-vehicle time } t_i^w} + \underbrace{\phi P^w}_{\text{in-vehicle time } t_j^w}}_{\text{time spent commuting } t^w} = E, \quad (2) \end{aligned}$$

where ψ and ϕ are the transport mode specific travel times needed for a commuting trip by car and by public transport, respectively. In addition, when commuting by car, workers not being able to park directly at the employer may be forced to cruise for parking and, as a consequence, need some extra search time, denoted η, to find a vacant parking spot [9]. For convenience, we do not explicitly distinguish between different parking forms, so this extra search time η because of cruising-for-parking may occur irrespective of whether the drivers parks on the curb or off-street. This rests upon the assumption that off-street parking areas occupied close to capacity can also induce cruising-for-parking and so cause extra search time for a vacant parking spot (Arnott *et al.*, 1991). As usual, commuters are viewed as atomistic and perceive times related to traveling (driving and cruising) as exogenous. Without loss of generality, we normalized the number of days an individual has to work for the contract period considered at one and fixed daily working time at one (hour). The former normalization implies:

$$A^w + P^w = 1, \quad (3)$$

meaning that A^w and P^w can be interpreted as the worker ¨ s travel mode shares. Because of constraint (3), E is to be interpreted as the exogenous daily time endowment.

The worker's monetary budget constraint is:

$$X^w + c_A^w A^w + c_P P^w = (1-t)w^w, \quad (4)$$

stating that expenditure on general consumption (the price of the composite commodity is normalized to one), car traveling and public transport are equal to net wage income, where the gross wage rate w is taxed at a flat rate t. The cost per (two-way) commuting trip by car c_A^w a type-w worker faces consists of a pecuniary round-trip car driving cost (energy, maintenance, etc.), c_A, plus a (potentially zero) public parking charge γ, thus $c_A^w = c_A + \gamma$. When using public transport, the workers pays a fare c_P for the (two-way) commuting trip.

Maximizing (1) subject to (2)–(4) yields the indirect utility function expressed in monetary terms:

$$V^w = (1-t)w^w + v^w\left(c_A^w, c_P, \psi, \eta, \phi\right) - q^w - y^w. \quad (5)$$

By applying Roy's identity, we find the following characteristics:

$$\frac{\partial V^w}{\partial c_A^w} = -A^w; \quad \frac{\partial V^w}{\partial c_P} = -P^w; \quad \frac{\partial V^w}{\partial \psi} = -\underbrace{\left(\theta_L^w + \theta_q^w\right)}_{\theta_{Lq}^w} A^w;$$

$$\frac{\partial V^w}{\partial \eta} = -\theta_{Lq}^w A^w \quad \frac{\partial V^w}{\partial \phi} = -\left(\theta_L^w + \mu\theta_y^w\right)P^w;$$

$$\frac{\partial V^w}{\partial \mu} = -\theta_y^w \phi P^w; \quad \frac{\partial V^w}{\partial t} = -w^w, \tag{6}$$

where $\theta_L^w \equiv \frac{du^w(L^w)}{dL^w}$ is the value of leisure, $\theta_q^w = \frac{dq^w\left(t_i^w\right)}{dt_i^w}$ is the disutility from in-vehicle car travel time, $\theta_y^w \equiv \frac{\partial y^w\left(\mu t_j^w\right)}{\partial\left(\mu t_j^w\right)}$ is the value of crowding discomfort, $\frac{\partial V^w}{\partial t_i^w} \equiv \theta_{Lq}^w = \left(\theta_L^w + \theta_q^w\right)$ and $\frac{\partial V^w}{\partial t_j^w} \equiv \theta_{Ly}^w = \left(\theta_L^w + \mu\theta_y^w\right)$ are the values of car and public transport travel time (Tirachini *et al.*, 2013; Small, 2012), respectively, all expressed in monetary units.

Having determined indirect utility V^w, we can derive the equilibrium wage w^w. Recalling that in equilibrium all employees will attain the same utility level $\overline{U}$, the equilibrium wage is found by setting indirect utility V^w to reservation utility $\overline{U}$. Solving (5) for the employee's wage rate yields:

$$w^w = \frac{\overline{U} - v^w(c_A^w, c_P, \psi, \eta, \phi) + q^w + y^w}{1-t}. \tag{7}$$

The impact of relevant parameters on the equilibrium wage w^w can be worked out by applying the implicit function theorem to the equation $V^w = \overline{U}$ and using (6):

$$\frac{\partial w^w}{\partial c_A^w} = \frac{A^w}{1-t}; \quad \frac{\partial w^w}{\partial c_P} = \frac{P^w}{1-t}; \quad \frac{\partial w^w}{\partial \psi} = \frac{\theta_{Lq}^w A^w}{1-t};$$

$$\frac{\partial w^w}{\partial \eta} = \frac{\theta_{Lq}^w A^w}{1-t} \quad \frac{\partial w^w}{\partial \phi} = \frac{\theta_{Ly}^w P^w}{1-t}; \quad \frac{\partial w^w}{\partial \mu} = \frac{\theta_y^w \phi P^w}{1-t};$$

$$\frac{\partial w^w}{\partial t} = \frac{w^w}{1-t}. \tag{8}$$

As expected, higher generalized commuting cost (captured by c_A^w, c_P, ψ, η, ϕ, μ) induce higher wages at the firm level to be compensated for a reduction in individual utility. This is consistent with empirical evidence suggesting that in the end employers bear a significant portion of the incidence of the costs of traveling to work (Kasper, 1983; Madden, 1985; Zax, 1991; Manning, 2003; Ross and Zenou, 2008).

2.1.1.2 Worker having access to employer parking. Now we turn to employees with access to workplace parking. Here superscript e is used to indicate that this worker parks his vehicle directly on specifically dedicated employer-provided parking lots.

Basically, the optimization program of the e-type employee is very similar. However, compared with the w-type worker there exist some differences in regard to the usage of the parking space. The differences can be summarized as follows: first, e-type workers are assumed to regularly use their car for commuting trips (Shoup and Willson, 1992; Vovsha and Petersen, 2009). That is, once employer-provided parking is available, the workers are making use of it (implying $A^e = 1$ and $P^e = 0$). Second, the firm is reasonably assumed to allocate its parking rights in such a way that there will be no excess demand. Hence, there is no parking search time (implying $\eta = 0$). Third, employees derive a direct utility (as opposed to the indirect effect of lower parking search time which works through the time constraint) stemming from the pure availability [10] and the usage [11] of an employer-provided parking space (implying that the combined term $z^e + \varepsilon^e$ enters the utility function). The deterministic parameter z^e is equal across all employees, whereas ε^e reflects idiosyncratic preferences distributed across workers with mean zero. Fourth, the worker has no (visible) parking cost to bear (implying that $\gamma = 0$ and $c_A^e = c_A^e$) [12]. Fifth, an imputed value ρ is added to the worker's taxable income. It reflects the treatment of workplace parking in the tax code. The higher the ρ, the more parking is regarded as a benefit in kind in the tax code and the less favorable it is for the worker to be provided with parking at the workplace. The usual practice of treating parking as a non-taxed fringe benefit implies $\rho = 0$.

The employee's utility function, the time constraint, and the monetary budget constraint can then be written as follows:

$$U^e = X^e + v^e(L^e) - q^e\left(t_i^e\right) + z^e + \varepsilon^e \tag{9}$$

$$L^e + (1+\psi)\underbrace{A^e}_{=1} = L^e + \underbrace{A^e}_{\text{time spent working}} + \underbrace{\psi A^e}_{\text{in-vehicle time } t_i^e = t^e} = E \tag{10}$$

$$X^e + c_A^e \underbrace{A^e}_{=1} = (1-t)w^e - t\rho. \tag{11}$$

Substituting (10) and (11) in (9) while recognizing that in equilibrium all workers will attain the same $\overline{U}$ yields the following daily wage of the e-type worker:

$$w^e = \underbrace{\frac{\overline{U} + t\rho - v^e(c_A^e, \psi) + q^e - z^e}{1-t}}_{w^{e*}} - \frac{\varepsilon^e}{1-t}. \tag{12}$$

Equation (2) reflects the nature of the wage negotiation process when it comes to fringe benefits offered by firms. A worker with average preference for an employer-provided parking space would earn the wage w^{e^*}, which includes a wage discount in exchange for the fringe benefit parking. Workers with strong (above average) preferences for workplace parking are willing to accept an even larger wage discount.

Writing the worker's indirect utility as:

$$V^e = (1-t)w^e - t\rho + v^e\left(c_A^e, \psi\right) - q^e + z^e + \varepsilon^e \tag{13}$$

and applying Roy' s identity to (13) yields:

$$\frac{\partial V^e}{\partial c_A^e} = -A^e; \quad \frac{\partial V^e}{\partial \psi} = -\theta_{Lq}^e A^e; \quad \frac{\partial V^e}{\partial \rho} = -t;$$

$$\frac{\partial V^e}{\partial t} = -(w^e + \rho); \quad \frac{\partial V^e}{\partial (z^e + \varepsilon^e)} = 1. \tag{14}$$

The implicit function theorem applied to the equation $V^e = \overline{U}$ and using (14) yields:

$$\frac{\partial w^e}{\partial c^e_A} = \frac{A^e}{1-t}; \quad \frac{\partial w^e}{\partial \psi} = \frac{\theta^e_{Lq} A^e}{1-t}; \quad \frac{\partial w^e}{\partial \rho} = \frac{t}{1-t};$$
$$\frac{\partial w^e}{\partial t} = \frac{w^e+\rho}{1-t}; \quad \frac{\partial w^e}{\partial (z^e+\varepsilon^e)} = -\frac{1}{1-t}. \tag{15}$$

Generalized commuting cost, the imputed value and the labor tax reduce individual utility whereas they increase the gross wage. The opposite is true for attitudes toward workplace parking. Because (free) parking is beneficial for workers, the employer offers lower wages in return.

2.1.2 Employer (firm)

We consider a representative firm that operates in a competitive output market and employs labor as variable input. The production function $f(n)$ captures the relationship between the total number of employees $n = n^w + n^e$ and aggregate output. The marginal product $f'(n)$ is assumed to be strictly positive and decreasing in the number of workers n. Without loss of generality, we further assume that the basic contribution of each employee to the firm's output does not depend on the travel mode used for commuting and the availability of an employer-provided parking space, thus $f'(n^w) = f'(n^e)$. However, because recent empirical evidence indicates a negative relationship between the extent of commuting and employee productivity (Ma and Ye, 2019; Goerke and Lorenz, 2017; Fernald, 1999; Prud'homme and Lee, 1999; Van Ommeren and Gutiérrez-i-Puigarnau, 2011; Winston, 2013), output is diminished by $g(t^w, t^e)$, where $g' > 0$ is the marginal productivity loss owing to longer commutes [13].

A key issue in the analysis on workplace parking refers to the cost of parking to the firm. Here we treat parking at the workplace as unbundled from other transactions (e.g. the rent of the firm property) meaning that parking standards (minimum parking requirements) are not imposed or are not binding [14]. The firm then faces an extra (daily) parking cost β when employing type-e workers. It can be interpreted as the capital and operating cost when the firm itself builds and maintains the parking space or, when it does not, as the rental price paid to landowners or garage operators.

The profit of the firm employing both types of workers can then be written as (output price is normalized at one):

$$\Pi(n^w, n^e) = f(n) - n^w g^w(t^w) - n^e g^e(t^e) - n^w w^w - n^e w^e - n^e \beta. \tag{16}$$

From the firm's perspective, the difference between employing a type-e or a type-w worker can be summarized as follows: the type-e worker earns (after the firm internal negotiation process) the wage rate w^e while causing additional parking cost in the order of β; the type-w worker is paid the wage w^w but causes no extra cost related to parking. Furthermore, both types of workers may affect firm profit differently, depending on personal commuting times.

3. Market provision of employer-provided parking in the absence of self-driving cars

We are now able to study workplace parking under different regimes, starting in this section with the market provision of employer-paid parking in the absence of self-driving cars. Firms will provide parking spaces if it is profitable to do so. They juxtapose the additional costs of parking provision with the benefits and choose the option with the highest profit (net benefit), perceiving the treatment of workplace parking in the income tax code (government variables t and ρ) as given. The corresponding condition in favor of workplace parking provision is:

$$\underbrace{f' - g^e - w^e - \beta}_{\partial\Pi^e/\partial n^e} > \underbrace{f' - g^w - w^w}_{\partial\Pi^w/\partial n^w}, \tag{17}$$

where $\partial\Pi^e/\partial n^e$ and $\partial\Pi^w/\partial n^w$ are the marginal profits associated with employing workers getting access and getting no access to workplace parking. Note that in (17), w^e is the wage rate that enables a worker to agree on the employer's parking offer (12). As we will see below, the firm in turn has an incentive to make the offer, in particular because of how parking is treated in the tax law. Using (12), condition (17) can be written as:

$$\varepsilon^e > (w^{e*} - w^w + \beta + g^e - g^w)(1-t). \tag{18}$$

Because we lack information about the distribution of idiosyncratic preferences for employer-provided parking across workers and to keep the analysis analytically tractable, we assume that ε^e is uniformly distributed over the interval $[-b, +b]$ with mean zero. The share F^* of employees who receive (and make use of) workplace parking can then be written as:

$$\mathrm{F}^* = \frac{1}{2b}\left[b + (w^w - w^{e*} - \beta - (g^e - g^w))(1-t)\right]. \tag{19}$$

Replacing w^w and w^{e^*} using (7) and (12) allows us to rewrite (19) as:

$$\mathrm{F}^* = \frac{1}{2} - \frac{\Gamma}{2b}, \tag{20}$$

with

$$\Gamma = \underbrace{(1-t)(\beta + (g^e - g^w))}_{\text{direct cost}} + \underbrace{(-z^e - (v^e - v^w) + (q^e - q^w) - y^w + t\rho)}_{\text{indirect cost/benefit via employer-employee negotiation}} \tag{21}$$

representing the employer's private generalized net cost of providing a parking space (per workday). It is composed of direct costs such as the resource cost of the parking space and of indirect costs (when positive) or benefits (when negative) which unfold over wages.

Figuring out how the most relevant variables affect the market outcome is straightforward. Because v^e and v^w are a function of transport-related variables, accounting for Roy's identity allows us to obtain the following results [15]:

$$\frac{\partial \mathrm{F}^*}{\partial \gamma} > 0; \quad \frac{\partial \mathrm{F}^*}{\partial \eta} > 0; \quad \frac{\partial \mathrm{F}^*}{\partial c_P} > 0; \quad \frac{\partial \mathrm{F}^*}{\partial \phi} > 0; \quad \frac{\partial \mathrm{F}^*}{\partial z^e} > 0;$$
$$\frac{\partial \mathrm{F}^*}{\partial y^w} > 0; \quad \frac{\partial \mathrm{F}^*}{\partial c_A} < 0; \quad \frac{\partial \mathrm{F}^*}{\partial \psi} < 0; \quad \frac{\partial \mathrm{F}^*}{\partial \beta} < 0;$$
$$\frac{\partial \mathrm{F}^*}{\partial \rho} < 0; \quad \frac{\partial \mathrm{F}^*}{\partial t} > 0 \tag{22}$$

An increase in parking cost and time (on- or off-street parking charge γ and cruising time η) and the generalized cost of public transport usage (c_P, ϕ) increase workplace parking. Only those employees not having access to workplace parking have to bear these costs so that employers are forced to pay higher wages when not providing parking spaces. This unambiguously increases workplace parking. Higher preferences for parking at the workplace (z^e) and stronger valuation of public transit crowding discomfort (y^w) will also induce firms to provide more parking spaces to economize on labor cost.

The opposite is true when the generalized cost of car commuting increases (c_A, ψ). Employees having access to workplace parking are more car-oriented and, as a consequence, will negotiate higher wages as a compensation for higher energy cost and more severe congestion during their commuting trips. As a result, this strengthens the incentive of firms to employ workers who are more transit-oriented than workers using car only and asking for parking spaces.

Higher costs at the firm level related to workplace parking (β, ρ) will obviously reduce the fraction of parking spaces provided. Higher parking cost β directly diminishes an employer's incentive to offer parking opportunities. The impact of the imputed parking value in the income tax code on the firm's cost and so on parking provision is less obvious because it works indirectly via the employee's salary. As $\rho > 0$, employees want to be compensated for taxing the fringe benefit through higher wages, thus providing parking spaces becomes less attractive to the employer.

The final relationship reveals that the tax code significantly affects the extent of workplace parking. An increase in the income tax will lead to more parking at the workplace if parking is not treated as a taxable fringe benefit in the tax code (low imputed value ρ). With a higher income tax, firms have an incentive to substitute parking for wages. Note also that to get the outcome that the tax system does not distort an employer's decision on parking provision, $\rho - \beta = 0$ must hold, i.e. the imputed value of the parking space in the tax code must exactly reflect the cost of the parking space. Hence, ρ could be used as policy instrument to reduce workplace parking.

4. The role of self-driving cars

The main finding of the literature on employer-provided parking is that the level of workplace parking as derived above is excessive, meaning that F^* exceeds the socially optimal level F^* [16]. In the light of this, reducing or even eliminating employer-provided parking should be the goal. One option how this could be achieved is to account for the fringe benefit workplace parking in the income tax code (via the imputed value ρ, see (22)). Another option is to force employers to offer commuters the option to choose cash in lieu of any parking subsidy offered by the firm, better known as " parking cash-out" (Shoup, 1997). However, as shown in previous work, these and other options have not become widespread. Governments seem to be reluctant to enforce these or similar policies to reduce the level of workplace parking.

Now imagine that self-driving cars would already be available today. Could this make a contribution to a reduction of employer-provided parking? To answer this question, we construct a scenario where self-driving cars are available to employees and adapt our approach accordingly. Meanwhile, the literature provides a comprehensive overview of the potential effects of partly and FAVs. Most of the effects, however, are highly uncertain not only in magnitude, but even in sign, quite simply owing to the fact that self-driving vehicles are not yet available to the public. This implies that there are currently no instances where the technology can be measured as part of an existing transportation system, which in turn makes it difficult to reliably predict the future impacts of the technology. Among the most significant impacts associated with self-driving cars are: time use adjustments during the trip, benefits and costs from vehicle repositioning, changes in the design of parking facilities, impacts on congestion. In the following, we briefly explain the role of FAVs in influencing the stakeholders involved regarding the employer-provided parking problem. Subsequently, we study market provision of workplace parking in the presence of self-driving cars.

4.1 General assumption on vehicle usage

Before we move to the description of specific FAV features, clarification is needed in regard to the role of autonomous vehicle technology in influencing the future mobility system in general (privately-owned FAV vs. mobility as automated ride (hailing) service). The clarification is necessary because the vast majority of studies dealing with autonomous technology agree that whether an autonomous vehicle will be owned or (just) used through e-hailed ride services is one of the largest uncertainties in modeling their impacts. For example, whether individuals use their own FAV or make use of shared/pooled autonomous mobility services may have impacts on empty vehicle repositioning or the evaluation of in-vehicle travel time (Wadud and Chintakayala, 2021).

Ownership of private car has been on the rise since the invention of the automobile. Autonomous vehicles technology could then be the stimulus for a new mobility system in which members can call up distant autonomous vehicles using mobile phone applications. That is, currently available services such as taxis or transportation network companies will emerge as a more widely used ride sourcing system as service providers employ FAVs at reduced labor cost. It is thus possible that these private mobility services will emerge as a widely used mode of transportation, replacing the still dominant system of privately owned vehicles in return (Khayati *et al.*, 2021).

However, recent results from stated-preferences studies suggest that, in general, people will (on average) continue to favor owning cars over sharing them even in an era of FAVs (Gkartzonikas and Gkritza, 2019; Harb *et al.*, 2021; Haboucha *et al.*, 2017; Pakusch *et al.*, 2018; Wadud and Chintakayala, 2021; Zmud and Sener, 2017). For example, Wadud and Chintakayala (2021) estimate the inherent attractiveness or convenience value of ownership of an automated vehicle as opposed to the adoption of an automated ride (hailing) service. They find a significantly positive (annual) willingness to pay for the convenience of autonomous vehicle ownership over exclusive-use ride services. They also uncover substantial inconvenience cost (>£2,000) associated with using pooled or shared automated ride services, thereby confirming the previous strand of findings on people's aversion to sharing rides with strangers. Apart from stated-preference approaches, comprehensive cost-based analysis of autonomous mobility services (Bösch *et al.*, 2018) reveals that in the era of autonomous vehicles, out-of-pocket costs of private car usage are likely to be still lower than for most other mobility concepts. Bösch *et al.* (2018) argue that even more than today, high fixed costs of private vehicles will continue to be accepted and people will agree to pay the associated premium, given the low variable cost and the various benefits of a private mobility robot. They conclude that a substantial share of vehicles may remain in private possession and that private cars, whether conventional or fully automated, will remain the preferred travel mode. In fact, most studies point out that when sharing services will grow owing to car automation, this will mainly be at the expense of public transport rather than private car ownership.

Against this background, to avoid the adoption of any kind of extreme scenarios (fully private ownership vs completely shared economy), we, on the one hand, proceed by maintaining the assumption that employees commute be private car, thereby allowing a straightforward comparison with the case of commuting by conventional cars (Millard-Ball, 2019). On the other hand, we do not rule out that some kind of vehicle sharing (e.g. intra-household sharing) may actually happen.

4.2 Special fully autonomous vehicles features

4.2.1 Time use

Once people adopt (fully) autonomous vehicles, they get access to one of the most significant and widely mentioned benefits of the technology, namely relieving drivers from the duty of paying attention to the road. Instead, FAVs allow them to engage in a wider range of activities during their daily commute, including working on their laptops, sleeping, eating meals, reading books, watching movies, resting, having quality time with family members, teaching children, calling friends and so on (Fagnant and Kockelman, 2015; Kyriakidis *et al.*, 2015). Let us assume that all activities other than working can be subsumed under leisure activities and that employees spend in-vehicle time on leisure [17], the time constraints of type-w and type-e employees change to:

$$\underbrace{\hat{L}^{w} + \underbrace{\psi S^{w}}_{\text{in-vehicle time } t_i^w}}_{\text{effective leisure } L^w} + \underbrace{(A^{w} + S^{w} + P^{w})}_{\text{time spent working}} + \underbrace{\underbrace{(\psi + \eta)A^{w}}_{\text{in-vehicle time } t_i^w} + \underbrace{\phi P^{w}}_{\text{in-vehicle time } t_j^w}}_{\text{time spent commuting } t^w} = E \tag{23}$$

and

$$\underbrace{\hat{L}^{e} + \psi S^{e}}_{\text{effective leisure } L^e} + \underbrace{(A^{e} + S^{e})}_{\text{time spent working}} + \underbrace{\psi A^{e}}_{\text{in-vehicle time } t_i^e = t^e} = E, \tag{24}$$

respectively, where S denotes the fraction of trips for which employees use a self-driving car. The set of available commuting options is now larger so that $A^w + S^w + P^w = 1$ and $A^e + S^e = 1$ must hold. Because commuters need not actively engage in driving-related activities anymore when riding in a FAV, active travel time turns into passive travel time. That latter can now be used alternatively and becomes part of effective leisure time L, which contributes positively to utility (Tscharaktschiew and Evangelinos, 2019). Most importantly, if utility functions remain structurally the same, this leads to:

$$\frac{\partial V^w}{\partial \psi} = -(\theta_L^w + \theta_q^w)A^w - \theta_q^w S^w;$$

$$\frac{\partial V^e}{\partial \psi} = -(\theta_L^e + \theta_q^e)A^e - \theta_q^e S^e. \tag{25}$$

The interpretation is straightforward. Adopting self-driving cars ($S > 0$) is beneficial as it diminishes the utility reducing effect of car commuting time (juxtapose (6) and (14) with (25)). From (25), it then follows $\frac{\partial V}{\partial t_i} \rightarrow \theta_q$ as $S \rightarrow 1$, implying a reduction in the value of travel time. This reflects the broad consensus in the literature that, other things equal, the ability to engage in various in-vehicle activities or productively use commute time will likely decrease commuters' overall sensitivity to in-vehicle travel time (see the review provided by Harb *et al.*, 2021) [18]. For convenience, in the following we abstract from explicitly modeling the choice between A and S. Instead, we assume that once a FAV is available, it will be used by both types of employees. This allows for a straightforward comparison between both extremes, only conventional (human-driven) cars and only self-driving cars.

4.2.2 Benefits and costs from vehicle repositioning

Generally, for FAVs there is no need to park close to their destination or even to park at all. Instead, FAVs can seek out free on- or off-street parking, just cruise (circle around) or even return home (Bahrami *et al.*, 2021; Millard-Ball, 2019; Zakharenko, 2016). So, self-driving cars may offer unprecedented opportunities to those not having access to and not making use of employer-provided and -paid parking.

Self-driving cars enable vehicle repositioning without human input, which substantially improves vehicle sharing within (and between) households (Khayati *et al.*, 2021). This allows households to reduce vehicle ownership without compromising overall household mobility. Working household members may economize on out-of-pocket curbside parking costs at work location when programing the FAV for returning home or riding to nonchargeable/cheaper and safer parking areas (Levin *et al.*, 2020; Tscharaktschiew *et al.*, 2022). They can be dropped off right at the company site without having to search for a parking spot or having to walk from that spot to the office or factory. For those household members who stayed at home, the returned FAV is available to bring other members safely and reliably to their destinations and at the end of the day to pick up the worker. Alternatively, the FAV can be parked at home (without further usage of household members), thereby benefiting from the merits of secure and safe parking alike to workplace parking. Also, after dropping people off at work the car can seek out other locations where parking is secure, protected from bad weather conditions and/or even costless. Just to circle around might be another option, albeit less likely for work-related trips (with several hours between dropping off and picking up the commuter).

The capability of empty self-driving cars to reposition only by means of destination or navigation input data is the most significant feature that distinguishes Level 3 from higher Level 4 automation according to the categorization provided by NHTSA (2013), respectively, Level 4 from Level 5 according to the definition in SAE (2016). Meanwhile, a number of studies are available deriving estimates of the willingness-to-pay for different levels of autonomy (Bansal and Kockelman, 2017, 2018; Bansal *et al.*, 2016; Daziano *et al.*, 2017; Morita and Managi, 2020; see also the reviews by Elvik, 2020 and Harb *et al.*, 2021). The majority of studies found that, on average, households are willing to pay a significant amount for automation and most importantly, they would be willing to pay a premium to add the final stage of autonomy, i.e. switching from Level 3 (4) to Level 4 (5).

This suggests that workers derive intrinsic monetary value from the possibility to park anywhere and/or to make the FAV available to other household members. Therefore, similar to the utility an employer parker attaches to the parking opportunity provided by the firm, nonemployer parkers (type-w workers) may attach utility to a vehicle's capability to reposition. More specifically, we denote by $z^w > 0$ the deterministic utility component equal for all workers and by ε^w individual-specific idiosyncratic preference for repositioning, again assumed to be uniformly distributed with mean zero ($E(\varepsilon^w) = 0$). The latter reflects the substantial heterogeneity in preferences for automation (Daziano *et al.*, 2017). Some individuals may derive smaller utility from the possibility of repositioning when placing the technology's drawbacks and other disadvantages in the foreground, e.g. not having the car immediately available when needed, loss of control, fear from software hacking and resulting misuse of the (empty) self-driving car (Fagnant and Kockelman, 2015; Zhang *et al.*, 2019b). Others in turn may attach greater utility when, e.g. particularly benefiting from intra-household autonomous car sharing because of a wide range of daily outdoor errands of many family members (Khayati *et al.*, 2021).

Beside the benefits, vehicle repositioning also comes at a cost. For a type-w employee whose FAV returns home, driving-related travel costs (c_A) double while additional on- or off-street parking costs (γ) cease to apply. For the case of parking elsewhere, parking costs can be smaller or greater than in the base case. The cruising option implies zero parking cost but higher driving-related travel costs than in the base case. The monetary budget constraint of the worker as displayed in (4) changes accordingly.

4.2.3 Employer parking facility cost

Self-driving cars not only have the potential to reduce the need for parking *per se* or to change the demand for parking at particular locations, but also to reduce the parking footprint by converting traditional parking lots into automated parking facilities that can store more AVs (compared to regular vehicles) in smaller areas. As vehicles become driver-less, the passengers no longer need to be physically present in car-parks. Driver-less cars drop off their passengers at the parking entrance (or at a designated drop-off zone) and head to a spot chosen by a car-park operator. In this automated parking system, the average space per vehicle is projected to decrease because the driving lanes become narrower, elevators and staircases become obsolete and the required room for opening a vehicle's doors becomes unnecessary [19]. Nourinejad *et al.* (2018) show that autonomous vehicle car-parks can reduce the overall need for parking space by more than half. Siddique *et al.* (2021) additionally show that in small parking lots, it is even possible to achieve 80% improvement in parking capacity, on average, than a traditional parking lot. This revitalization of space that was previously used for parking can be socially beneficial if car-parks are converted into commercial and residential land uses.

With this in mind, we reasonably presume a reduction of the opportunity cost per parking space β, while taking into account that the saving in parking space probably cannot be transferred to overall cost savings on a one-to-one basis because a car-park operator might be necessary to relocate some of the vehicles to create a clear pathway for a blocked vehicle to exit. Hence, the relative cost saving will probably be somewhat lower than the percentages stated above.

4.2.4 Other determinants

As shown in Section 3, a wide range of further determinants may affect the level of employer-provided parking, e.g. the level road congestion, the extent of crowding in public transit, the arrangement of policy instruments such as parking fees or the treatment of workplace parking in the income tax code ((22) and Appendix 1). However, analyzing the literature dealing with the impact of FAVs on these indicators reveals strong ambiguity [20]. Apart from that, there is also a natural lack of knowledge regarding future transport policy and general tax policy so that we keep our focus on the determinants described previously.

5. Employer-provided parking in the presence of self-driving cars

We are now in the position to reconsider the market provision of employer-provided parking in the presence of self-driving cars, asking whether the market may generate less workplace parking when FAVs are available. Given marginal profits associated with employing a worker of type w and e, respectively, it is profitable for a firm to provide a worker with a parking lot if:

$$\frac{\varepsilon^e}{(1-t)} - \frac{\varepsilon^w}{(1-t)} > w^{e*} - w^w + \beta + (g^e - g^w). \tag{26}$$

Using (12) along with information on FAV features, this inequality can be rewritten as:

$$\varepsilon^e - \varepsilon^w > \Gamma \tag{27}$$

with

$$\Gamma = (1-t)(\beta + (g^e - g^w)) - (z^e - z^w) - (v^e - v^w) + (q^e - q^w) - y^w + t\rho \tag{28}$$

representing the employer's private generalized net cost of providing a parking space in the presence of self-driving cars.

Importantly, as one can see from (27), the firm's profitability now depends on the difference of idiosyncratic preferences. In the light of this, it is important to recognize that when $\varepsilon^e \sim$ *uniform*$(-b, b)$ and $\varepsilon^w \sim$ *uniform*$(-b, b)$, it follows $\varepsilon^e - \varepsilon^w \sim$ *triangular*$(-2b, 2b)$, meaning that the difference of two uniformly distributed random variables follows a triangular distribution on the interval $[-2b, 2b]$ with mode zero. For a triangular distribution, to calculate the probability that $\varepsilon^e - \varepsilon^w > \Gamma$, one needs to distinguish between two cases: $\varepsilon^e - \varepsilon^w$ is below the mode and $\varepsilon^e - \varepsilon^w$ is above the mode, where the mode corresponds to $\Gamma = 0$. Then, by making use of the corresponding probability density function, we can determine the market share of employer-provided parking in the presence of self-driving cars. We get:

$$F^* \equiv P(\varepsilon^e - \varepsilon^w > \Gamma) = 1 - \frac{1}{2} \times (\Gamma + 2b)\frac{2(\Gamma + 2b)}{(2b - (-2b))2b}$$
$$= \frac{1}{2} - \frac{\Gamma}{2b} - \frac{1}{2}\left(\frac{\Gamma}{2b}\right)^2 \tag{29}$$

for $\varepsilon^e - \varepsilon^w < 0$ and

$$F^* \equiv P(\varepsilon^e - \varepsilon^w > \Gamma) = \frac{1}{2} \times (2b - \Gamma)\frac{2(2b - \Gamma)}{(2b - (-2b))2b}$$
$$= \frac{1}{2} - \frac{\Gamma}{2b} + \frac{1}{2}\left(\frac{\Gamma}{2b}\right)^2 \tag{30}$$

for $\varepsilon^e - \varepsilon^w > 0$, respectively.

Now let us denote all variables related to the autonomous vehicle case by a tilde, e.g. $\tilde{F}^*$ for the market level of employer-provided parking when self-driving cars are available to employees. Rewriting (29) and (30) in such a way that $\tilde{F}^*$ is expressed as a function of F^* then yields:

$$\tilde{F}^* = \begin{cases} F^*(\Gamma) + \frac{\Delta\Gamma}{2b} - \frac{1}{2}\left(\frac{\tilde{\Gamma}}{2b}\right)^2 & \text{for} \quad \varepsilon^e - \varepsilon^w < 0 \quad (\text{or } \tilde{\Gamma} < 0) \\ F^*(\Gamma) + \frac{\Delta\Gamma}{2b} + \frac{1}{2}\left(\frac{\tilde{\Gamma}}{2b}\right)^2 & \text{for} \quad \varepsilon^e - \varepsilon^w > 0 \quad (\text{or } \tilde{\Gamma} > 0) \end{cases}, \tag{31}$$

where $\Delta\Gamma \equiv \Gamma - \tilde{\Gamma}$ is the employer's (deterministic) overall generalized cost saving (per parking space and workday) owing to the emergence of self-driving cars. The market level of workplace parking in the presence of FAVs depends on three components: the level of workplace parking in the absence of FAVs (F^*), the FAV-induced generalized cost saving to the employer (net cost difference $\Delta\Gamma$) and the overall generalized net cost of parking provision in the presence of FAVs (absolute net cost $\tilde{\Gamma}$).

Comparative static analysis of (29) and (30) shows that the influence of the most relevant variables on the level of employer-provided parking is weaker in the presence of FAVs, regardless of whether the impact of the respective variable is to increase or reduce workplace parking [21]. There are mainly two reasons: a reduction of the generalized cost of travel, which makes employer parking provision less sensitive to e.g. traffic congestion and the (idiosyncratic) utility nonemployer parkers derive from vehicle repositioning, which leads to the third (quadratic) term in (31) and causes workplace parking supply to be less sensitive to changes in the employer's net cost of parking provision $\tilde{\Gamma}$ (see the elaboration of the case $\Delta\Gamma = 0$ below for more details).

Whether the market level of employer-provided parking $\tilde{F}^*$ will in the end be higher or lower with self-driving cars available to employees crucially depends on $\Delta\Gamma$, the second term in (31).

Case $\Delta\Gamma = 0$:

Let us first consider the special case that $\Delta\Gamma = 0$, i.e. FAVs do not affect an employer's generalized net cost of parking provision [the middle terms in (31) drop out]. At first sight, if $\Delta\Gamma = 0$, one would expect that $F^* = \tilde{F}^*$, but owing to idiosyncratic preferences for both types of parking, this will not be the case. Figure 1 depicts the market shares of employer-provided parking F^* and $\tilde{F}^*$ as a function of $\Gamma\ (= \tilde{\Gamma})$. [22] As can be seen, when the employer's net parking cost is generally positive ($\Gamma > 0$ or $\varepsilon^e - \varepsilon^w > 0$) – implying market shares below 0.5 – self-driving cars cause the level of employer-provided parking to increase. Figure 2 in turn gives the rationale for this finding. The figure sketches the probability density functions with the area under the curves representing the market supplies of workplace parking. Note first that, graphically, F^* is the area of the rectangle $ABCD$, where line BC coincides

Figure 1 Market level of employer-provided parking without and with FAV (assuming $\Delta\Gamma = 0$)

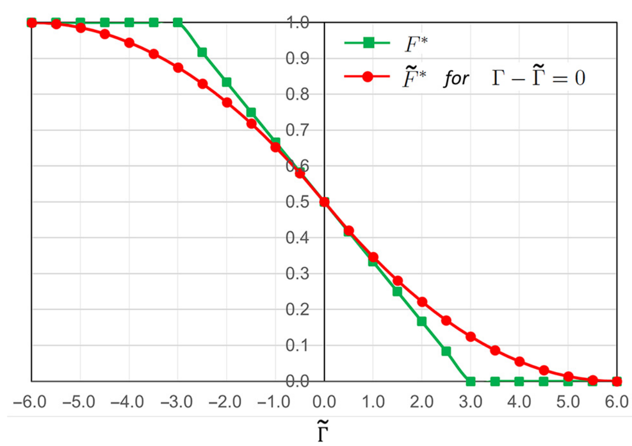
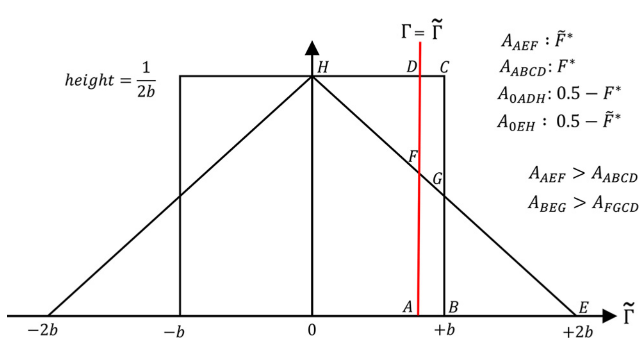


Figure 2 Probability density functions of employer-provided parking without and with FAV



with the upper interval of idiosyncratic parking preference $(+b)$.

Suppose that $\tilde{\Gamma} = \Gamma \rightarrow b$, i.e. the (red) line AD would coincide with line BC in the figure. Then, F^{*} obviously becomes zero (area A_{ABCD} vanishes; see also (20)) but $\tilde{F}^{*}$ still exceeds zero (area A_{BEG} does not vanish). Hence, for $\Gamma > 0$, implying low levels of F^{*}, it follows $\tilde{F}^{*} > F^{*}$, i.e. more employer-provided parking in the presence of FAVs (see the right side of Figure 1). The same pattern applies when $\tilde{\Gamma} = \Gamma < b$, i.e. the (red) line AD in Figure 2 is to the left of the line BC. Then $F^{*} > 0$ (area A_{ABCD}) but $\tilde{F}^{*}$ (area A_{AEF}) is larger than F^{*} (because area A_{BEG} exceeds area A_{FGCD}).

The intuition is as follows: some employees not having access to workplace parking have a distinctive idiosyncratic aversion to some features of self-driving cars; in our case driverless repositioning which is relevant for non-workplace parking. At the same time some employees who have access to workplace parking have a distinctive positive idiosyncratic preference for firm parking. As a result, at any $\Gamma > 0$ (respectively $\varepsilon^{e} - \varepsilon^{w} > 0$), the probability density is more elongated in a world with self-driving cars and this strengthens the case toward more employer-provided parking. Therefore, as long as the employer's net parking cost is positive, we have $\tilde{F}^{*} > F^{*}$. However, the opposite is true when an employer's net parking cost is negative ($\Gamma < 0$). Self-driving cars will then contribute to less employer-provided parking and the line of reasoning is precisely the reverse (see the left side of Figure 1). Whether $\Gamma > 0$ or $\Gamma < 0$ is utmost case sensitive and cannot be answered in general. However, we are in the fortune position to observe current levels of workplace parking. Hence, when employer-provided parking (at the firm level, the regional level or what else) is found to be substantial ($F^{*} > 0.5$), $\Gamma < 0$ must obviously hold. This can only be the case when the employer's opportunity resource cost of the parking spot are relatively small. As a result, we can conclude that if FAVs leave an employer's net cost of parking provision almost unaffected ($\tilde{\Gamma} = \Gamma$) and employer-provided parking is initially substantial (implying $\Gamma < 0$), the emergence of self-driving cars would lead to less employer-provided parking, presumably good news. In contrast, if employer-provided parking is initially of minor importance, e.g. because of high β, self-driving cars would raise the level of employer-provided parking, presumably bad news.

Case $\Delta\Gamma \lessgtr 0$:

So far, the analysis has focused on the assumption that $\Delta\Gamma \equiv \Gamma - \tilde{\Gamma} = 0$, i.e. FAVs do not affect (or hardly affect) an employer's deterministic net cost of providing parking spaces to employees. From (31) it is clear that the market provision of workplace parking increases $\left(\tilde{F}^{*} > F^{*}\right)$ when self-driving cars reduce the employer's cost of parking provision (meaning $\Delta\Gamma > 0$, i.e. cost saving because of FAV), but decreases $\left(\tilde{F}^{*} < F^{*}\right)$ when self-driving cars raise the employer's net cost of parking provision (meaning $\Delta\Gamma < 0$). Obviously, elaborating the sign of $\Delta\Gamma$ is essential. Subtracting (28) from (21) gives:

$$\Delta\Gamma \equiv \Gamma - \tilde{\Gamma} = \Delta\Gamma_{(1)} + \Delta\Gamma_{(2)} + \Delta\Gamma_{(3)}, \tag{32}$$

where

$$\Delta\Gamma_{(1)} = \underbrace{(1-t)\big(\beta - \tilde{\beta}\big)}_{\text{parking design cost (1): } >0} \tag{33}$$

$$\Delta\Gamma_{(2)} = \underbrace{(1-t)(g^{e} - \tilde{g}^{e}) - (1-t)(g^{w} - \tilde{g}^{w})}_{\text{labor productivity (2): } >0} \tag{34}$$

$$\Delta\Gamma_{(3)} = \underbrace{\underbrace{\left[(\tilde{v}^{e} - \tilde{q}^{e}) - (v^{e} - q^{e})\right]}_{(3a):\ >0} - \underbrace{\left[(\tilde{v}^{w} + \tilde{z}^{w} - \tilde{q}^{w}) - (v^{w} - q^{w})\right]}_{(3b):\ >0}}_{\text{comparative labor cost (3): } <0} \tag{35}$$

Term (1) refers to parking design cost. As argued above, self-driving cars are likely to make parking allocation more compact, thereby inducing a cost saving for the firm. With $\beta - \tilde{\beta} > 0$, term (1) can be assumed to be positive. Term (2) reflects productivity effects stemming from FAV availability. The term can be worked out to be greater than zero (Appendix 3). This is because employees who park at the workplace are more car-oriented and so benefit more from more pleasant time use in FAVs. Firms capture these benefits through productivity gains which in turn makes firms better off when providing a parking space. Terms (3*a*) and (3*b*) reflect the net utility gain employees derive when self-driving cars become available. Meanwhile, a wide range of empirical studies indicate a utility gain – in other words a positive willingness to pay – for car automation on average, meaning that both terms can be assumed to be positive. However, because nonemployer parkers additionally benefit from vehicle repositioning, Term (3*b*) overcompensates Term (3*a*), implying a negative sign for the combined Term (3).

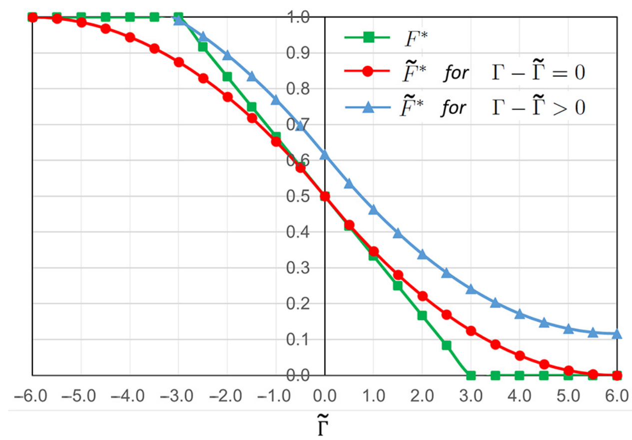
The most striking feature of the above elaboration is that we cannot fix the sign of $\Delta\Gamma$ unambiguously owing to the countervailing effects captured by the Terms (1)–(3). However, having the recent literature on autonomous vehicles in mind, it is possible to approximate the magnitude of the terms.

The resource (opportunity) cost of parking spaces of course depends on, e.g. location (downtown, urban, rural) and type of parking (surface, street garage, underground). We rely on studies by Immowelt (2019), Shoup (2017), van Ommeren and Wentink (2012), Small and Verhoef (2007) and assume a monthly cost of around €100 which corresponds to β = €5 per working day. As noted above, FAVs are suggested to have major impact on parking facility designs. According to Nourinejad *et al.* (2018), autonomous vehicle car-parks have the potential to reduce the need for parking space by an average of 62% and a maximum of 87%. Accouting for some additional cost for operating the car park, a reasonable estimate for a corresponding cost cutting may thus be around 50%. However, because of the fringe benefit character of workplace parking, the cost difference must be corrected by the labor tax. Setting the tax at 0.4 – which is a rough best guess estimate for many countries – Term (1) equals €1.5 per workday.

The line of reasoning for the approximation of the combined effect of Terms (3*a*) and (3 *b*) is as follows: Term (3*a*) reflects the utility gain of those employees having an employer parking space. For employer parkers, vehicles repositioning is not an issue so that their utility gain can in particular be traced back to more convenient and efficient in-vehicle time use [23]. Employees not being provided with an employer parking spot [Term (3*b*)] also benefit from in-vehicle time use (albeit to a somewhat smaller degree because they are less car-oriented (see above)), but additionally gain from driverless vehicle repositioning. The difference between both utility gains, (3*a*) – (3*b*), is thus mainly caused by the overall (deterministic) merits of vehicle repositioning. While the time use aspect can be seen as the main feature of the leap from Level 2 to Level 3 (NHTSA, 2013), respectively, from Level 3 to Level 4 [Society of Automotive Engineers (SAE), 2016] automation, vehicle repositioning undoubtedly characterizes the quantum leap toward the final level of automation, i.e. to Level 4 according to National Highway Traffic Safety Administration (NHTSA) (2013), respectively to Level 5 using the definition by SAE (2016). The combined (negative) third effect can then be interpreted as (minus one times) the willingness-to-pay for enhancing car automation from the penultimate stage of automation to the final level of autonomy (self-driving car). To capture this effect, we relied on information of several willingness-to pay studies performed for various region and derived the following values [24]: $3,950 as of 2014 (Bansal *et al.*, 2016); $3,400 as of 2015 (Bansal and Kockelman, 2017); $3,000 as of 2014 (Bansal and Kockelman, 2018); $1,400 as of 2014 (Daziano *et al.*, 2017); $600 as of 2014 (Morita and Managi, 2020); and –€2,600 as of 2019 (Rodrigues *et al.*, 2021). As regards this numbers, it is worth noting that they include the respondents expectations about the merits of self-driving cars in principle, so they include the expected benefits of letting the vehicle return home, parking elsewhere, circling around etc., taking into account to what extent they expect to make use of these options. As one can see, the estimates range from less than $1,000 [25] to almost $4000 and refer to how much more respondents are willing to pay on top of what they would pay for the next lower level of autonomy when purchasing the car [26]. This implies that values derived are to be converted into a daily figure. Assuming an average vehicle life span of 15 years and fixing the willingness-to pay-value at $3,500, we obtain about – €0.58 per day (average exchange rate as of April 2022: €0.90 per US$1) as an order of magnitude for the combined Term (3).

With the first term being +€1.5 and the third term being significantly lower than €1 in absolute terms, we can refrain from further elaborating the magnitude of the (positive) second term in (32), which is very hard to pin down. Gathering all information of the above exploration and using (32) then tells us that $\Delta\Gamma$ is unlikely to become negative. As a matter of fact, $\Delta\Gamma$ is likely positive. The implication of this finding can be deduced from (31), with the middle term not dropping out now. For better exposition it is visualized by Figure 3. The (blue) line with triangles depicts $\tilde{F}^*$, exemplarily assuming a conservative estimate in the order of $\Delta\Gamma = 0.7$. What we can see is that the importance of workplace parking has increased over the whole range of $\tilde{\Gamma}$. Most importantly, even when the share of employer-provided parking is already high initially (left side of the figure), the emergence of self-driving cars raises it even further.

Figure 3 Market level of employer-provided parking without and with FAV (assuming $\Delta\Gamma \geq 0$)



6. Conclusions and outlook

Recent studies on commuter parking in an age of self-driving cars suggest that with the capability of FAVs to get rid of the need to park close to the workplace, the number of parking spaces demanded by commuters will decline. This would be good news, because, as of today, parking is one of the largest consumers of urban land. None of the studies, however, is concerned with the special case of employer-provided parking, although workplace parking is a widespread phenomenon and in many instances the dominant form of commuter parking. This paper has analyzed whether the finding of the existing literature – less commuter parking in an age of self-driving cars – carries over to the case of employer-provided parking. Our perspective on commuter parking differs from the recent literature because in the case of employer-provided parking, the firm's decision to offer its employees a parking space and the incentive of employees to accept the offer are closely interrelated because of the fringe benefit character of workplace parking. We developed an economic equilibrium model that maps the employer–employee relationship, taking into account the explicit treatment of parking provision and parking policy in the income tax code and accounting for relevant commuting and parking externalities. We determined the market level of employer-provided parking in the absence and presence of FAVs and identified the factors that drive the difference. We then approximated the magnitude of each factor, relying on recent (first) empirical evidence on the impacts of FAVs.

We found that FAVs are no guarantee to end up with less employer-provided parking. In fact, the opposite might be the case, implying that car commuting and the adverse effects it entails, may be as severe as today. Consequently, the regime of switching from employer-paid parking to employee-paid parking – whether it be through policy intervention in the form of fringe benefit taxation [see $\partial F^*/\partial\rho$ in (22)] or by means of other measures such parking cash-out – may be even more justified in a world of self-driving cars than today.

There are two obvious caveats to the present analysis which should be kept in mind and could be addressed in future research.

The first is related to the relationship between parking supply in terms of the number of parking spaces and the aggregate land occupied by parking lots. We find that the emergence of fully autonomous vehicle technology might even increase workplace parking in terms of the number of commuters making use of an employer-provided parking. One driving force of this result is the reduction in parking cost owing to the possibility to construct and operate more compact car parks. As the average amount of land per parking space required declines, it might be possible that there will nevertheless be a reduction in total land area devoted to parking, although the number of commuters parking at the workplace remains the same of even increases. On the one side, this does not affect our main conclusion that when commuter parking takes the form of employer-provided parking, the merits of FAVs may be more limited than expected because of the extensive margin of parking space demand (number of employees willing to commute by car and park). On the other side, relieving land that was formerly devoted to parking for other uses may induce spatial effects, in particular positive agglomeration economies.

Second, because of the aggregate nature of the approach, we cannot say anything about the impact of self-driving cars on workplace parking for particular firms, respectively locations. To do so, data on the distribution of commuting distances/times across workers and information on local particularities (e.g. parking costs at and in the vicinity of the workplace) are indispensable. Then it would be possible to concretely determine the channel through which employees may benefit from self-driving cars (e.g. whether returning home would be an option at all) and, based on this, to assign case-sensitive orders of magnitude to the parameters and variables determining the market level of employer-provided parking under emerging self-driving vehicle technology [see the terms captured by (33)–(35)].

Notes

1 See Duarte and Ratti (2018) for some illustrative examples.

2 Greenberg *et al.* (2017) provides orders of magnitude for a sample of US metropolitan areas.

3 Under plausible assumption, the monthly costs (including planning, construction, land, recurring operation and maintenance) of parking structures amount to at least $180 per parking space (Rivadeneyra *et al.*, 2017; Shoup, 2017). Brueckner and Franco (2018) report that commuter parking spaces provided by the US firms have net worth of several billions of dollars.

4 Throughout the paper, employer-provided parking, employer-paid parking and workplace parking are used synonymously.

5 Policymaking may even become more complicated (Tscharaktschiew and Evangelinos, 2022).

6 See e.g. Brueckner and Franco (2018), De Borger and Wuyts (2011), Fetene *et al.* (2016), Gutiérrez-i-Puigarnau and van Ommeren (2011), and van Ommeren *et al.* (2006).

7 One can imagine that the work package is formed either through direct negotiation between employer or employee or is the result of a "silent" agreement, meaning that the employee is almost invisibly compensated for the fringe benefit through lower wages (Brueckner and Franco, 2018).

8 Public transport crowding imposes disutility on transit riders in several ways, e.g.: less personal space; feeling of invasion of privacy because of physical proximity of fellow travelers; limited access to certain amenities of the vehicle; smell; loss in productivity for passengers being unable to work while standing; concerns about biosecurity and hygiene; the requirements to wear a mask.

9 The available evidence suggests that cruising-for-parking is very substantial in many regions around the world (Shoup, 2006; Inci *et al.*, 2017; Dalla Chiara and Goodchild, 2020). Hampshire and Shoup (2018) summarize the results of 22 studies of cruising in 15 cities. They found that between 8% and 74% of the traffic was cruising for parking, and the average time to find an on-street parking space ranged between 3.5 and 14 min. On average, 34% of traffic was cruising, and the average time it took to find a space was 8 min.

10 One can think of the comfort not to be worried about finding a right parking space in time, having the opportunity to depart later from home in the morning on account of a guaranteed parking right, having the chance to park even outside working hours, status effect, etc.

11 For example: having the car in view from office, secure parking, having the car immediately available if suddenly needed, in case of parking garages having the car protected from vandalism and adverse weather conditions, having the possibility to recharge the electric vehicle at the workplace etc.

12 A number of studies examine the impacts of pricing workplace parking, put differently, of switching from employer-paid to employee-paid parking (Brueckner and Franco, 2018; De Borger and Wuyts, 2009; Evangelinos *et al.*, 2018; Khordagui, 2019; Marsden, 2006; Pons-Rigat *et al.*, 2020; Shoup, 1997; Shoup and Willson, 1992; Willson and Shoup, 1990). As outlined in the introduction, employer parking typically takes the form of employer-paid parking, so we follow this path.

13 One reason is that workers with long commutes are more likely to fall ill, e.g. because of increased fatigue (Koslowsky *et al.*, 2013), and are therefore more likely absent for sickness reasons than workers with short commutes (Künn-Nelen, 2016; Zenou, 2002).

14 If it were strictly binding for all levels of type-e employment, parking demand could be satisfied by the initial supply caused by the parking standard. In this case, the regulation would turn the marginal cost of parking into a fixed cost through bundling the cost of parking spaces into the total cost of development and the firm would bear no extra parking cost when hiring another type-e worker (Shoup, 1999; Inci, 2015). Minimum parking requirements are more common in the USA than in

Europe where they are usually not binding or not existing (Kodransky and Hermann, 2011; van Ommeren and Wentink, 2012). However, even in the USA, cities are considering to relax or even eliminate the regulation (Hess and Rehler, 2021).

15 Appendix 1 shows the derivatives in more detail.

16 See the arguments presented in the introduction. For a formal elaboration of the $F^{*} > F^{**}$ proposition, see in particular Brueckner and Franco (2018) and Tscharaktschiew and Reimann (2021).

17 Note that assuming in-vehicle time is used for working rather than leisure would somewhat change the math, but not the main conclusion of the impact of automated vehicle technology on the value of travel time (see below). So the assumption is less restrictive than it seems at first glance.

18 Rashidi *et al.* (2020) and Singleton (2019) provide a discussion on situations in which this might not be case.

19 An essential strategy to exploit these benefits is to stack the FAVs in several rows, one behind the other (Nourinejad *et al.*, 2018). Existing layouts divide the car-park into a number of islands and roadways. The islands are used to store vehicles while the roadways separate the islands and allow cars to maneuver when searching for a desirable parking lot. To ensure that no car gets blocked, islands hold no more than two rows of vehicles in conventional car-park designs which leads to waste of space. With FAV technology, however, the islands can have more than two rows and the roadways can be narrower.

20 In particular the net effect of FAVs autonomous vehicle technology on road traffic congestion is heavily debated in the literature (Fagnant and Kockelman, 2015; Simoni *et al.*, 2019). Basically, the impact of vehicles on road congestion can be separated into two (counteracting) margins of adjustments. The marginal contribution of a single vehicle to travel time delays (intensive margin) and the aggregate number of vehicles on the road (extensive margin). On one hand, automated technologies can improve road network performance by reducing traffic crashes (and the delays they entail) and increasing traffic throughput by making better use of intersections and by ensuring tighter headways between vehicles (Subraveti *et al.*, 2021; Talebpour and Mahmassani, 2016). By allowing vehicles to operate more closely to each other, which will be possible given computers' superior reaction times, this would reduce the intensive margin of road traffic congestion. On the other hand, FAVs will also likely increase the number and the distance of car trips in particular by reducing the burden of driving (see above), by making car-travel more accessible, e.g. to persons not owning cars and those with disabilities (Harper *et al.*, 2016; Zhang *et al.*, 2018), by creating unoccupied trips, and by inducing a demand shift at the expense of traditional public transport services (Kröger *et al.*, 2019).

21 Appendix 2 shows the concrete derivatives.

22 Under the assumption of uniformly distributed preferences, excess supply because of not taxing employer parking as a fringe benefit in kind (implying $\rho = 0$) is $(1/2b)\beta t$. Using the finding of van Ommeren *et al.* (2012) that about one third of observed supply is in excess and assuming appropriate parameter values for β and t (5 €per workday and 0.4, respectiviely) gives us a taste of the magnitude of b, the upper bound of the interval of the idiosyncratic preference for employer-paid parking, which is b = €3 per day.

23 It becomes more clear when making travel sub-utility explicit: $\tilde{v}^{e}\left(\tilde{\theta}^{e}_{q}, (\cdot)\right) - v^{e}\left(\theta^{e}_{Lq}, (\cdot)\right) > 0$ since $\tilde{\theta}^{e}_{q} < \theta^{e}_{Lq}$.

24 We collected the willingness-to-pay estimates for the various stages of vehicle automation and calculated the difference between the final two stages. All values refer to the average willingness-to-pay reported.

25 The negative value found by Rodrigues *et al.* (2021) refers to (highly educated) Portuguese drivers. The estimate implies that individuals are in fact willing to pay less for a self-driving car than for a vehicle featuring the next lower level of autonomy. According to the authors, a possible reason may be that Portuguese drivers attach considerable value to the pleasure of (manual) driving. So the $600 willingness-to pay as found by Morita and Managi (2020) might not be the actual lower bound.

26 An upper bound of roughly $4,000 also seems to be consistent with two further studies. Ellis *et al.* (2016) report an average willingness-to-pay estimate of $6,900 while Laidlaw *et al.* (2018) found that around 60% of the respondents are willing to pay less than $5,000. However, both studies consider willingness-to-pay for full automation compared to conventional vehicles with the current stage of automation technology. Hence, with a higher level of automation as benchmark, lower values than those reported can be expected.

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Appendix 1. Effects of variables on market provision of employer-provided parking (without FAVs)

$$\frac{\partial F^*}{\partial \gamma} = \frac{A^w}{2b} \tag{A.1}$$

$$\frac{\partial F^*}{\partial \eta} = \frac{\left(\theta^w_{Lq} + (1-t)g^{w'}\right)A^w}{2b} \tag{A.2}$$

$$\frac{\partial F^*}{\partial c_P} = \frac{P^w}{2b} \tag{A.3}$$

$$\frac{\partial F^*}{\partial \phi} = \frac{\left(\theta^w_{Ly} + (1-t)g^{w'}\right)P^w}{2b} \tag{A.4}$$

$$\frac{\partial F^*}{\partial z^e} = \frac{1}{2b} \tag{A.5}$$

$$\frac{\partial F^*}{\partial y^w} = \frac{1}{2b} \tag{A.6}$$

$$\frac{\partial F^*}{\partial c_A} = -\frac{1-A^w}{2b} \tag{A.7}$$

$$\frac{\partial F^*}{\partial \psi} = \frac{\left(\theta^w_{Lq} + (1-t)g^{w'}\right)A^w - \left(\theta^e_{Lq} + (1-t)g^{e'}\right)A^e}{2b} \tag{A.8}$$

$$\frac{\partial F^*}{\partial \beta} = -\frac{1-t}{2b} \tag{A.9}$$

$$\frac{\partial F^*}{\partial \rho} = -\frac{t}{2b} \tag{A.10}$$

$$\frac{\partial F^*}{\partial t} = \frac{\beta + (g^e - g^w) - \rho}{2b} \tag{A.11}$$

Appendix 2. Effects of variables on market provision of employer-provided parking (with FAVs)

$$\frac{\partial \tilde{F}^*}{\partial \gamma} = \begin{cases} \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b}\tilde{A}^w & \text{for } S^e = 0 \\ 0 \quad \text{for } S^e = 1 \end{cases} \tag{B.1}$$

$$\frac{\partial \tilde{F}^*}{\partial \eta} = \begin{cases} \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{\left(\theta^w_{Lq} + (1-t)\tilde{g}^{w'}\right)\tilde{A}^w}{2b} & \text{for } S^e = 0 \\ 0 \quad \text{for } S^e = 1 \end{cases} \tag{B.2}$$

$$\frac{\partial \tilde{F}^*}{\partial c_P} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b}\left(\tilde{P}^w\right) \tag{B.3}$$

$$\frac{\partial \tilde{F}^*}{\partial \phi} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{\left(\theta^w_{Ly} + (1-t)g^{w'}\right)\tilde{P}^w}{2b} \tag{B.4}$$

$$\frac{\partial \tilde{F}^*}{\partial \tilde{z}^e} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b} \tag{B.5}$$

$$\frac{\partial \tilde{F}^*}{\partial \tilde{z}^w} = -\left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b} \tag{B.6}$$

$$\frac{\partial \tilde{F}^*}{\partial \tilde{y}^w} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b} \tag{B.7}$$

$$\frac{\partial \tilde{F}^*}{\partial c_A} = -\left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b}\left(1 - (\tilde{A}^w + 2\tilde{S}^w)\right) \tag{B.8}$$

$$\frac{\partial \tilde{F}^*}{\partial \psi} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b}\left(\tilde{A}^w\left[\theta^w_{Lq} + (1-t)\tilde{g}^{w'}\right] + \tilde{S}^w\left[\theta^w_q + (1-t)\tilde{g}^{w'}\right] - \tilde{A}^e\left[\theta^e_{Lq} + (1-t)\tilde{g}^{e'}\right] - \tilde{S}^e\left[\theta^e_q + (1-t)\tilde{g}^{e'}\right]\right) \tag{B.9}$$

$$\frac{\partial \tilde{F}^*}{\partial \tilde{\beta}} = -\left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{1}{2b}(1-t) \tag{B.10}$$

$$\frac{\partial \tilde{F}^*}{\partial \tilde{\rho}} = -\left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\frac{t}{2b} \tag{B.11}$$

$$\frac{\partial \tilde{F}^*}{\partial t} = \left(1 - \frac{1}{2b}|\tilde{\Gamma}|\right)\left[\frac{\left(\tilde{\beta} + (\tilde{g}^e - \tilde{g}^w) - \rho\right.}{2b}\right] \tag{B.12}$$

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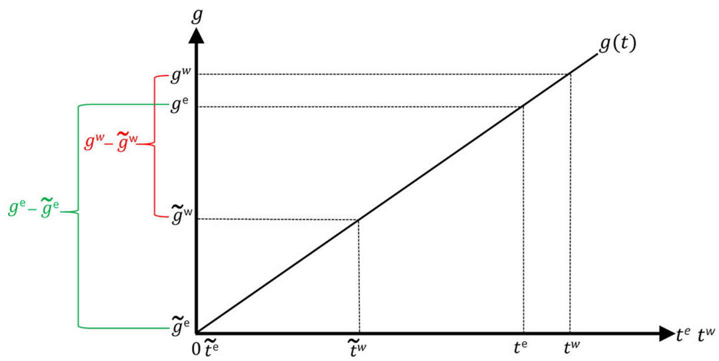
Appendix 3. Sketching the second term in (32)

Figure A1 Impact on productivity



Notes: $g'(t) > 0$ because firms face loss in productivity owing to longer active/stressful commutes of employees $g^w > g^e$ because $t^w > t^e$ (type-w workers have higher door-to-door travel times, provided that road congestion is not too severe) $g^e - \tilde{g}^e > g^w - \tilde{g}^w$ because $\tilde{t}^w >> \tilde{t}^e$ (type-e workers are more car-oriented and so benefit more from FAVs in-vehicle time use)

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