Title

On the build-operate-transfer projects of automated roadways

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Introduction

Autonomous vehicles (AVs) are widely recognized as the solution of future urban mobility (Fagnant & Kockelman, 2015; Schreurs & Steuwer, 2015). Amid the development of AV technology, however, it is increasingly debated that the advantages of AVs can only be fully exploited with the support of automated roadways (Mahmassani, 2016; Aziz, 2018; Li et al., 2020).

Indeed, the automated roadways aim to enhance the AV travels via vehicle-to-everything (V2X) technology. The envisioned automated roadway should include several components and functionality (Figure 1), e.g., roadside units (RSU), roadside sensors, mobile-edge-computing-based (MEC-based) infotainment service and cloud control platform, so as to link individual AVs, the road infrastructure and other road agents seamlessly (*Intelligent Roadside Perception Industry Report*, 2020).

Nevertheless, the upgrade from regular to automated road and its subsequent operations can be costly and technically complex. It is foreseeable that city authorities tend to seek private sectors for both financial and technical support on the automated road upgrade. Meanwhile, more than 40 private corporations globally, ranging from emerging IT giants to car manufacturers, also show strong interests in the industry of vehicle autonomy ("40+ Corporations Working On Autonomous Vehicles," 2020; Shen, 2020; Toh et al., 2020). With the onset of competitions, private sectors wish to seize the initiative to gain benefits from the development of AVs and automated roadways. In other words, AV manufacturers tend to be the stakeholders of automated roads developers, and vice versa.

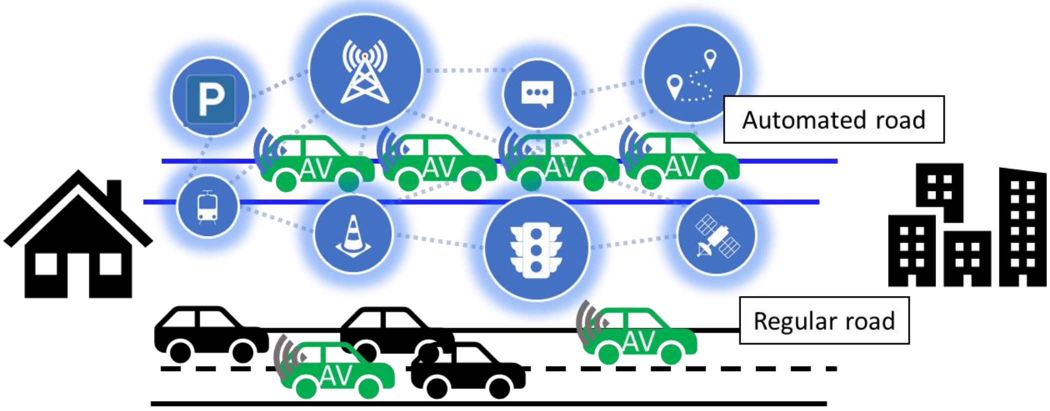

Figure 1 Automated road and regular road in the single O-D corridor.

Therefore, we look at the scenario when city authorities outsource the automated road upgrade projects to private firms, who are also the stakeholders of AV manufacturers. The private firms need to upgrade and operate the automated roadway during the concession period. With a similar process to the regular build-operate-transfer (BOT) projects, we refer to the upgrade of automated roadway as AV-road-BOT for conciseness.

In fact, recent literature has started to examine automated road for AVs. (Chen et al., 2016; Chen et al., 2017a; Chen et al., 2017b; Ghiasi et al., 2017; Liu & Song, 2019; Movaghar et al., 2020). Nonetheless, one critical assumption made is the public ownership of automated road. The infusion of private capitals has not been studied. On the contrary, regarding the regular road construction, there has been a large body of literature focusing on private road franchising (Verhoef et al., 1996; Yang & Meng, 2000; De Borger & Van Dender, 2006; Xiao et al., 2007; Wu et al., 2011; Wang et al., 2013; Feng et al., 2016; Tan et al., 2016; Bao et al., 2017). Yet all these studies are conducted in the context of regular road, rather than automated roads.

However, though with similar concepts, it is worth noting that the AV-road-BOT is distinct from regular BOT in fourfold aspects. Firstly, being stakeholders of AV manufacturers, private firms yield profits from not only the automated road service but also the AV car sales. Secondly, instead of simple charges per usage, private firms of automated road provide *en-route* technical supports to AV manufacturers with royalty fees, which is passed on to AV consumers. Thirdly, in addition to social travel cost minimization, city authorities aim to boost the AV penetration to enlarge social welfare. Fourthly, the anticipated evolvement of AV penetration also indicates that the latent demand for automated roads is no longer a constant as were often assumed in the studies of regular BOT.

In view of these essential differences between AV-road-BOT and regular BOT and thereby the underlying research gaps, for the first time, we model and examine the AV-road-BOT explicitly. The questions will be thoroughly addressed on how private firms in AV-road-BOT would make decisions differently from those in regular BOT, how travellers respond regarding AV usage and route choice, and more importantly, how government can utilize AV-road-BOT to maximize the social welfare.

Methodology and results

As shown in Figure 2, a multi-phase tri-level model is developed in a city corridor with a proportion $\theta^a \in [0,1]$ of automated roads (lanes), encapsulating the interplay between three groups of players (city authority, private firm and travellers).

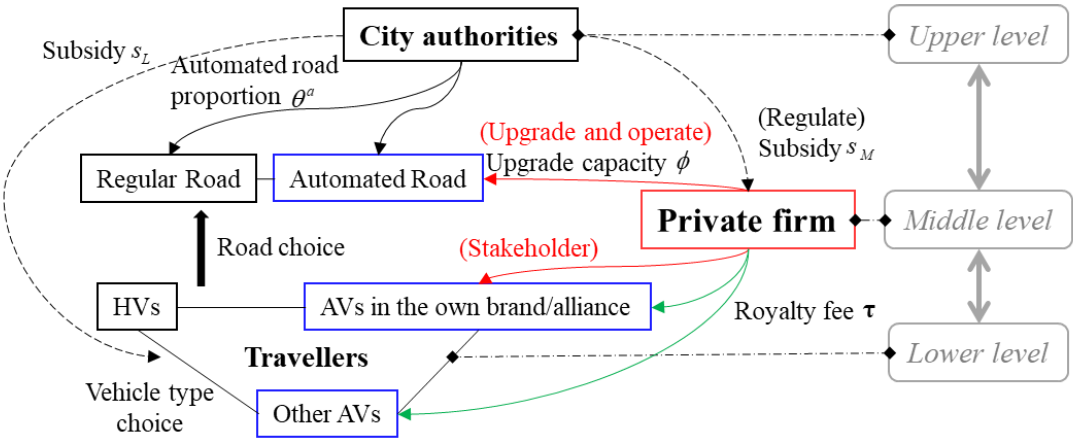

Figure 2 The diagram of AV-road-BOT.

Foremost, in the lower level, the equilibrium travel behaviours of $N\left(=\sum_m N_m\right)$ myopic travellers are examined with given vehicle type m ($m=\mathrm{H}$ for HVs, A1 for AVs in the own brand or alliance of private firm, and A2 for other AVs), choosing from their available roads r ($r=a$ for automated roads and h for regular roads). At user equilibrium, no travellers in the same vehicle type can reduce his/her travel cost by changing routes unilaterally, i.e.,

$$\left(t\left(v^r,c^r\right)-t_m^*\right)x_m^r=0,\ x_m^r\geq 0,\ t\left(v^r,c^r\right)-t_m^*\geq 0, \sum_m x_m^r=v^r \text{ and } \sum_r x_m^r=N_m .$$

An *ex-ante* royalty fee $\boldsymbol{\tau}$ per phase is further imposed on automated road users. By the end of each phase, travellers can reselect their vehicle type based on their net utilities $\mathbf{u}$.

Next, in the middle level, the market behaviours of the private firm in AV-road-BOT are scrutinized. With given traveller structure, private firm determines road capacity increase ϕ via adjusting the investment $I(\phi)\theta^a$. Additionally, differentiated royalty fee $\boldsymbol{\tau}$ is adopted to privilege its own AVs from other AVs. It also gains revenue from upgrade subsidy and AV car sales. Hence, the private firm's profit at each phase is

$$p = \sum_{m=A1,A2} \tau_m N_m + s_M + yN_{A1} - I(\phi)\theta^a .$$

Besides, private firm's AV market share $\frac{N_{A1}(T)}{1-N_H(T)}$, as well as the overall AV penetration $\frac{1-N_H(T)}{N}$, are endogenously determined by travellers' net utilities $\mathbf{u}(T-1)$, which is enclosed in a nested logit diffusion of innovation (DOI) model. We notice that with different objectives (profit maximization or market share increase) at phase T, the private firm has different design strategies on $\phi(T)$ and $\boldsymbol{\tau}(T)$.

Last but not least, in the upper level, city authority predetermines θ^a to be outsourced and regulates the private firm in AV-road-BOT. With the target of AV penetration, city authority designs the subsidy plan (s_L, s_M) for both AV travellers and the private firm to incentivize the popularization of AV and automated roads. From the dimensions of social travel cost, total public payoffs, level of service (v/c) and AV penetration, we compare the performance of AV-road-BOT to two benchmark cases with rigorous proofs. One benchmark is the revenue-neutral road upgrade without private capitals and the other studies the regular BOT by an independent firm without conflict of interest in AV sales. We further illustrate the AV-road-BOT over the entire period with numerical examples.

It is observed that during the early phases with low AV market penetration, due to the similar interest in AV promotion, it is socially beneficial to introduce private sectors in AV-road-BOT. In the latter phases, nonetheless, regulations should be imposed on the private firm to manage the level of service. Besides, the private firm in AV-road-BOT is more passionate in automated road investment than that in regular BOT due to the larger profit sources. Lastly, numerical examples exemplify that AV-road-BOT accelerates the adoption of AVs with unchanged total public payoffs.

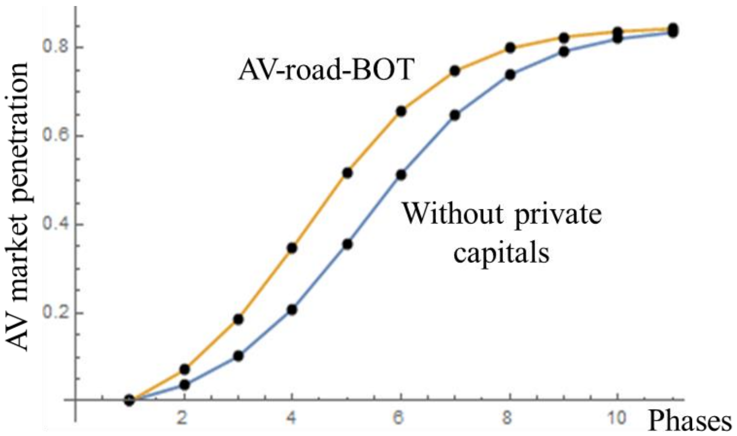

Figure 3 The evolution of AV penetration with AV-road-BOT (Numerical examples).

Conclusion

This paper explicitly examines the AV-road-BOT in a multi-phase tri-level model while explicitly considering three groups of players. The strength and weakness to introduce private AV stakeholders in the upgrade and operation of automated road are fully identified, offering managerial insights for city authorities to better leverage on private capitals towards vehicle autonomy.

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