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Autonomous cars and dynamic bottleneck congestion: The effects on capacity, value of time and preference heterogeneity

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A B S T R A C T

'Autonomous cars' are cars that can drive themselves without human control. Autonomous cars can safely drive closer together than cars driven by humans, thereby possibly increasing road capacity. By allowing drivers to perform other activities in the vehicle, they may reduce the value of travel time losses (VOT). We investigate the effects of autonomous cars using a dynamic equilibrium model of congestion that captures three main elements: the resulting increase in capacity, the decrease in the VOT for those who acquire one and the implications of the resulting changes in the heterogeneity of VOTs. We do so for three market organizations: private monopoly, perfect competition and public supply. Even though an increased share of autonomous cars raises average capacity, it may hurt existing autonomous car users as those who switch to an autonomous car will impose increased congestion externalities due to their altered departure time behaviour. Depending on which effect dominates, switching to an autonomous vehicle may impose a net negative or positive externality. Often public supply leads to 100% autonomous cars, but it may be optimal to have a mix of car types, especially when there is a net negative externality. With a positive (negative) externality, perfect competition leads to an undersupply (oversupply) of autonomous cars, and a public supplier needs to subsidise (tax) autonomous cars to maximise welfare. A monopolist supplier ignores the capacity effect and adds a mark-up to its price.

1. Introduction

'Autonomous cars' are cars that drive themselves and have an automated speed choice. They can drive closer together and at more uniform speeds than 'normal' human driven cars. All else being equal, a group of autonomous cars can move at a greater density for any given speed than 'normal cars', thereby increasing the capacity of roads (Chang and Lai, 1997). Besides this favourable capacity effect, people adopting an autonomous car instead of a normal car may gain a decrease in their value of travel time (VOT) as time in the car can be spent on other activities besides driving. This makes travel time more useful and lowers its costliness. As a result, the VOT may become more heterogeneous for a mix of drivers using normal and autonomous cars. Such heterogeneity may alter the effects of introducing autonomous cars and of policies such

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Nomenclature

α	Value of time (VOT) for normal car users: the cost of an hour of travel time.
β	Value of schedule delay early: the cost of an hour earlier arrival than the preferred arrival time t^*.
γ	Value of schedule delay late: the cost of an hour later arrival than the preferred arrival time t^*.
δ	Compound preference parameter: $\delta \equiv \beta\gamma/(\beta+\gamma)$.
θ	VOT reduction parameter for an autonomous car: the VOT for an autonomous car is $\theta \cdot \alpha$ with $\beta/\alpha < \theta < 1$.
ΔC	Change in travel cost when switching from a normal car to an autonomous car: $\Delta C = C_a - C_n$.
C_i	Travel cost for car type $i = \{a, n\}$ with $_a$ indicating an autonomous car and $_n$ a normal car. Travel cost is the sum of free-flow travel time cost and bottleneck cost, which equals the queuing time cost plus the schedule delay cost.
CB	Bottleneck cost equals the queuing time cost plus the schedule delay cost.
f	Fraction of users with an autonomous car.
MC_a	Marginal automobile cost of the autonomous car. The corresponding cost for a normal car is set to zero. MC_a gives how much higher or lower the sum of the fuel cost and per trip marginal production cost is for an autonomous car.
MEB	Marginal external benefit of marginally increasing the number of the users with an autonomous car; it equals the change in travel cost minus the change in average social cost: $MEB = \Delta C - (\partial TTC/\partial f)/N$.
MU_a	Per trip mark-up on the autonomous car. The mark-up on the normal car is normalised to zero.
N	Total number of users.
P	(Generalised) price equals the travel cost plus the per trip marginal automobile cost and the mark-up.
$r[f]$	Function determining the effective bottleneck capacity for autonomous cars of $s/r[f]$.
s	Bottleneck capacity for a normal car.
t	Arrival time.
t^*	Preferred arrival time.
t_e	Moment that the last car arrives and thus the peak ends.
t_s	Moment that the first car arrives and thus the peak starts.
TT	Travel time, which equals free-flow travel time plus queueing time.
TT_{ff}	Free-flow travel time.
TTC	Total travel cost of $N \cdot (f \cdot C_a + (1-f)\, C_n)$.
TC	Total cost of $TTC + f \cdot N \cdot MC_a$.

as congestion pricing and capacity expansion. It also enforces the relevance of considering distributional effects of policies (see, e.g., Arnott et al. (1988), Lindsey (2004) and Van den Berg and Verhoef (2011a, b)).

Autonomous cars may also lead to fewer accidents, to a smaller or larger total car fleet, to fewer parking spots, to higher speed limits, and to reduced fuel use.[1] There are also potential problems, including the question of liability for accidents, reliability, loss of privacy, and risks of hacking of autonomous cars. For more detailed overviews see Anderson et al. (2014) and Fagnant and Kockelman (2015).

Autonomous cars can be expected to have a considerable influence on urban transport and in the long run on the layout of our cities. This explains the strong interest of policymakers, the media and the general public in autonomous cars as a solution to our transport problems. This paper investigates the welfare impacts of the uptake of autonomous cars. It concentrates on how autonomous cars affect congestion via three channels: the resulting increase in capacity, the decrease in the VOT and the implications of the resulting changes in the heterogeneity of the VOT. We do not consider heterogeneity other than that due to the decision to obtain an autonomous car or not. The VOT is the same for everyone who has the same car. Section 6 gives an exploratory discussion of some model extensions, including pre-existing heterogeneity. Our focus on the congestion effects of autonomous cars reflects the emphasis this has received in policy debates and the media in a congested country like the Netherlands. We could add differences in environmental or safety externalities between the two types of vehicles. However, from an analytical perspective, this would be rather straightforward and would divert attention from the behavioural and congestion impacts in which we are interested.

We are the first to consider the effects of autonomous cars via the VOT, and to consider autonomous cars with endogenous departure time and car type decisions. To achieve this objective, we use the bottleneck model, as do Lamotte et al. (2016). They also have an endogenous choice of car type. However, they have separate roads for normal and autonomous cars and assume that autonomous cars cooperate by having a departure rate equal to the capacity of their road. In their setting, autonomous cars do not affect preferences. Levin and Boyles (2016) use a cell transmission model to study the route choice equilibrium with autonomous and normal cars, but the choices of departure time and car type are exogenously fixed.

[1] If only autonomous cars use a road, it may become possible to redesign it: e.g., to reduce lane widths and turn a two-lane highway into a three-lane one.