Effects of Autonomous Vehicles on Highway Congestion

Introduction

Autonomous vehicles (AVs) can potentially change the way we live, leading us to rethink nearly everything related to transportation, from the way we design our urban areas to how we spend our commute time. Thus, it is important to thoroughly investigate various effects of this new generation of vehicles on our lives and our societies.

In this paper we focus on one particular effect: we investigate how the large-scale production of AVs will affect highway congestion. AVs potentially have several advantages over human drivers with respect to highway driving. Since they are able to communicate with each other, AVs move (and brake) more smoothly, and in general have smaller reaction times than human-driven (regular) vehicles. This allows AVs to reduce their inter-vehicle gap in highways, and travel together in larger platoons (or batches) than regular vehicles. While these should be advantages, it is unknown how highway congestion will change if AVs are allowed on highways, or how they will affect regular vehicle traffic. Various policies have been proposed to regulate AVs on the roads, yet no in-depth comparison of these policies exists. We address these shortcomings.

As a benchmark, we first model a segment of a highway as a queueing model in the absence of AVs. We then propose two models for a highway with both regular vehicles and AVs: the designated-lane policy and the integrated policy. Under the designated-lane policy, one lane is designated to AVs, to separate them from regular vehicles. Under the integrated policy, AVs travel together with regular vehicles.

Model

Benchmark. We model traffic flow on a segment of a highway as an $M/G_n/c/c$ queueing model. Vehicles arrive individually to the segment, according to a Poisson process, and the service time of a single vehicle is defined as the amount of time the trip takes from the beginning of the segment to the end of it. This travel time, and hence the speed of a vehicle, depends on the state of the queueing system which is defined as the number of vehicles present on the segment. Thus, we use the state-dependent speed of vehicles as a measure of a service rate. The capacity $c$ of this segment is the maximum possible number of vehicles on the segment when flow comes to a stop (forming a jam). We assume a vehicle that finds $c$ other vehicles on the segment upon its arrival turns away, possibly taking an alternative route.
Designated-lane policy. Under this policy the highway is divided into two separate $M/G_n/c_1/c_1$ and $M/G_n/c_2/c_2$ (where $c_1 + c_2 = c$) queues: one for regular vehicles, and another for AVs that constitute a proportion of vehicles. The regular vehicle queue is similar to that of the benchmark model, except it has one fewer lane. The AV queue has one lane, in which AVs form larger platoons with smaller inter-vehicle headways than regular vehicles. At a fixed vehicle density a smaller headway leads to a higher speed, so AVs drive faster than an equally congested group of regular vehicles. To model the speed of AVs we utilize a Markovian arrival process (MAP), which connects the three correlated variables that affect the mean headway: the headway between two vehicles (intraplatoon headway), the headway between two consecutive platoons (interplatoon headway), and the size of platoons. The calibration of our MAP to data is described below. Note that despite the name Markovian Arrival Process we use our MAP to control the formation of platoons, not the arrival of vehicles to the stretch of highway we consider; as mentioned above arrivals occur according to a standard (homogeneous) Poisson process.

Integrated policy. Under this policy we have one $M/G_n/c/c$ queue, where a proportion of arrivals to the highway are AVs. Regular vehicles and AVs jointly use the segment, so the headway between any pair of consecutive vehicles is affected by the types of these two vehicles. There are four different pairs: AV-AV, AV-regular, regular-AV, and regular-regular, where X-Y means vehicle X is followed by vehicle Y. We incorporate these different possible pairings into our MAP, extending it to model the headway (and the speed) of the integrated policy, again calibrating it with data.

Model Calibration

The arrival rate to a highway can differ depending on the highway location, but the speed of vehicles primarily depends on the number of vehicles currently driving on the highway, so we focus on estimating the state-dependent speed of vehicles. First, we estimate this value in the benchmark model (see Figure
1(a)) as well as the regular vehicle queue in the designated-lane policy based on data from highways in Arizona (Arizona DOT 2017). Next, we estimate the speed of vehicles in the AV queue of the designated-lane policy and the integrated policy. Because these policies are yet to be implemented in reality, we set the intraplatoon headway, the interplatoon headway, and the platoon size equal to the parameter values used in the field experiments of AVs, see for example Amoozadeh et al. (2015). Using these values, we are able to estimate the speed of vehicles under these policies.

**Results**

We show that the designated-lane policy outperforms the benchmark case only when both the arrival rate and the AV proportion are high; see Figure 1(b). This is different from recent industry proposals: For example, Bierstedt et al. (2014) propose that at the beginning of the mass appearance of AVs, i.e. when the AV proportion is relatively low, one lane of highways should be designated for AVs. The Colorado Department of Transportation (CDOT) is also considering a proposal for assigning one lane to AVs (Aguilar 2018). However, our analysis shows that this policy may not work very well for small AV proportions. For example, in a 3-lane highway, dedicating one out of three lanes to AVs leads to a lower mean travel time than the benchmark case only when AVs constitute at least 60% of vehicles: In order for the designated-lane policy to reduce the mean travel time, a majority of vehicles need to be AVs! This can only be expected to occur a number of years after AVs first appear on highways.

Next, we prove that the performance of the integrated policy is always better than the benchmark case. According to Bierstedt et al. (2014) when the fleet mix is at least 75% AVs, the integrated policy will make a tangible difference by achieving 25 -- 35% reduction in the mean travel time. In contrast, we observe that even a small proportion of AVs decreases the mean travel time under this policy, and for a highway with a mild to heavy arrival rate, a 50% decrease in the mean travel time is achievable by having only 15 -- 30% AVs. We offer insights into the underlying drivers of this result.

**References**


