LEMUR: Fall 2017 Research Proposal

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Introduction

Traffic jams are responsible for billions of dollars in losses and wasted energy. Although traffic jams occur when vehicle density exceeds a certain threshold, they may also occur without any trigger at all. The instability of equilibrium flow in traffic systems is a fundamental consequence of the way humans drive – their reactions to drivers in front of them causes small perturbations to propagate down a single chain of vehicles and amplify.

Autonomous vehicles present an opportunity to mitigate this problem as they can be programmed to behave in a manner as to prevent disturbances from equilibrium flow from magnifying, thus halting the propagation of a traffic wave. However, it will be a long time before autonomous vehicles fully replace human drivers, and in the near future human drivers and autonomous vehicles will be sharing the same roads.

In mixed autonomy situations, it is still possible for autonomous vehicles to improve traffic flow. If we can program autonomous vehicles to influence people to drive better, they may attenuate traffic waves and improve vehicle throughput. Advances in autonomous vehicle technology provide us with the opportunity improve safety, get people to their destinations faster, and dramatically increase the capacity of existing highways without requiring major overhauls or additions to our transportation infrastructure.

Previous Work

Dynamic modeling of traffic jams has been a subject of research going back to the 1930's [1]. The most used models in research today are the (OVM) [3] and the Intelligent Driver Model (IDM) [4]. In both models, a traffic system consisting of N vehicles is modeled as a $2N$ dimensional system of ordinary differential equations which can be solved numerically to predict the formation and behavior of traffic jams. The OVM is discussed in more detail in the technical overview section.

Both the IDM and OVM reproduce the ability of traffic jams to form spontaneously, an important feature which has been observed in real world experiments [2]. The spontaneous formation of traffic jams suggests that jams occur not only when the capacity of a given road is exceeded but is a fundamental consequence of the instability of the system [8], which can be seen in various mathematical models. Any small perturbation from the equilibrium condition will propagate down a string a vehicles and magnify[5].

As a result, we can view the problem of managing traffic as a control problem, where an unstable process must be stabilized by controlling some 'actuator'. Traditionally these 'actuators' are placed a fixed locations along a highway and include systems such as variable speed limits [6] and ramp meters [7]. The drawback of these systems is that they have limited flexibility and require modifying transportation infrastructure, thus making them prohibitively expensive.

Advances in self driving technology provide the opportunity to use autonomous vehicles as 'mobile actuators', where vehicles sharing the road with drivers halt the propagation of traffic waves and attenuate oscillations of the system. Recent work has focused on connected systems [9, 10, 11], where a number of cars equipped with a vehicle-to-vehicle communications system cooperate to control the system.

However, recent experiments conduct by Daniel Work et al. suggested a small number of vehicles acting independently may dissipate stop and go waves on highways. [12]. In the paper, a controller called the FollowerStopper designed to target a specific velocity successfully attenuated oscillations on a ring road consisting of 20 vehicles.

The controller requires precise knowledge of the characteristic velocity of the system, which is a function of vehicle density, in order to achieve optimal performance. In their field experiments, this velocity was known ahead of time, but it is unlikely that a vehicle operating in real world conditions would have access to this information. Hence the problem of identifying the correct velocity for a controller to target is still open.

Big Picture Overview

Our research builds on the results of Daniel Work et al. The goal is to develop a controller for a single autonomous vehicle capable of completely dissipating stop and go waves on a ring road. It has been shown that with prior knowledge of the density of the vehicles in a system, a controller designed to maintain a given velocity computed from this density may fully attenuate any oscillations. Hence, the problem may be reduced to identifying global information about a system using only local measurements available to the autonomous vehicle.

Using numerical simulations, our first objective is to collect data on traffic jams in varying situations. We will then use machine learning to develop a model that associates traffic jams with the characteristic velocity of the system. With this model, we then design a controller for an autonomous vehicle capable of identifying the characteristic velocity in real time, while simultaneously trying to maintain this velocity. Finally using simulations we hope to demonstrate that this controller is just as effective at attenuating traffic jams as the one designed by Work et al. while being flexible enough to operate in a variety of conditions.

Techincal Overview

We model traffic behavior as a dynamical system called the Optimal Velocity Model. It consists of N vehicles on a circular road of length L, arranged so that vehicle i is immediately behind vehicle $i-1$. A pair (x_i, v_i) describes the state of each vehicle where x_i gives the position of the front bumper of the car, and v_i gives the velocity. Let l be the length of the vehicle (for simplicity we can assume that l is the same for each car). We define the headway of vehicle i as the bumper to bumper distance to the vehicle in front, given by $h_i = x_{i-1} - x_i - l$ for $i = 2, \ldots, N$ and $h_1 = (x_N + L) - x_i - l$. The dynamics of the system obey:

$$\begin{aligned} \dot{x}_i &= v_i \\ \dot{v}_i &= \alpha \left(V(h_i) - v_i \right) + \beta \dot{h}_i \end{aligned}$$

where α and β are constants, and $V : \mathbb{R}^+ \to \mathbb{R}^+$ is the optimal velocity function describing the velocity vehicle i wants to maintain given the headway is h. Typically, V is chosen such that the following properties are satisfied

1. There exists a minimum headway $h_{\min} > 0$ such that $V(h) = 0$ for all $h < h_{\min}$.

2. There exists a maximum speed $v_{\max}$ such that $V(h) \to v_{\max}$ as $h \to \infty$.

3. V is nondecreasing

Generally in most literature on traffic modeling, V is defined piecewise such that $V(h) \equiv 0$ for $h < h_{\min}$, $V(h) \equiv v_{\max}$ for $h > h_{\max}$ and for $h_{\min} < h < h_{\max}$, V is one of the following:

$$V(h) = v_{\max} \left[\frac{h - h_{\min}}{h_{\max} - h_{\min}} \right] \tag{1}$$

$$V(h) = \frac{v_{\max}}{2} \left[1 - \cos\left(\frac{\pi (h - h_{\min})}{h_{\max} - h_{\min}} \right) \right] \tag{2}$$

Suppose that at $t = 0$ the vehicles are evenly spaced and the headway between any two of the vehicles is $\bar{h}$. Then the system admits the solution:

$$\begin{aligned} x_i(t) &= x_i(0) + V(\bar{h})t \\ v_i(t) &= V(\bar{h}) \end{aligned}$$

We refer to solutions where the velocity is constant as uniform flow. Generally the uniform flow solution is unstable unless the spacing $\bar{h}$ is close to $h_{\min}$ or $h_{\max}$, and small perturbations cause the system to settle to oscillatory solution (traffic jam).

Our objective is to attenuate the oscillations in the system by replacing one of the vehicles with an autonomous vehicle that can be programmed to behave according to $\dot{v}_i = f(h_i, \dot{h}_i, v_i)$ for any function f of our choice. For instance, we might choose f so that the controller tries to maintain a velocity of V^* except when approaching the vehicle in front. Under the choice of f above, all solutions converge to a uniform flow with a velocity of V^* if we choose $V^* \leq V(\bar{h})$, but for $V^* > V(\bar{h})$ oscillations are still present(this has also been verified in physical experiments [**?**, 12]).

Ideally we would choose $V^* = V(\bar{h})$ as this maximizes vehicle throughput while attenuating oscillations. In practice, however, the full state of the system is not known by the autonomous controller. We assume that the only information that we have access to is the vehicles own state, h, and $\dot{h}$. Under these constraints, how do we determine the optimal choice for V^*?

We remark that given a fixed value of N, a traffic system may be characterized by specifying either the length of road, L, or the average distance between vehicles $\bar{h}$. Essentially we are using these quantities as proxies for the vehicle density in order to determine the appropriate velocity to target – smaller densities allow for larger velocities V^*, with the largest velocity being $V(\bar{h})$. So the equivalent question we may ask is: given the response of a single vehicle, $v_i(t)$, how do we determine the parameter L of the system from which it was generated?

Project Timeline

- Week 3: Collect more data on traffic jams. Implement n-PWL approximations for traffic jams for arbitrary n. Familiarize myself with Tensorflow.
- Week 4: Perform linear regression on n-PWL, implement basic feedforward network in Tensorflow.
- Week 5-6: Experiment with more sophisticated machine learning methods, including recurrent neural nets / LSTM. If successful, begin integrating machine learning with existing controllers.
- Week 7: Collect data on new controller's ability to improve traffic flow. Write up results for possible paper submission.
- Week 8: Proofread and revise writeup. Literature review on connected vehicle problem.
- Week 9-10: TBD

References

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