Dissipation of Traffic Waves

Rahul Bhadani

Stop-And-Go Traffic

Experimental Design

Workflow for Controller Design

Velocity controllers

Conclusion

Analysis and Design of Velocity Controllers for Dissipation of Stop-and-Go Traffic Waves

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Outline

1. Stop-And-Go Traffic
2. Experimental Design and Test Setup
3. Workflow for Controller Design
4. Velocity Controllers to Dissipate Traffic Waves
5. Conclusion

Stop-And-Go Traffic

- Prominent phenomenon on highways with heavy traffic
- Can be interpreted as non-equilibrium physical system of moving particles with asymmetric interaction.
- Can be modeled as many-particle system: instability occurs by enhancement of fluctuations
- Occurs when average vehicular density exceeds a critical threshold; gives rise to traffic waves.
- Human drivers tend to overreact in response to brake slammed by the driver ahead.

Stop-And-Go Traffic

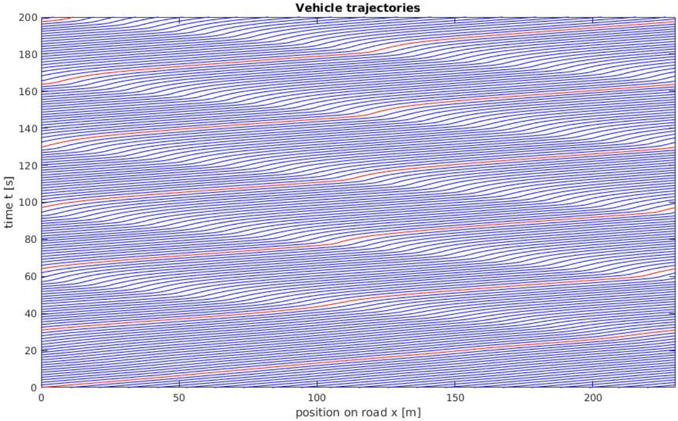


Figure : Traffic waves via simulation of car-following model

Experimental Design

Test Track

- A single lane circular track of circumference 260m.
- Single autonomous test vehicle (called as CATVehicle) per 20-22 normal cars.

Sensors and Hardware used

- ROS based framework to communicate with CATVehicle's actuator.
- CATVehicle equipped with SICK LMS 291 Lidar sensor to measure the distance of the leading vehicle; we measured the distance along the trajectory.
- A 360-degree camera placed at the center of track to record experiment.

Workflow for Controller Design

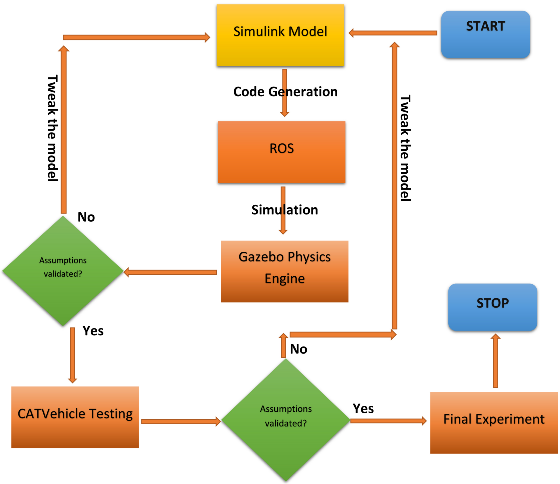


Figure : Workflow for designing controller and software

Workflow for Controller Design

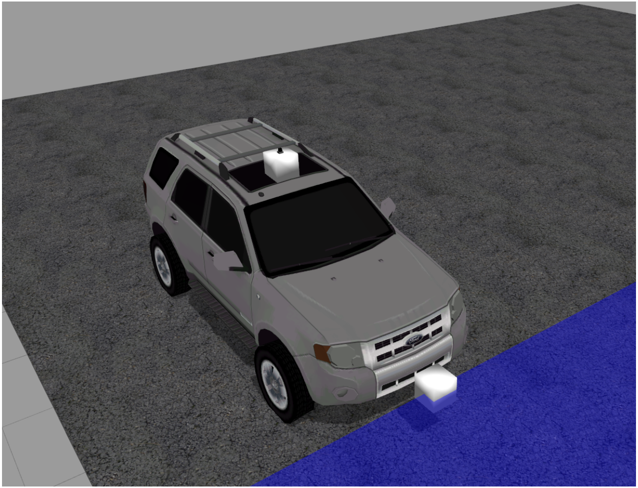


Figure : A gazebo model for CATVehicle in simulation

Supervisory Controller Based on Quadratic Band Called as Followerstopper

Premise

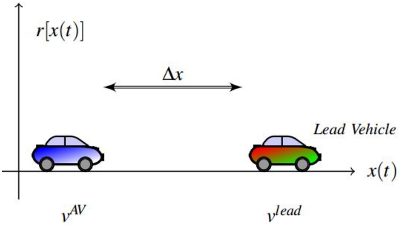
Command exactly desired velocity U whenever safe otherwise $v_{cmd} < U$ based on v_{lead}, the leader's velocity.

Definitions

Δx: gap between front bumper of the CATVehicle and rear of the lead vehicle as a function of time in meter.

$\Delta v = \frac{d}{dt}\Delta x$: relative velocity of the lead vehicle wrt CATVehicle

$v_{lead} = \Delta v + v_{AV}$ where v_{lead} is the estimated velocity of the lead vehicle and v_{AV} is the velocity of CATVehicle.



Followerstopper Controller

Quadratic bands of followerstopper have the $\Delta v - \Delta x$ phase space divided into three regions:

- A safe region where $v_{cmd} = U$
- A stopping region, where a zero velocity is commanded
- An adaptive region, where weighted average of the desired velocity and the lead vehicle's velocity is commanded. This adaptive region has two parts.

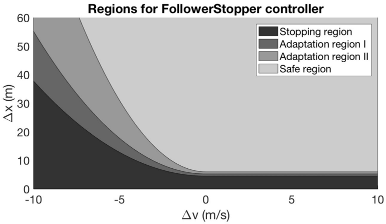


Figure : Regions defined in FollowerStopper controller

Followerstopper Controller

The boundaries between regions are parabolas in the $\Delta v - \Delta x$ phase space (trajectories that the AV-lead vehicle pair would traverse when decelerating at constant rates), defined as

$$\Delta x_j = \Delta x_j^0 + \frac{1}{2d_j}(\Delta v_-)^2 \quad (1)$$

where j = 1, 2, 3 and $\Delta v_- = min(\Delta v, 0)$ which ensures that when CATVehicle starts falling behind, $v_{AV} = v_{lead}$.

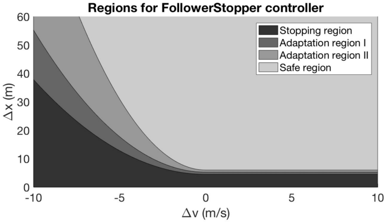
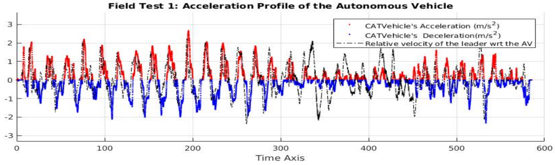
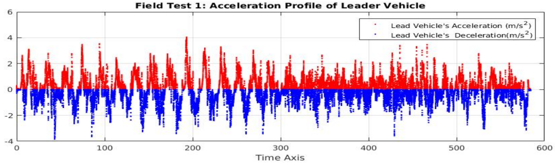


Figure : Regions defined in FollowerStopper controller

Followerstopper Controller: Design Consideration and Parameter Choices

Test run (from physical experiment) to determine good values for parameters:





Frequent oscillations observed in the acceleration profile with fairly high amplitude in CATVehicle (driven manually for this set of experiment) as well as in the lead vehicle.

Followerstopper Controller: Design Consideration and Parameter Choices

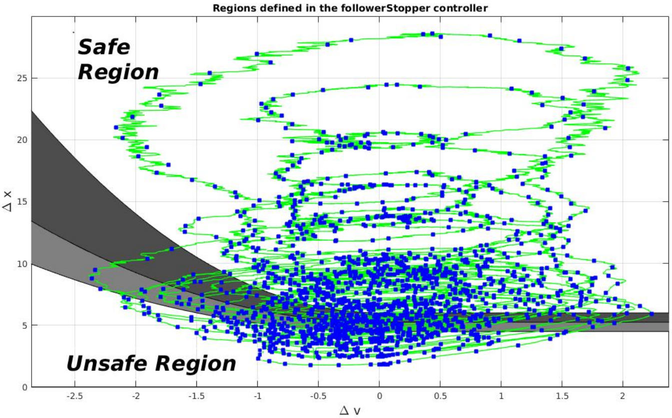


Figure : Phase-space plot of the test run : CATVehicle spends significant time in the unsafe region which represents non-uniformity in traffic flow.

Followerstopper Controller

Based on the region boundaries defined in previous slides, our commanded velocity function looks like as follows:

$$U_{\text{command}} = \begin{cases} 0, & \text{if } \Delta x \leq \Delta x_1 \\ v \frac{\Delta x - \Delta x_1}{\Delta x_2 - \Delta x_1}, & \text{if } \Delta x_1 < \Delta x \leq \Delta x_2 \\ v + (U - v) \frac{\Delta x - \Delta x_2}{\Delta x_3 - \Delta x_2}, & \text{if } \Delta x_2 < \Delta x \leq \Delta x_3 \\ U, & \text{if } \Delta x_3 < \Delta x \end{cases} \tag{2}$$

where $v = min(max(v_{lead}, 0), U)$ is the lead velocity if positive or desired velocity, whichever is the smaller.

From our observations made through experiments, we chose $\Delta x_1^0 = 4.5m$, $\Delta x_2^0 = 5.25m$ and $\Delta x_3^0 = 6.0m$ and deceleration values $d_1 = 1.5m/s^2$, $d_2 = 1.0m/s^2$ and $d_3 = 0.5m/s^2$ using number of separate tests both using simulations and real world experiments.

Followerstopper Controller: Results from 22 Cars Experiment

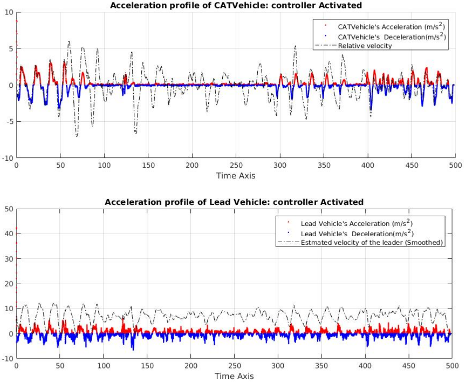


Figure : Controller activated at t=126s & stays active upto t=463s. Oscillations in acceleration profiles is almost gone

Followerstopper Controller: Results from 22 Cars Experiment

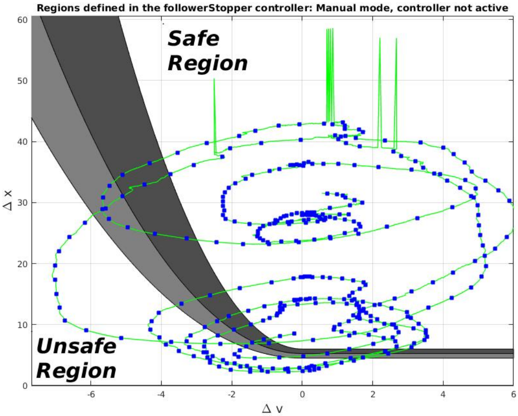


Figure : Plot showing portion time from t=0 to t=126s when controller was off. Significant amount of time spent in unsafe region.

Followerstopper controller: results from 22 cars experiment

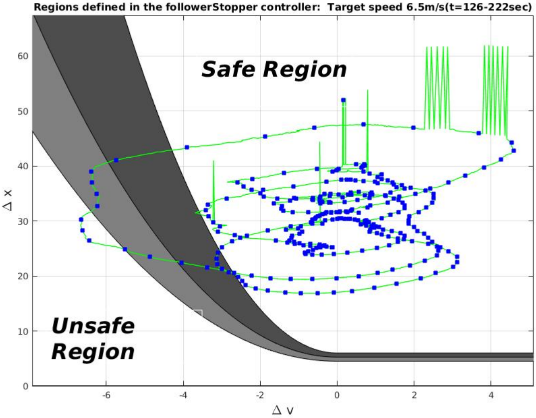


Figure : Controller activated with target speed of 6.5 m/s at t=126s. CATVehicle comes in unsafe region but quickly pulls back in safe region.

Followerstopper Controller: Results from 22 Cars Experiment

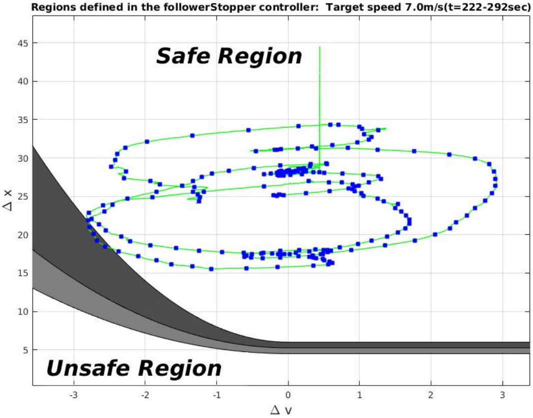


Figure : Target speed set to 7.0 m/s at t=222s. In this duration CATVehicle didn't do any unsafe manoeuvres.

Followerstopper Controller: Results from 22 Cars Experiment

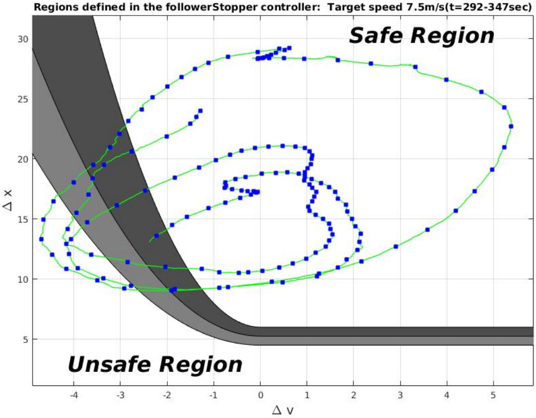


Figure : Target speed set to 7.5 m/s at t=292s. CATVehicle quickly corrected for safe manoeuvres.

Followerstopper Controller: Results from 22 Cars Experiment

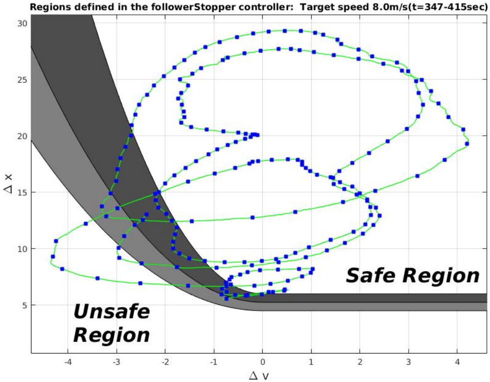
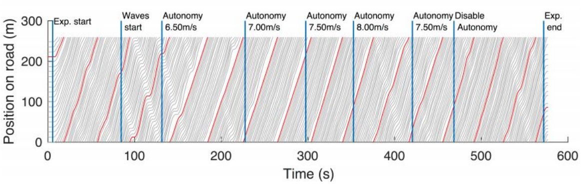
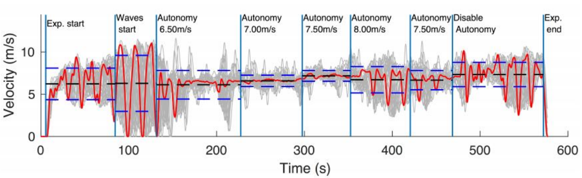


Figure : Target speed set to 8.0 m/s at t=347s. CATVehicle quickly corrected for safe manoeuvres.

Followerstopper Controller: Results from 22 Cars Experiment



(a) Trajectories of all vehicles in Experiment A, CAT Vehicle shown in red.



(b) Velocity profiles of all vehicles (gray) and the CAT Vehicle (red) in Experiment A. Horizontal blue dashed lines are one standard deviation above and below the mean speed of traffic in the interval.

Figure : Trajectories and standard deviation in velocity

The PI with Saturation Controller

Main idea

Estimate the desired velocity U as the temporal average of CATVehicle's own velocity over a large enough temporal and drive according to the estimated average speed.

$$U = \frac{1}{m}\sum_{j=1}^{m} v_{AV_j} \tag{3}$$

The PI with Saturation Controller

- Deviation from the average speed : error signal in PI controller.
- Paired with saturation to avoid dangerous situations as well as filling up the gap.

Desired velocity is translated into target velocity as a function of gap between CATVehicle and the lead vehicle as follows:

$$v_{target} = U + v_{catch} \times min(max(\frac{\Delta x - g_l}{g_u - g_l}, 0), 1) \qquad (4)$$

The PI with Saturation Controller

The new velocity command is chosen as weighted average of prior commanded velocity, the target velocity given by the equation in the previous slide and the lead vehicle's velocity:

$$v_{j+1}^{cmd} = \beta_j(\alpha_j v_j^{target} + (1-\alpha_j)v_j^{lead}) + (1-\beta_j)v_j^{cmd} \tag{5}$$

where j is index of time steps and

$$\alpha = min(max(\frac{\Delta x - \Delta x^s}{\gamma}, 0), 1) \tag{6}$$

and

$$\beta = 1 - \frac{1}{2}\alpha \tag{7}$$

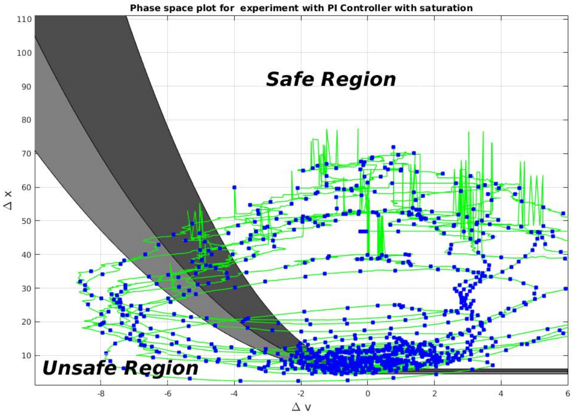
where Δx^s is a safety distance and γ controls how fast α transitions from 0 to 1.

The PI with Saturation Controller: Parameter Choices

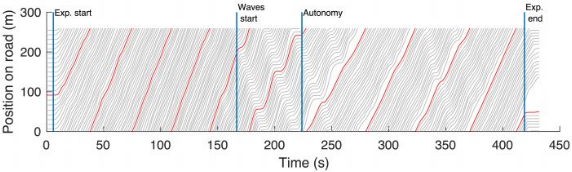
- Lower gap limit $g_l = 7$m, $g_u = 30$m.
- $v_{catch} = 1$ m/s
- $\Delta x_s = \max(2\text{s X } \Delta v, 4\text{m})$ based on 2 second rule with lower bound of 4m.

The PI with Saturation Controller: Results from 22 Car Experiments

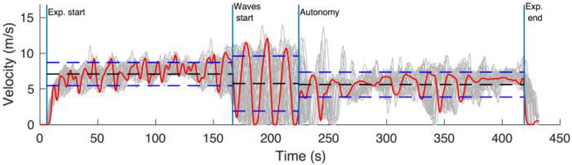
- Phase space analysis of the result



The PI with Saturation Controller: Results from 22 Car Experiments



(a) Trajectories of all vehicles in Experiment C, CAT Vehicle shown in red.



(b) Velocity profiles of all vehicles (gray) and the CAT Vehicle (red) in Experiment C. Horizontal blue dashed lines are one standard deviation above and below the mean speed of traffic in the interval.

Figure : Trajectories and standard deviation in the velocity

Conclusion

- Demonstrates that a simple controller with proper strategy is sufficient to achieve good results.
- Proves that only a sparse number of autonomous vehicles (One in every 20-22 normal vehicles) is enough to control the traffic flow.
- Results show that it mitigates traffic congestions to some extent as well.
- We don't require dedicated actuation infrastructure for controlling the traffic flow.
- Fuel consumption is significantly decreased (approx 42.5%).