# Traffic Flow Theory in the Era of Autonomous Vehicles

**Michael Zhang**

**University of California Davis**

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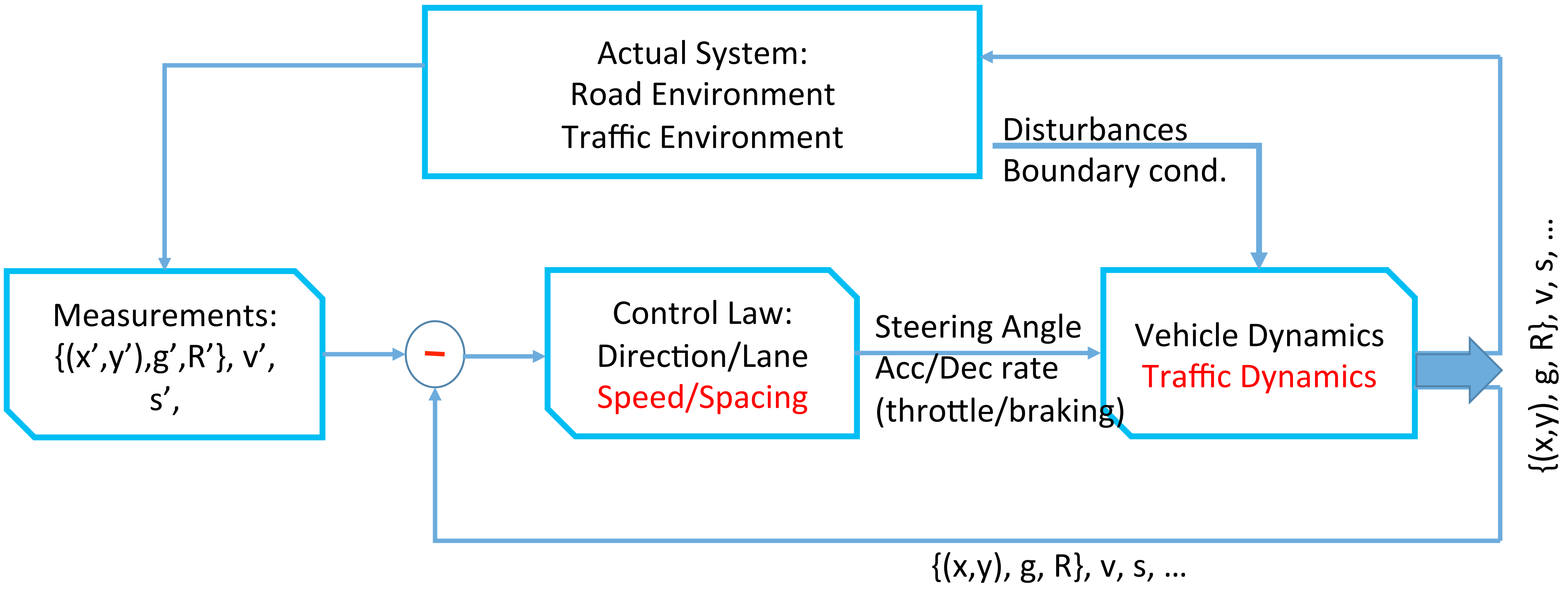
# Outline

- From individual driving to traffic flow
- Prominent features of traffic flow
- Models of traffic flow-human driven vehicles
- Models of traffic flow-autonomous vehicles
- The future of traffic flow

# The Driving Task as Feedback Control



# Human Drivers vs Autonomous Vehicles From A Control Perspective

## Human Drivers

- Sensing is imprecise but more versatile
- Response is slower but more robust
- Best at processing fuzzy information and is highly adaptive
- Strength:  handles complex tasks such as lane tracking, obstacle avoidance more easily

## Autonomous Vehicles (Robo Cars)

- Sensing is more precise but less versatile
- Response is faster but less robust
- Best at exercising precise controls and is less adaptive:
- Strength: handles procedural tasks such as speed control, car following more easily

# The Essence of Traffic Flow Theory is to Infer

- The Speed-Spacing Control Law of Each Driver

$$v_n(t) = \{?\}(s_n(t), \cdots, E)$$

E={speed limits, grades, radius, surface conditions, visibility, ….}

- And the collective dynamics of an OPEN "Many-Particle" Dynamical System with "random" insertions and removals (reflecting LANE CHANGE interactions) controlled by these driver control laws

$$\{x_n(t) = v_n(t),\ n = 1, 2, \cdots, N\}$$

# Example: The California Motor Code Rule

- For every 10 mph of speed, leave one car length of space

- This translates to

$$s(t)-l=v(t)/10\ l\equiv Tv(t)$$

or

$$v(t)=s(t)-l/T$$

with speed limits

$$v(t)=min\{V_f ,s(t)-l/T \}$$

# If Human Drivers are Identical Robots

with super fast reaction time and vehicles capable of infinite acceleration and deceleration

- Micro model

$x\ (t)=v(t)$
$v\ (t)=a(t)$

$a(t)=\{■0,$
$T\ ,\ v(t)<V\downarrow f$

$v(t)=V\downarrow f\ @u(t)-v(t)/$

- Traffic Stream Model (steady-state)

$$V(s)=min\{V\downarrow f\ ,\ s/T\}$$

- Macro (continuum) model (in vehicle coordinate)

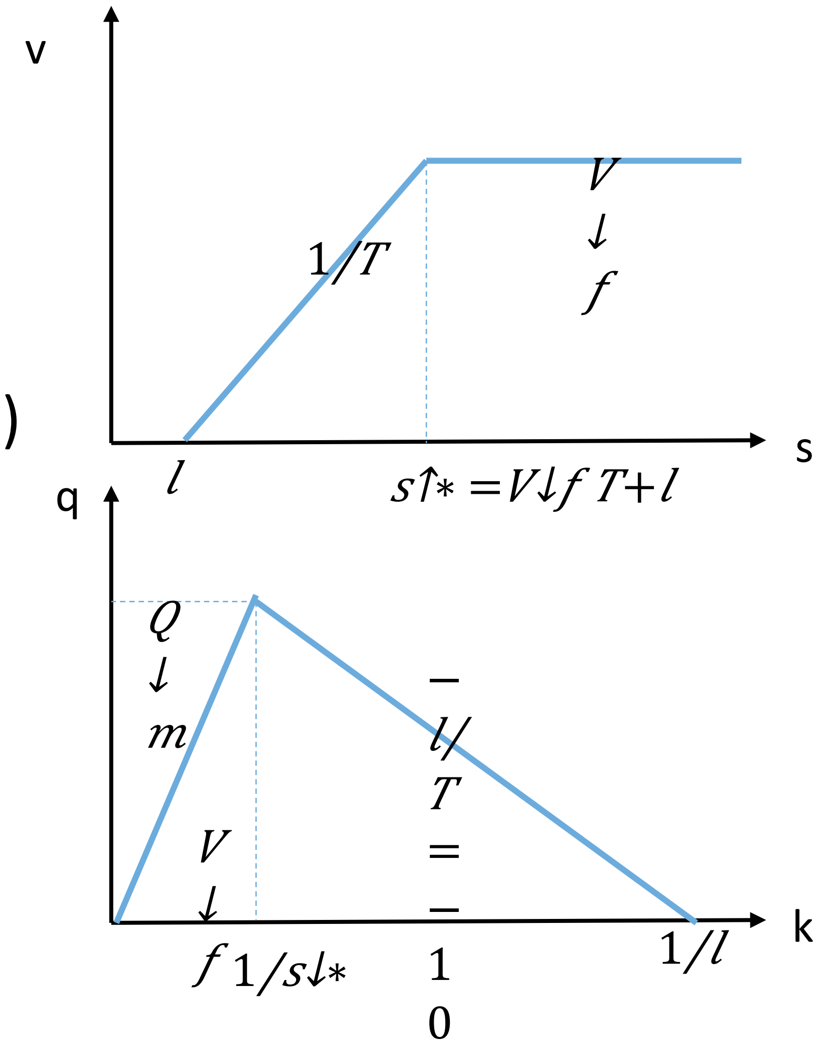
$$s\downarrow t-v\downarrow n=0,\ v=V(s)$$

# What are These Models and what phenomena do they produce?

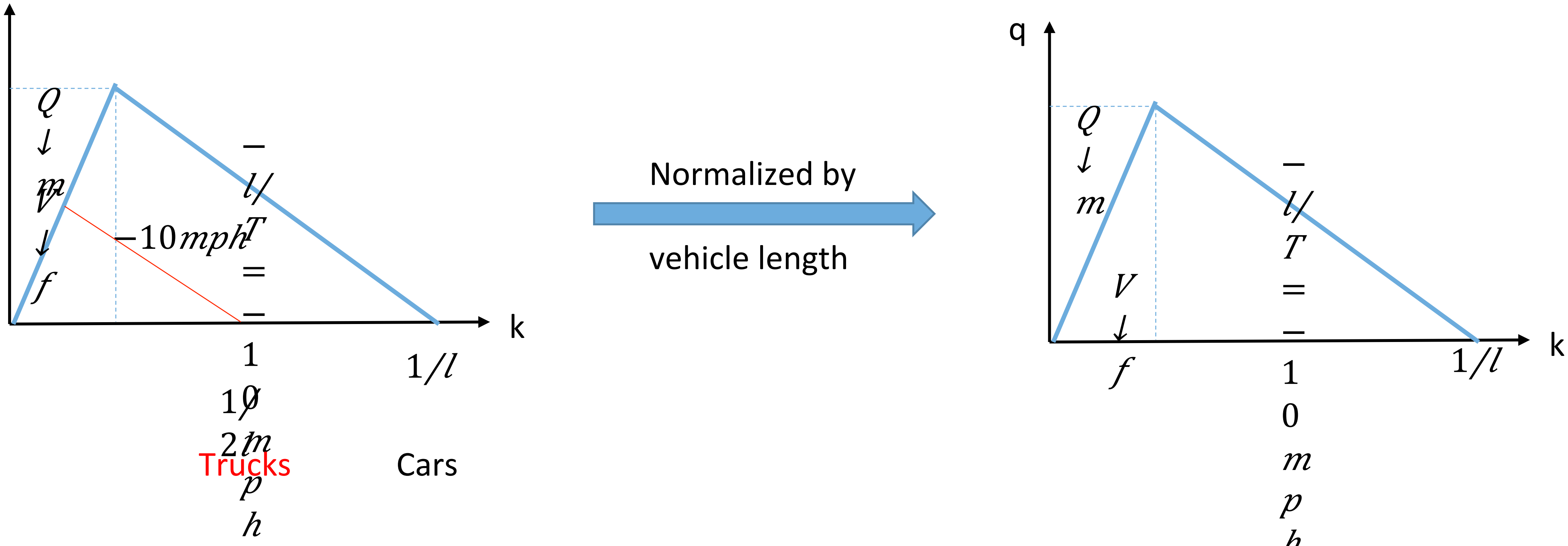
- Micro model: “linear” CF model of Pipes
  - Acceleration waves
  - Deceleration waves
- Stream model:  Triangular FD
  - Capacity: 2640 pcphpl (l=20ft, T=1.36sec, Vf=60mph)
  - Jam wave speed:  -10 mph
- Macro model:  LWR with Triangular FD

$$k_t + Q_x(k) = 0$$

  - Shock waves
  - Expansion (acceleration) waves



# When All Vehicles Follow the Same Rule




The slope of the jam wave speed is a good indicator whether drivers of different type of vehicles follow the same driving rule or not

# In reality, human drivers

- Differ from each other in driving ability and habits
- Cannot assess motion and distances precisely
- Respond with delay and finite acceleration/deceleration
- Do not follow rules exactly

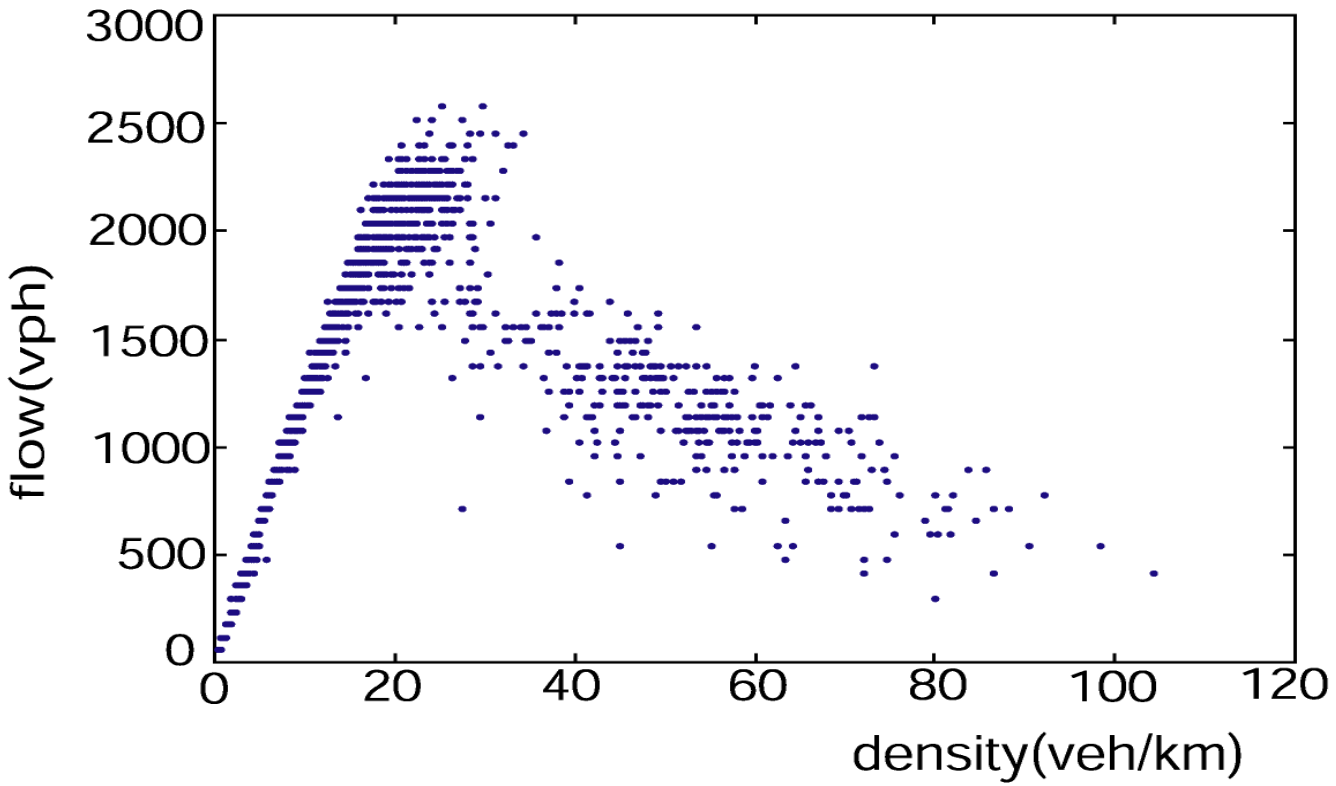
# Consequence:

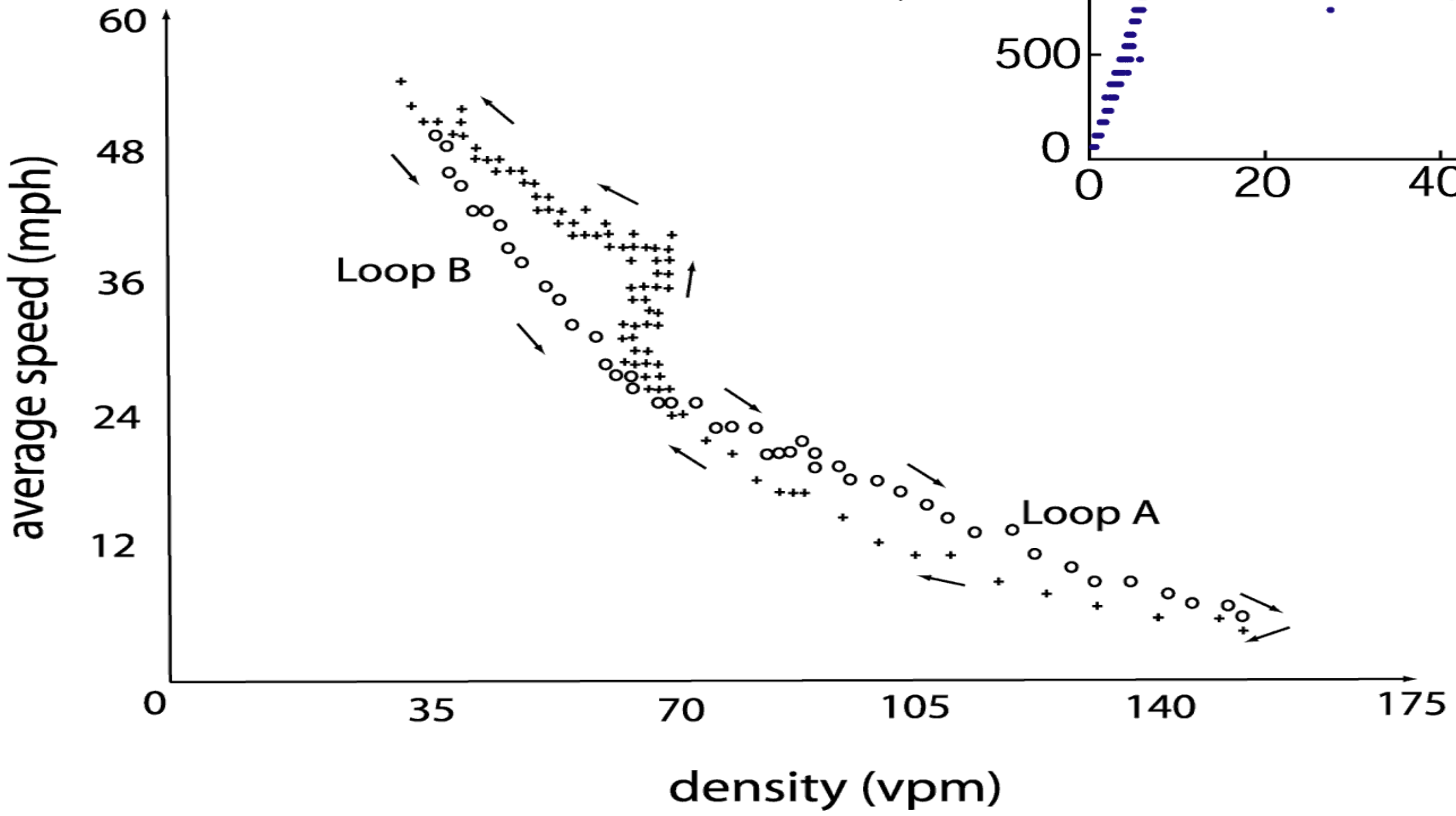
Traffic flow in the real world is much more complex

# Prominent Features of Real Traffic Flow

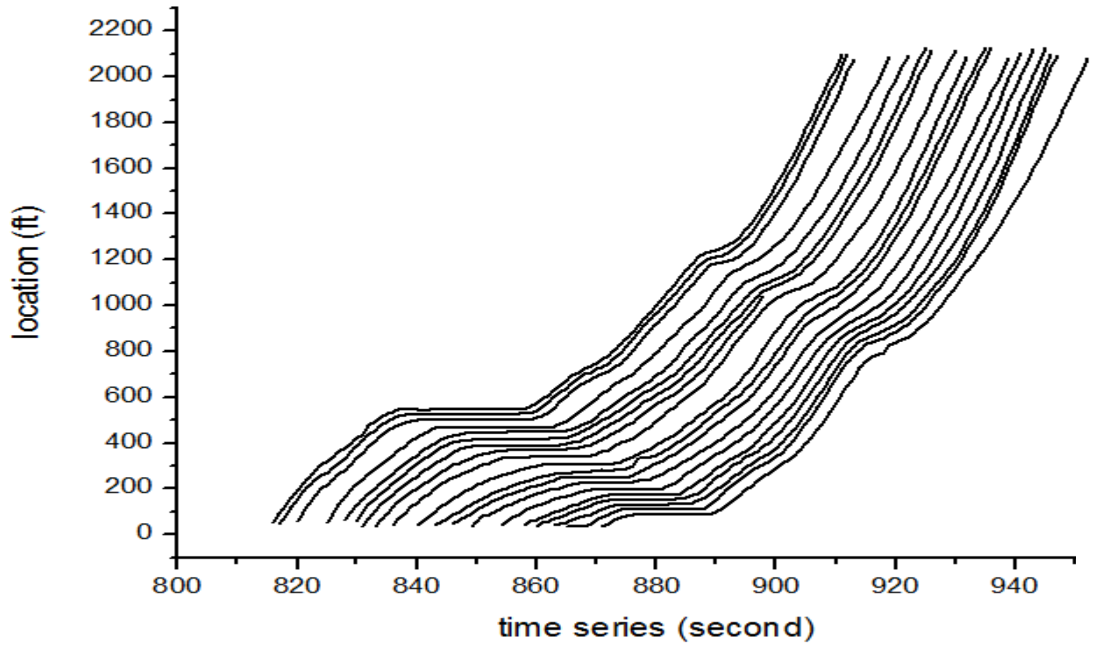
- Phase transitions
- Nonlinear waves
- Stop-and-Go Waves (periodic motion)

# Phase transitions

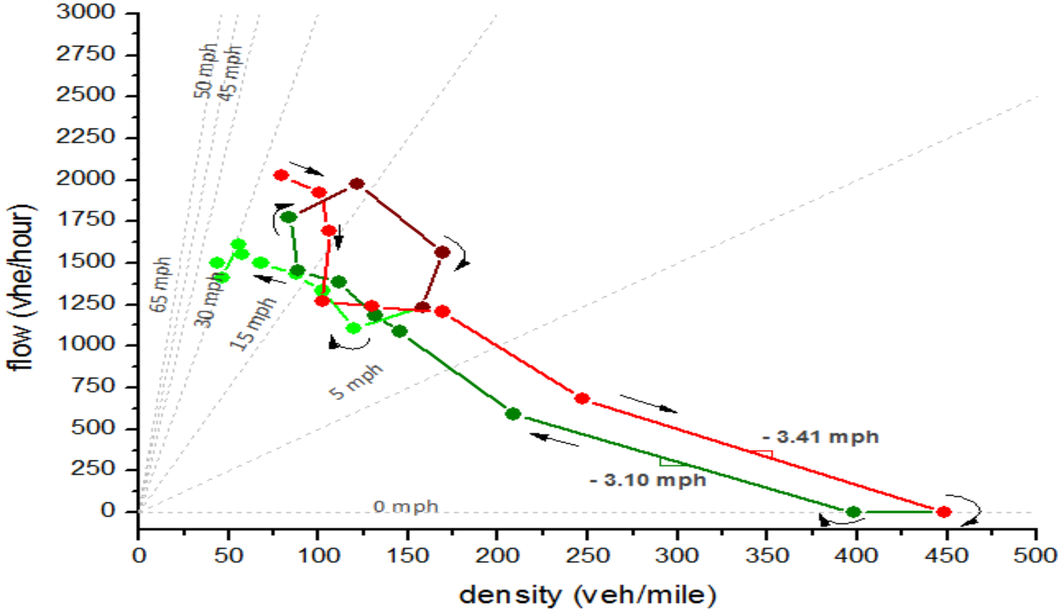


# Nonlinear waves

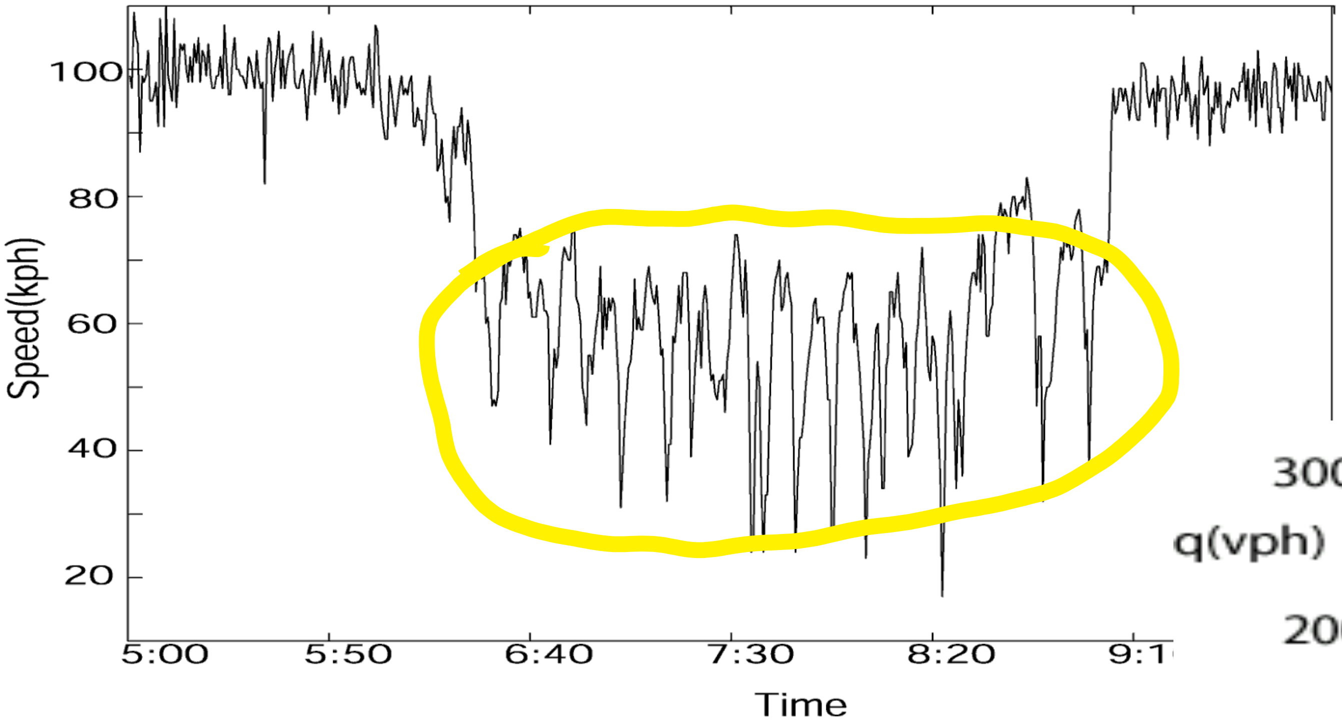



Vehicle platoon traveling through
two shock waves

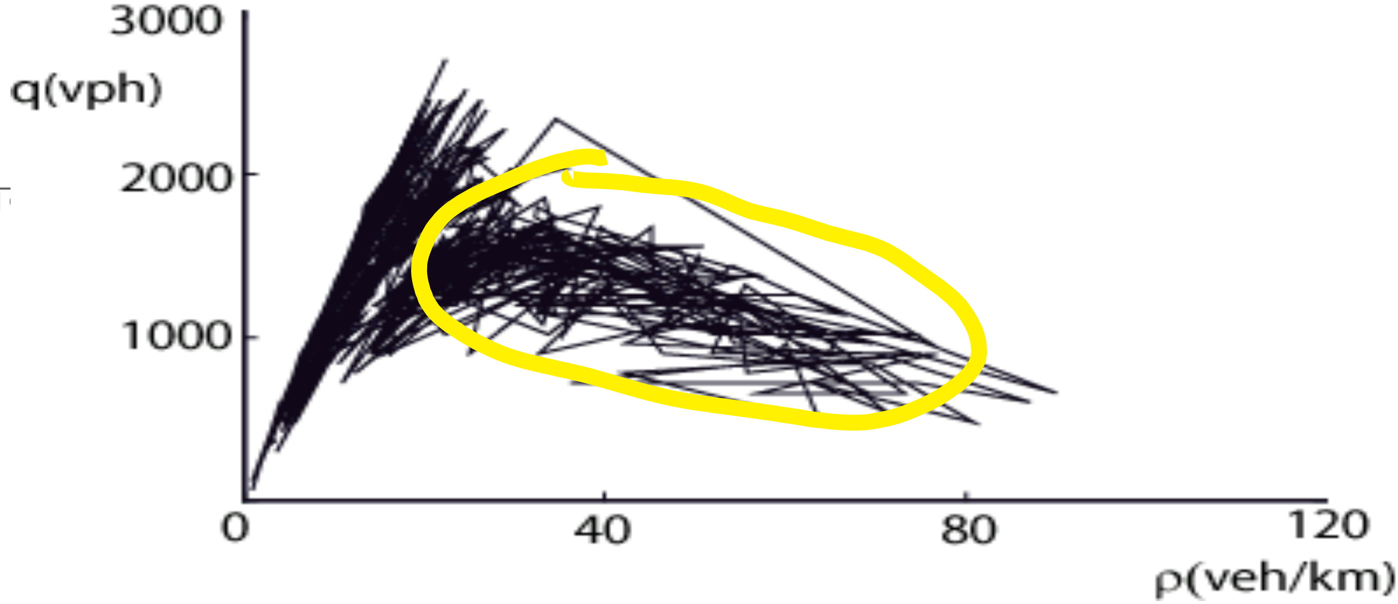



flow-density phase plot

# Stop-and-Go Waves (Oscillations)




Scatter in the phase diagram is closely related to stop-and-go wave motion



# Some Classical Traffic Models

- Microscopic
  - Modified Pipes' model
  - Newell' Model
  - Bando' model

$$\dot{x}_n = \min\left\{v_f, \left(s_n(t) - l\right)/\tau\right\}$$

$$\dot{x}_n(t+\tau) = v_f\left[1 - \exp\left\{-\lambda\left(s_n(t) - l\right)/v_f\right\}\right]$$

$$\ddot{x}_n(t) = a\left[\left(u_*(s_n) - \dot{x}_n\right)(t)\right],\ a = 1/\tau$$

$$\rho = 1/s,\ u_*(s) = v_*(\rho),\ q = \rho v,\ q_*(\rho) = \rho v_*(\rho)$$

- Macroscopic continuum
  - LWR model
  - Payne-Whitham model
  - Aw-Rascle, Zhang model

$$\rho_t + q_*(\rho)_x = 0$$

$$\rho_t + (\rho v)_x = 0, \quad v_t + (vv)_x + \frac{c_0^2}{\rho}\rho_x = \frac{v_*(\rho) - v}{\tau}$$

$$\rho_t + (\rho v)_x = 0,\ v_t + \left(v - c(\rho)\right)v_x = \frac{v_*(\rho) - v}{\tau}$$

$$c(\rho) = -\rho v_*'(\rho)$$

- v-s (speed-spacing) relation is central to all these models

# The Difficulty of Modeling Real Flow

- Each driver is different
- Driving rules are hidden
- Sensing is imprecise
- Behavior is adaptive, nonlinear, and perhaps inconsistent
- (Driving environment is complex)

# When Robo Cars Take Over the Road

- Behavior is uniform and consistent
- Sensing and control is more precise
- Rules are always obeyed
- (Driving environment is still complex)

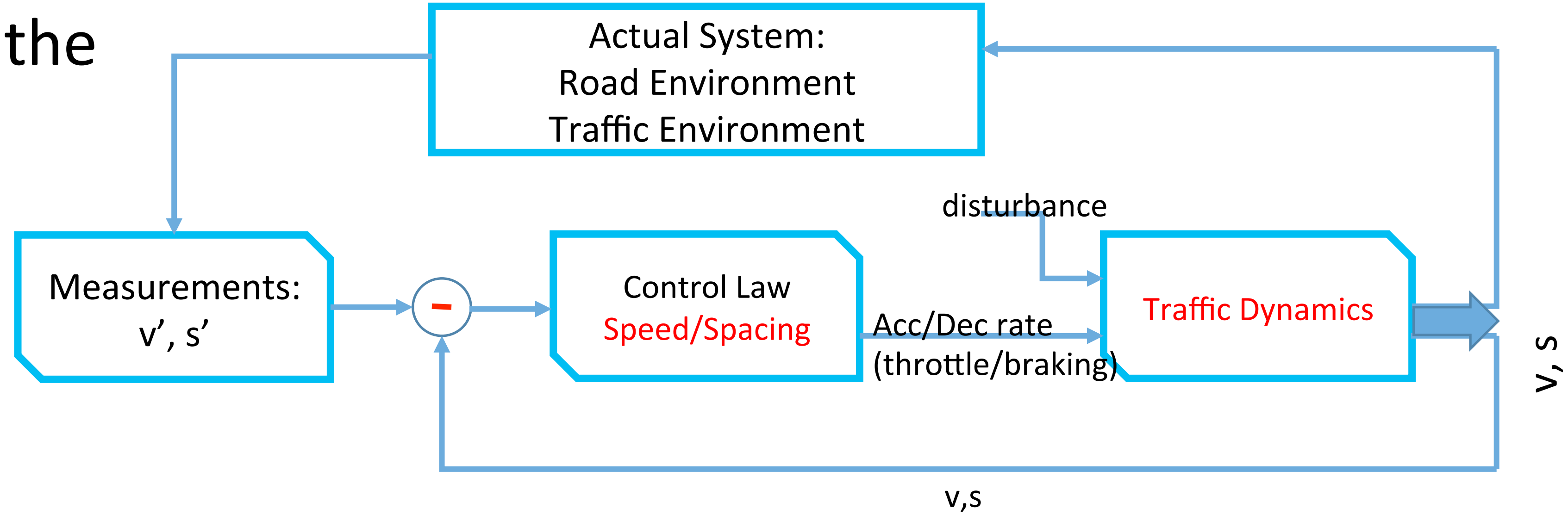
More importantly, driving rules are by design, leaving rooms for optimizing flow and safety → Feedback Control Problem

# Traffic Flow Theory For Robo Cars- Longitudinal Control

- Example RoboCar#1

$$a(t+\tau)=k_r\{V(s)-v\}, V(s)=min\{V_f, s/T\}$$

- Human: $\tau$=1-2s, T=1.36-2s; Robo Car: $\tau$=0.4-0.6s, T=0.8-1.2s, Capacity: $\approx 1/T$, $+70\%$,
- But this may be too rosy a prediction in the initial deployment stage (liability)

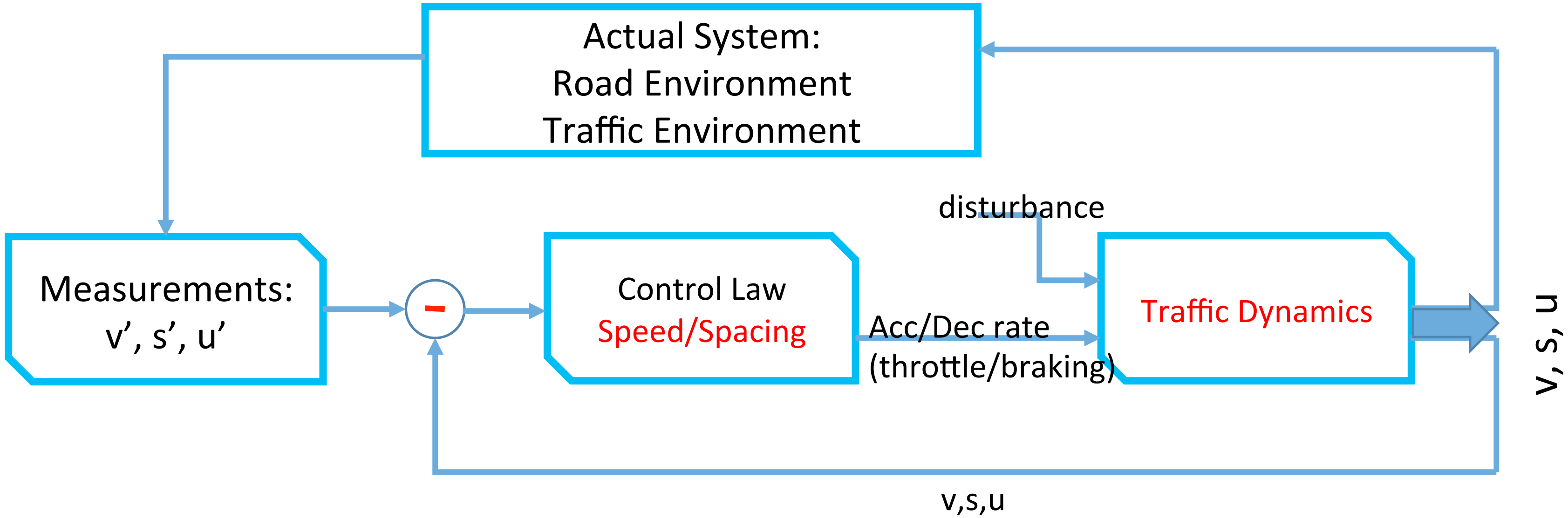


# Example RoboCar#2

$$a(t+\tau)=k_r\{V(s)-v\}+k_v\{u-v\}$$

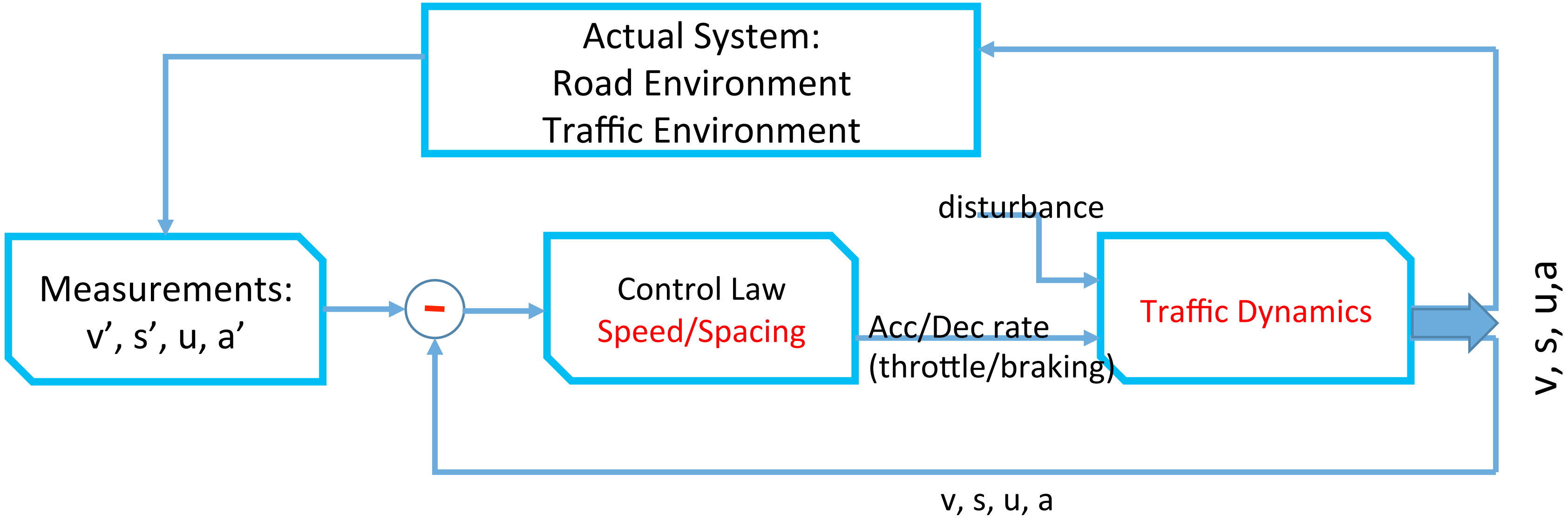
Faster response and higher throughput than RoboCar#1

$\tau$=0.4-0.6s, T=0.6-0.75s



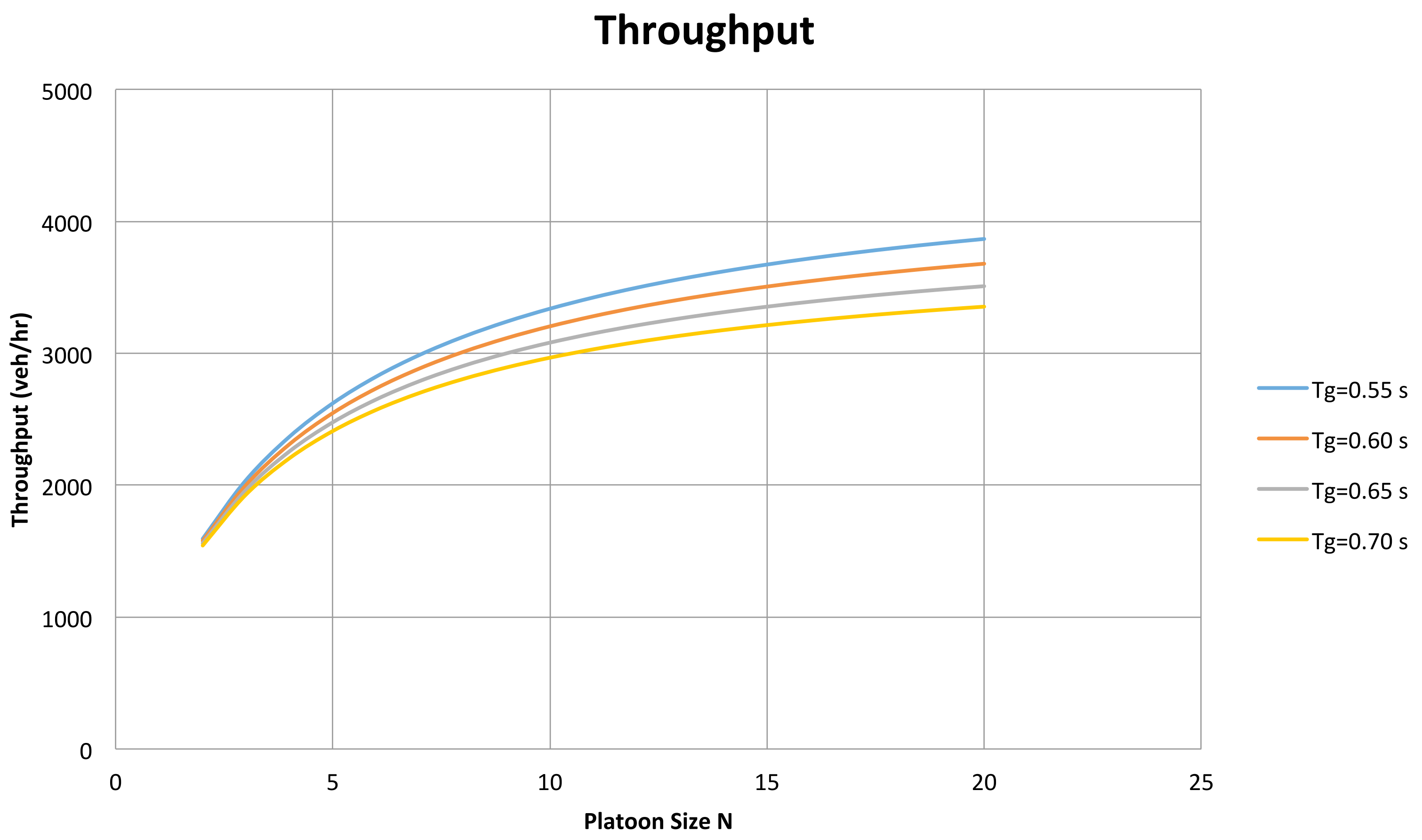
# Example RoboCar#3 (RoboCar#2 with V2V)

$$a(t+\tau)=k_a a_u(t)+k_r\{V(s)-v\}+k_v\{u-v\}$$




And the list goes on: you can come up with other models that meet safety and stability requirements

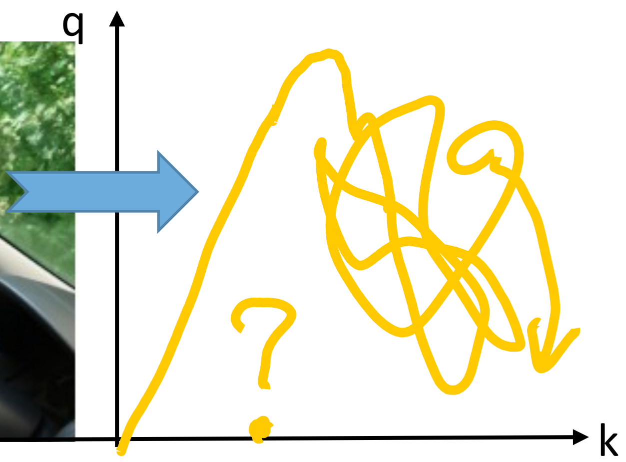
# Expected throughput with vehicle platooning



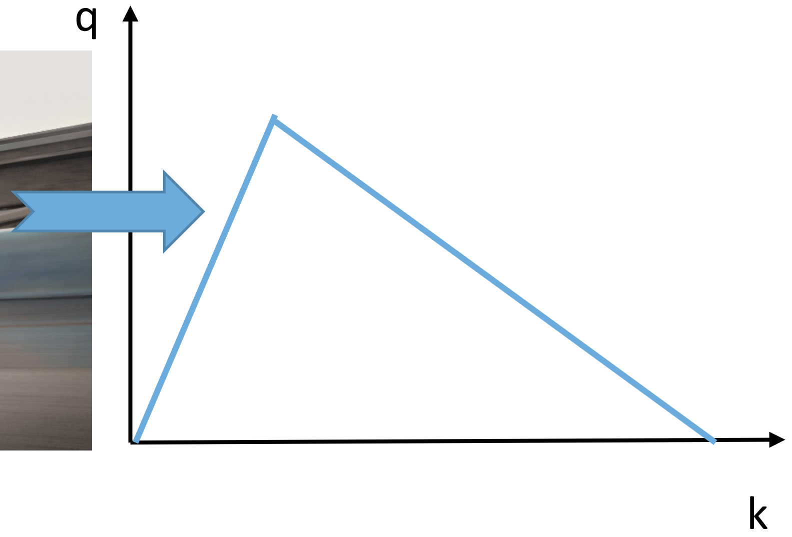

Throughput of CACC platooning with different platoon size and intra-platoon time gap setting

# Future of Traffic Flow Theory Research (1)

- Do the Arrival of Robo Cars Mean The End of Traffic Flow Research?
  - Automation creates uniformity and standardization, suppresses randomness: From billions of drivers to a handful: Google Car, GM Car, Toyota Car ….
  - Behavior of each Robo Car is consistent and known








From Human Drivers to Robots

# Future of Traffic Flow Theory Research (2)

- In the short term
  - design of driving models for Robo cars
  - Robo car friendly infrastructure
- In the intermediate term
  - Mixed traffic with Robo Cars,
  - Platooning of Robo Cars
  - Lightless intersections with in-vehicle signal control
  - Rich micro level data for understanding and modeling traffic, and validating traffic models

# Future of Traffic Flow Theory Research (3)

- In the long term, full automation of highway traffic
  - Optimal scheduling and pricing for congestion free networks
  - Robust Recovery from Disruptions
- New services and shared use of autonomous vehicles
  - Robo Taxi Services
  - Last and first-mile of transit (flexible transit)
  - Seamless integration of multiple modes
  - And the list goes on

# Concluding Remarks

Autonomous Vehicles will

- In the long run bring more order to traffic flow and simplify traffic flow theory
- Produce rich data for traffic flow research
- Brings a host of brand new research problems for modeling, design and operations of transportation systems