Phantom Traffic Jams and Autonomous Vehicles

Benjamin Seibold
Associate Professor of Mathematics

April 21, 2016

CST Board of Visitors Meeting

TEMPLE UNIVERSITY

The driver ahead of you brakes, so you brake, which causes braking behind you. But there is no discernable cause. . .

Phantom Traffic Jam

Initially uniform traffic flow of vehicles becomes inhomogeneous, in the absence of obstacles.

Jamiton

- Traveling wave in traffic flow [c.f. *soliton* = nonlinear wave in physics]
- Vehicles run into a sharp front, break heavily, then slowly speed up.
- Hot-spot for accidents; increased fuel consumption.

Research Goals

- Understand causes and dynamics of phantom traffic jams.
- Use this knowledge to devise technology to prevent/dissolve them.


Schuylkill River
Schuylkill Expy
Conshohocken
West Conshohocken
Gladwyne
Rosemont College
Bryn Mawr
Haverford College
Haverford
Ardmore
Narberth
Merion Station
Bala Cynwood
Wissahickon Valley Park
Cathedral Village
Rolling Hill Park
Philadelphia Country Club
Merion Golf Club East
Bala Golf Course

Observation: Jamitons on Long Road (video: [D. Helbing])

TEMPLE UNIVERSITY

Experiment: Jamitons on Circular Road [Sugiyama et al.: New J. of Physics 2008]

Traffic Models

Microscopic: N Vehicles on Road

- Position of j-th vehicle: x_j
- Velocity of j-th vehicle: v_j
- Acceleration of j-th vehicle: a_j

Physical Principles

- Velocity is rate of change of position: $v_j = \dot{x}_j$
- Acceleration is rate of change of velocity: $a_j = \dot{v}_j = \ddot{x}_j$

"Follow the Leader" Model

Accelerate/decelerate towards velocity of vehicle ahead of you:

$$a_j = \frac{v_{j+1} - v_j}{x_{j+1} - x_j}$$

"Optimal Velocity" Model

Accelerate/decelerate towards an optimal velocity that depends on your distance to the vehicle ahead:

$$a_j = V(x_{j+1} - x_j) - v_j$$

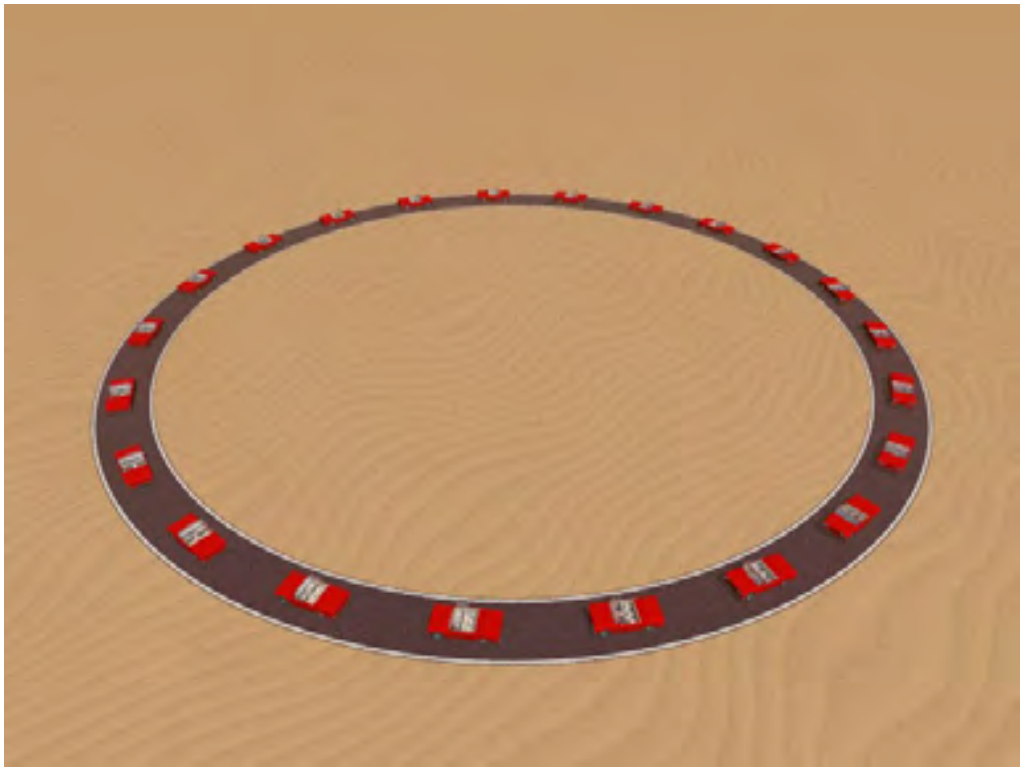
use computers to simulate $\longrightarrow$

Combined Model

$$a_j = \alpha \frac{v_{j+1} - v_j}{x_{j+1} - x_j} + \beta \left(V(x_{j+1} - x_j) - v_j \right)$$

Microscopic Traffic Models

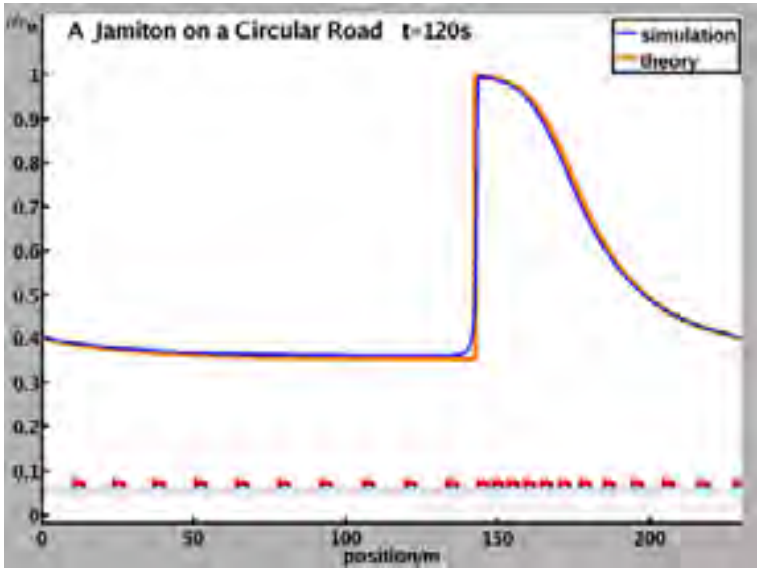
Simulation: phantom jams and jamitons



Macroscopic Traffic Models

$$\begin{cases} \rho_t + (\rho u)_x & = 0 \\ (u+h)_t + u(u+h)_x & = \frac{1}{\tau}(U-u) \end{cases}$$

Describe traffic via fluid dynamics.



$\longrightarrow$ up-scale simulations to large metro areas

$\longrightarrow$ incomplete data and privacy

TEMPLE UNIVERSITY

Key Point: Instability

- In real traffic there are constant perturbations: road bumps, engine hick-ups, driver inattention, etc.
- These effects are too small to produce large-scale phenomena (such as traffic waves) alone.
- Phantom traffic jams are arise when uniform traffic flow is unstable.
- Stable traffic flow: small perturbations of uniform flow decay.
- Instability: small perturbations of uniform flow amplify, and eventually grow into large traffic waves ("jamitons").
- Traffic models reveal: there is a critical threshold density ρ_c (depending on driver behavior):
  Below ρ_c, uniform flow is stable; above ρ_c, unstable.

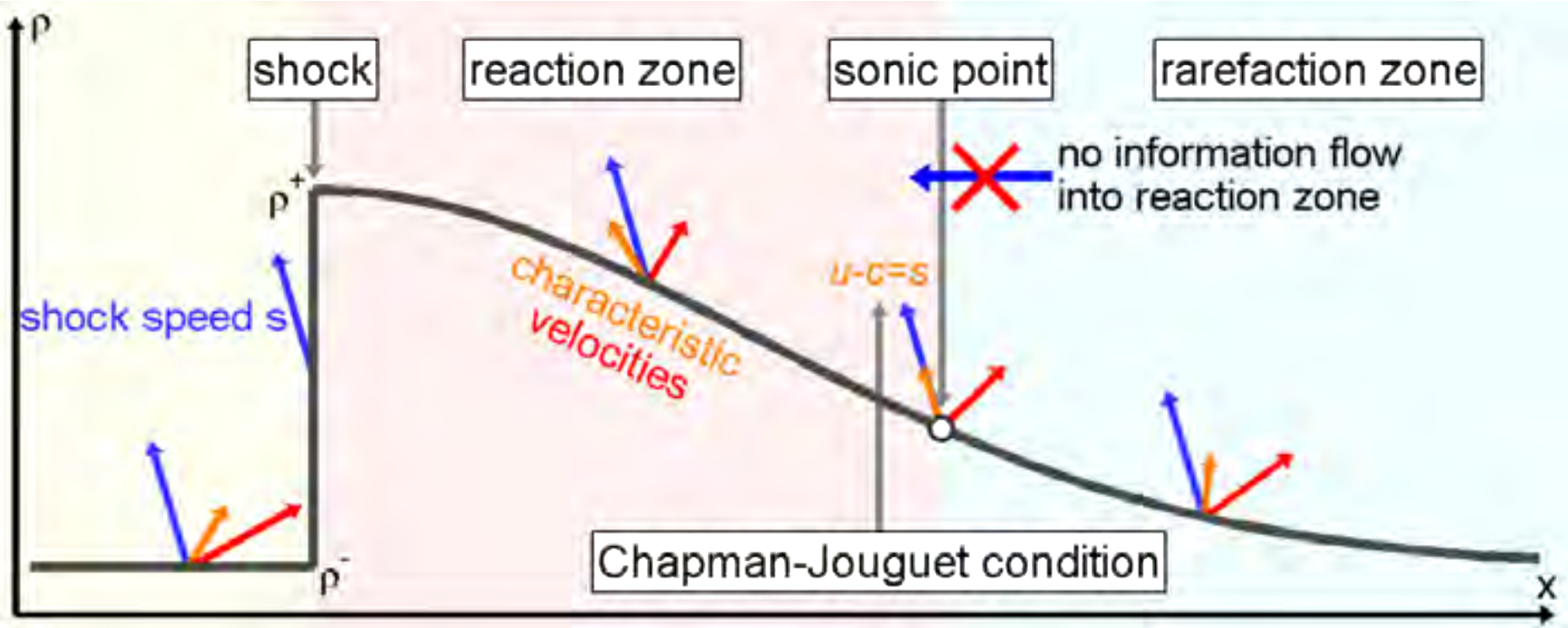
Crucial Practical Insight

Phantom jams can result from collective driving behavior;
no bad drivers needed for them to arise.

Jamitons are mathematical analogs of detonation waves

Self-Sustained Detonation Wave

Vehicle acceleration plays role of chemical reactions.

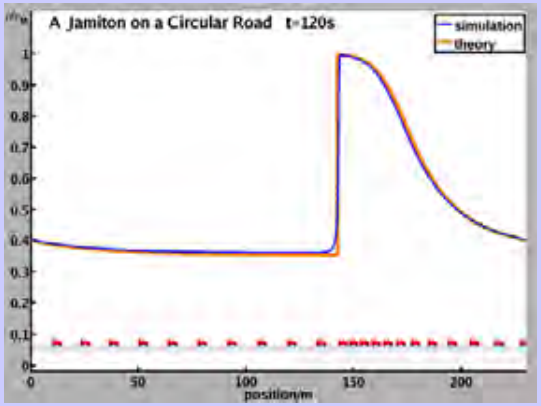


Vehicles run into a sharp increase in density ("shock" = braking zone).
Attached to shock is a "reaction zone" that ends at a sonic point.
Sonic point is event horizon: once passed, a vehicle cannot affect jamiton.

Founders of Detonation Theory

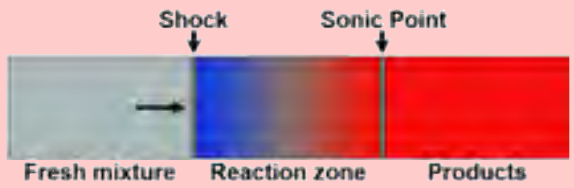
Roll waves

Traffic wave



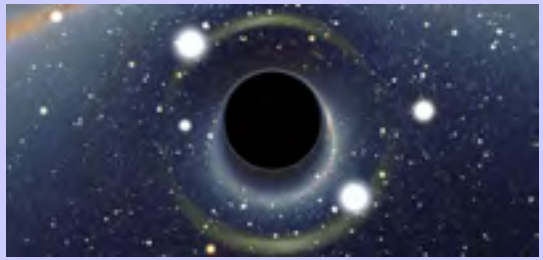
Detonation wave

A shock supported by a trailing exothermic reaction



Black hole

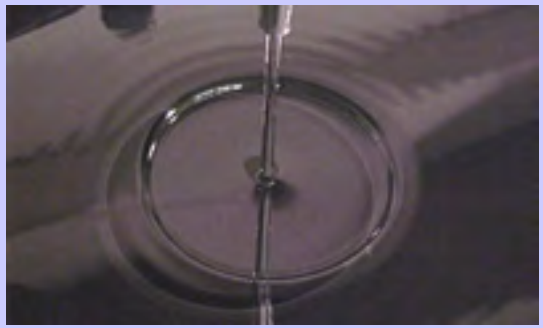
sonic point = event horizon

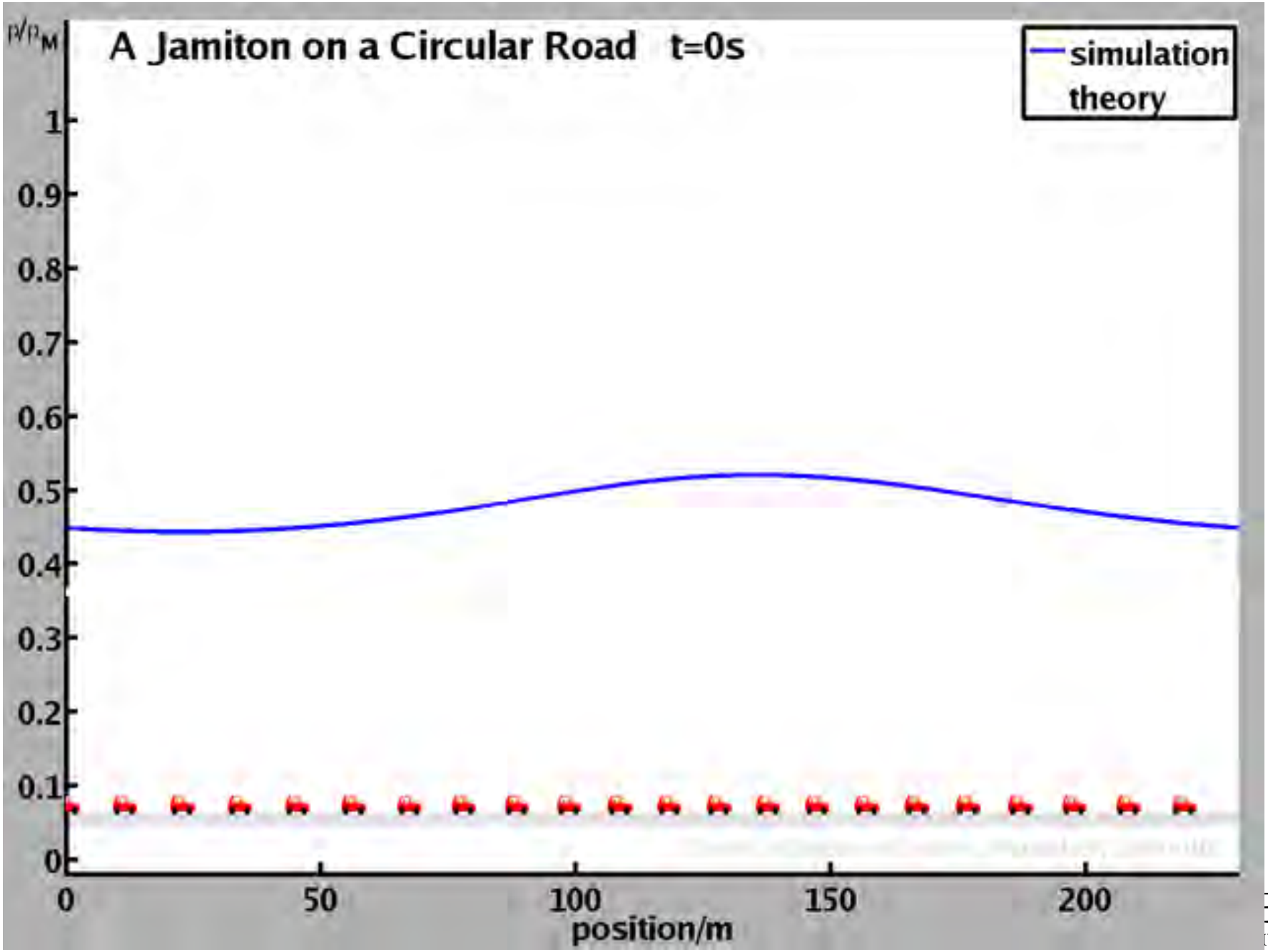


Detonations

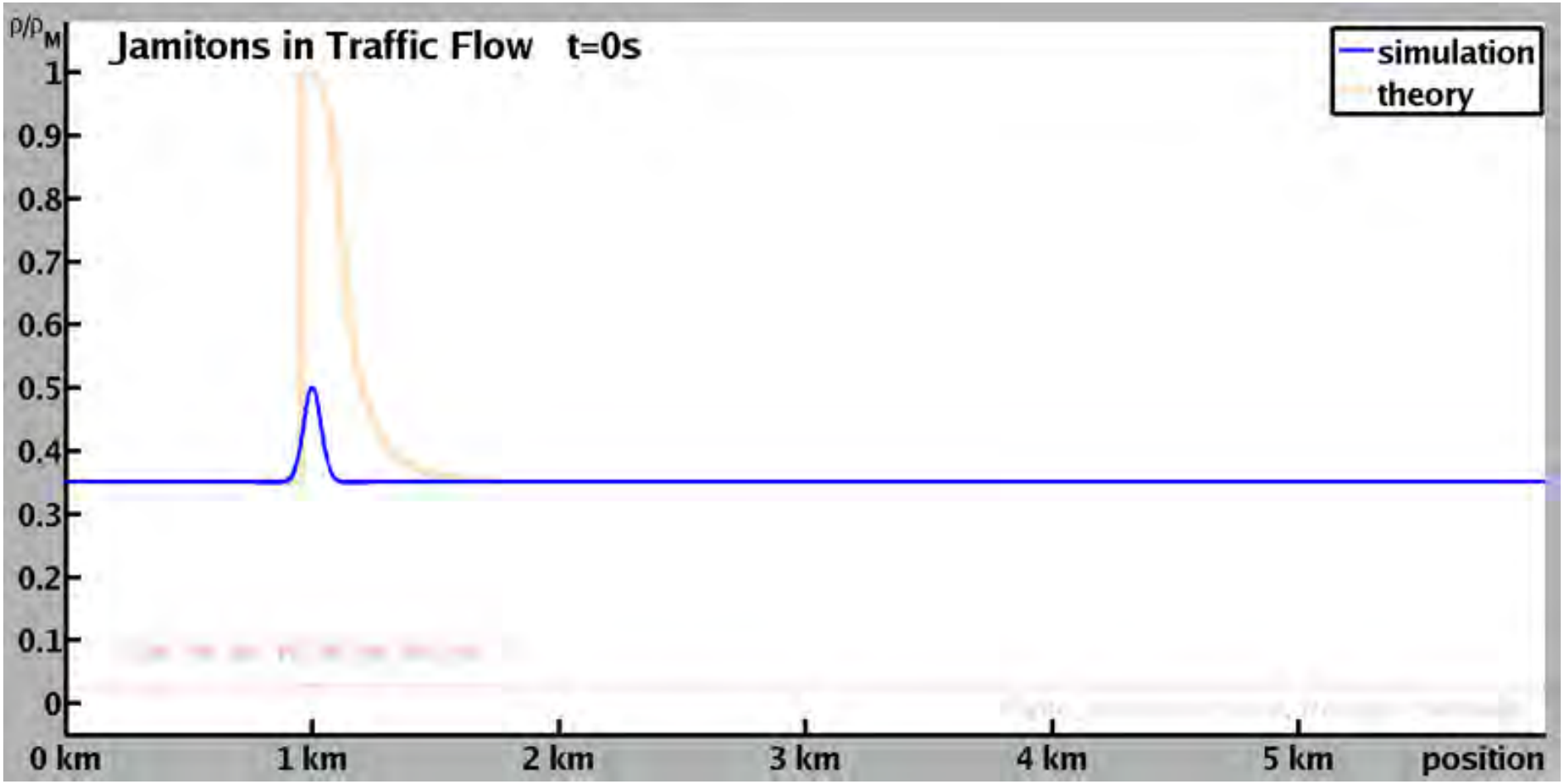
- combustion
- certain explosions

Hydraulic jump




A Jamiton on a Circular Road t=0s
simulation
theory
ρ/ρM
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
position/m

Infinite road; lead jamiton gives birth to a chain of "jamitinos".



Collaborators

Benedetto Piccoli (Rutgers Math)
Jonathan Sprinkle (U of Arizona ElecEng)
Daniel Work (UIUC Civil Eng)

Support

NSF CNS–1446690

CPS: Synergy: Control of vehicular traffic flow via low density AVs

- traffic science: understand traffic flow via models, analysis, and computation
- traffic engineering: develop future traffic control to prevent/dissolve traffic waves (make whole flow safer and more fuel efficient)
- traditional highway traffic controls: ramp metering, variable speed limits (neither can break up traffic waves)
- use autonomous vehicles (AVs); low cost: in 10–15 years, AVs will be on our roads anyways
- human factor in a cyber-physical system: humans interact with AVs; fundamental need to better understand human driving behavior

Univ. of Arizona AV

Collaborators

Rodolfo Ruben Rosales (MIT Math)
Aslan Kasimov (KAUST)
Morris Flynn (Alberta MechEng)

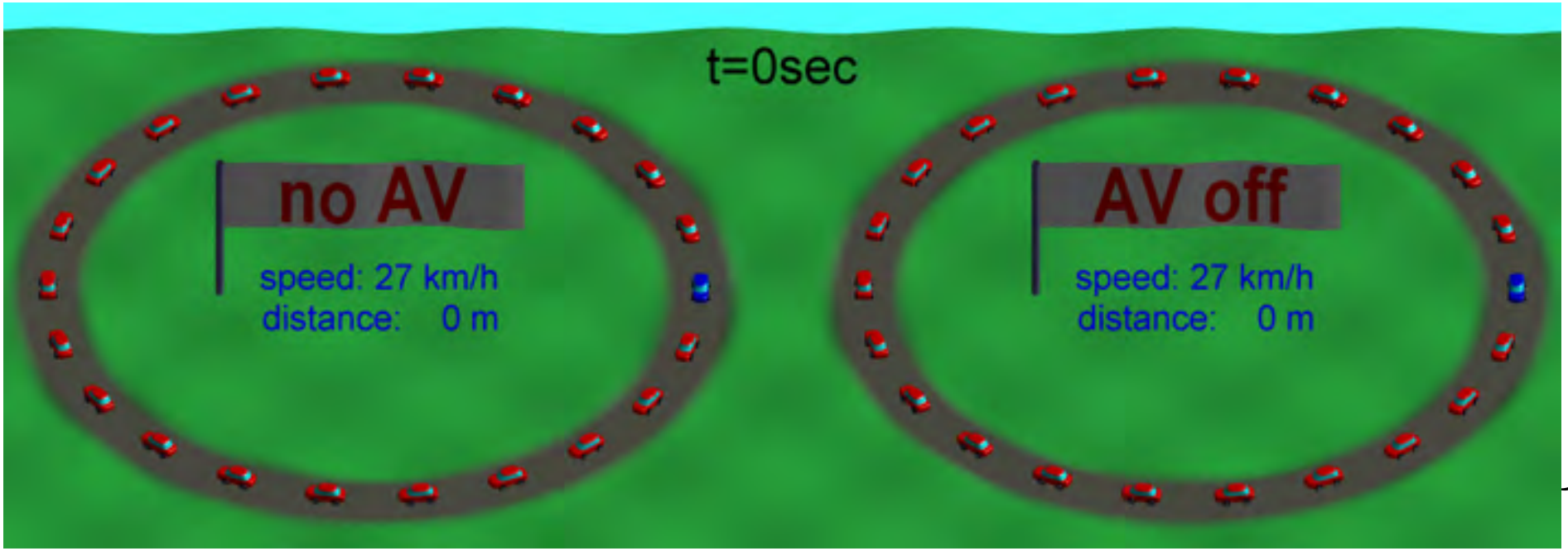
Support

NSF DMS–1007899

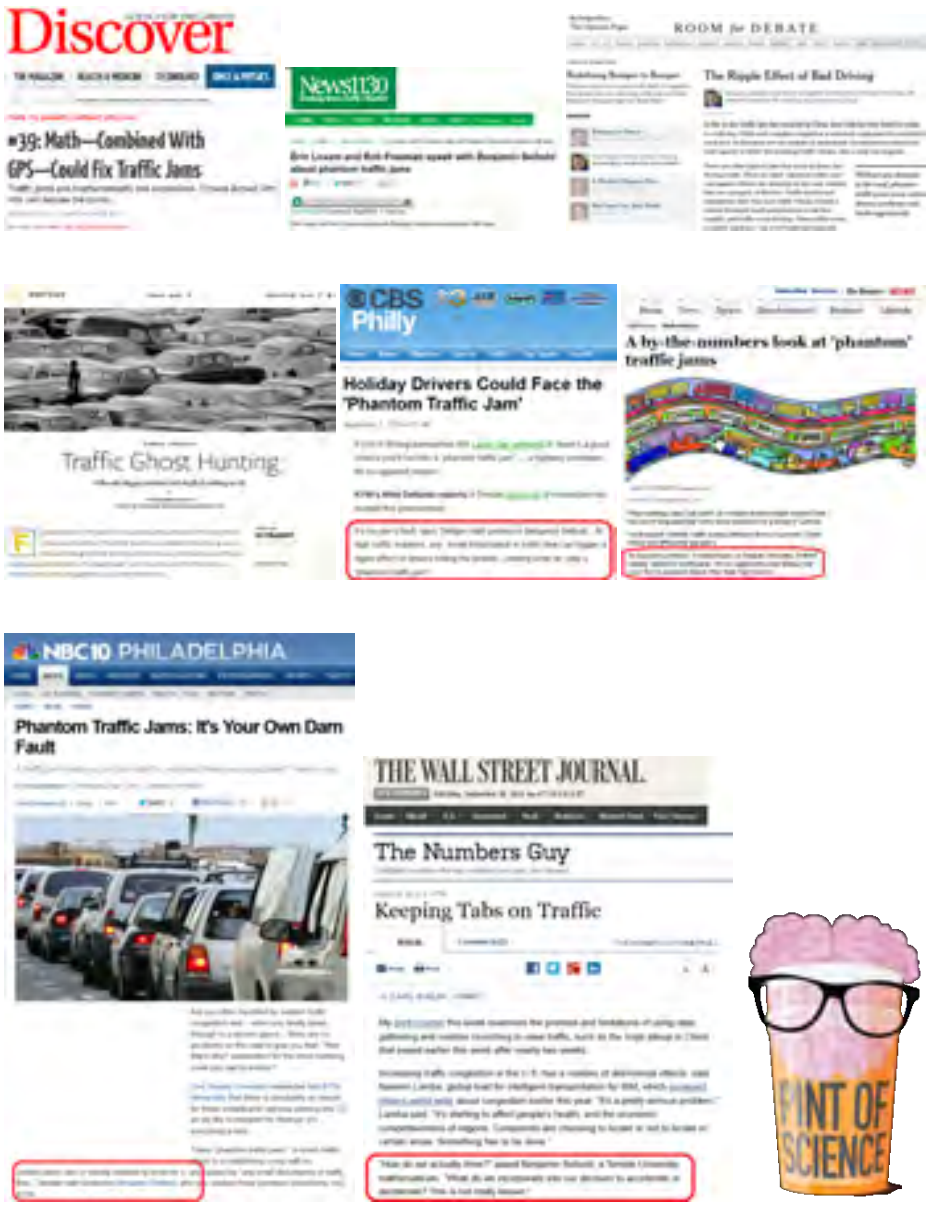
Phantom traffic jams, continuum modeling, and detonation wave theory

Experimental measurements of human driving

Simulation: uncontrolled vs. AV-controlled traffic flow



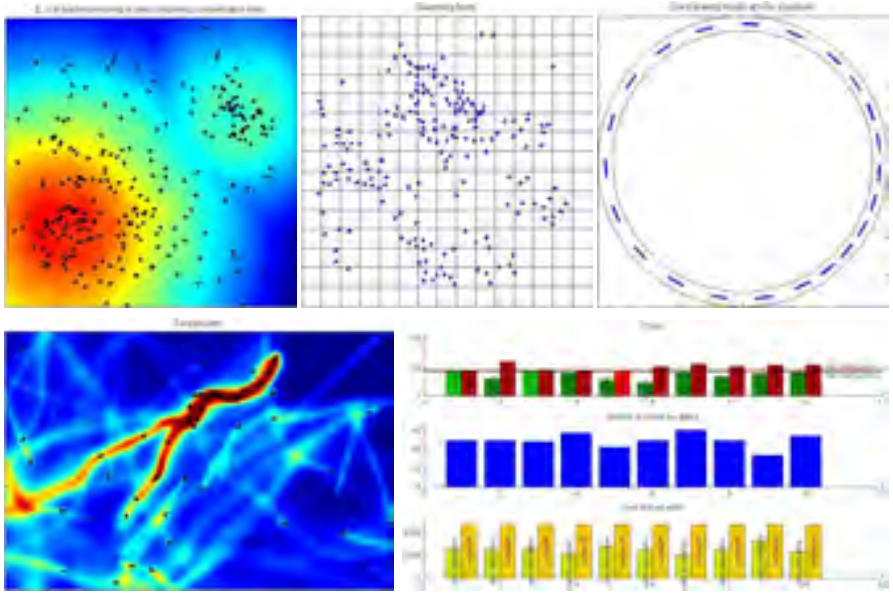
Media



Education

New course (Spring 2016):

CST 2100: Topics in Science and Technology: Modeling and Simulation in Science and Technology



Without formal programming background, students engage in agent-based modeling and simulation: swarming ants and birds, population dynamics, traffic flow and human crowds, bacterial motion, stock market models, etc.

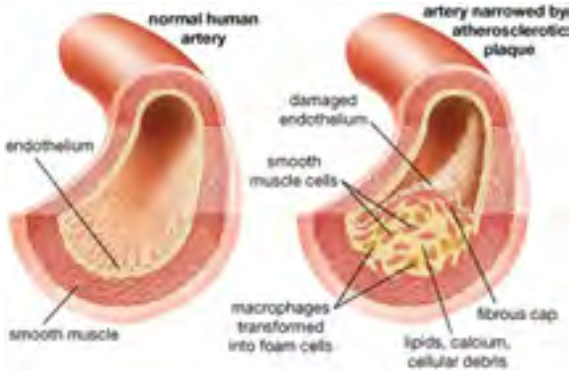
Atherosclerotic Plaque Growth

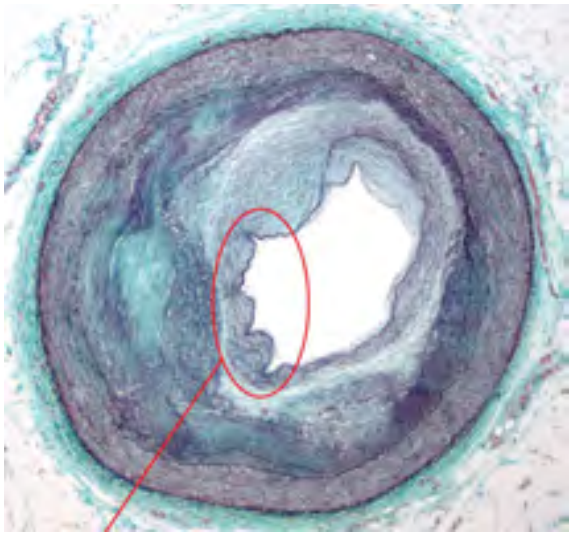
Modeling and simulation of long-term (30 years) growth:

$$
\begin{aligned}
\text{LDL \& LDLox:} \quad & d_c \Delta c - k_c c M = 0 && \text{in } \Omega(t) \\
\text{macrophages:} \quad & d_M \Delta M - k_M c M = 0 && \text{in } \Omega(t) \\
\text{foam cells:} \quad & F_t + \nabla \cdot (\vec{v} F) = (k_c + k_M) c M && \text{in } \Omega(t) \\
\text{growth field:} \quad & \nabla \cdot \vec{v} = (k_c + k_M) c M && \text{in } \Omega(t) \\
\text{domain motion:} \quad & \dot{\Omega} = \vec{v}
\end{aligned}
$$

Key Messages

- Research: Ripples observed on plaques can be explained via an instability of the model equations.
- Tiny imperfections grow into wave structures that fundamentally affect the properties of the structure (e.g. risk of rupture) — same as in traffic waves.
- Applied and Computational Mathematics: model- and equation-driven research; advance mutual insight in seemingly disconnected fields.





Result: ripples can be explained via instability of equations.

Collaborators

Kurosh Darvish (Temple MechEng)
Pak-Wing Fok (U Delaware)
Sunnie Joshi (Temple University)

Support

NSF DMS–1318641

A computational framework for athero-sclerotic plaque growth simulations