Energy Impact of Automated Vehicles Used as Sparse Traffic Controllers

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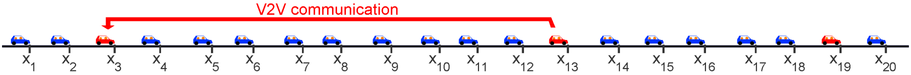
Projects

DOE DE–EE000887 (EERE, VTO)
CIRCLES: Congestion Impact Reduction via CAV-in-the-loop Lagrangian Energy Smoothing

NSF CNS–1446690
CPS: Synergy: Control of vehicular traffic flow via low density autonomous vehicles

Motivation

- While autonomous vehicles are still the future, automated vehicles (AVs) are already here: adaptive cruise control systems (ACCs).
- What will be the impact of adding a few AVs to the traffic flow?
- Hope: increased safety; AVs themselves more efficient; serendipitous efficiency benefits to other vehicles ("speed harmonization").
- Here, more aggressive paradigm: Use sparse AVs to actively control traffic flow. Objective: steer whole flow to more efficient flow regime.
- New Lagrangian traffic flow control, complementing traditional Eulerian controls (ramp metering, variable speed limits, etc.)
- Focus here: dissipation of traffic waves; prevention of phantom jams.



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Overview

Overview

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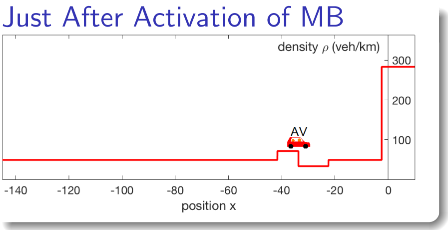
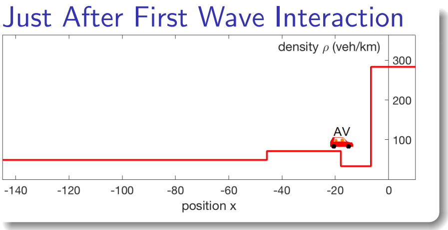
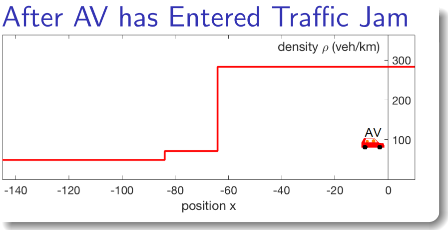
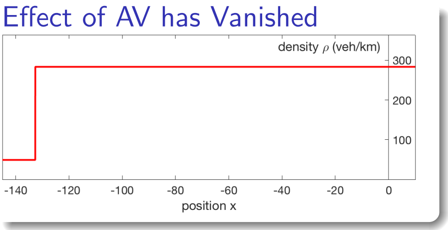
A Non-Waves Idea: Control via AV as Moving Bottleneck









Example: German highway ($v_{\max}$=140 km/h). Fuel savings: 1087 ℓ/h.
Equilibrium dynamics only (air drag reduction), no traffic waves.
[arxiv.org/abs/1702.07995]

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Experiment 1: Wave Dampening via a Single AV

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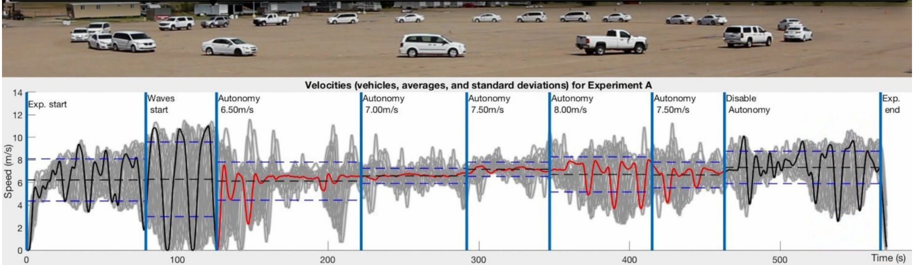
Time (s)	Interval	Velocity st. dev (m/s)	Fuel consumption (liters/100km)	Braking (events/vehicle/km)	Throughput (vehicles/hour)
000	Experiment start	1.87	18.8	1.66	1809
079	Waves start	3.31	24.6	8.58	1827
126	Autonomy 6.50m/s	1.69	18.0	3.45	1780
222	Autonomy 7.00m/s	0.67	15.0	0.21	1915
292	Autonomy 7.50m/s	0.64	14.1	0.12	2085
347	Autonomy 8.00m/s	1.56	17.7	2.50	1952
415	Autonomy 7.50m/s	1.14	16.7	0.31	1938
463	Disable Autonomy	1.44	17.4	2.95	2133
567	Experiment end	-	-	-	-

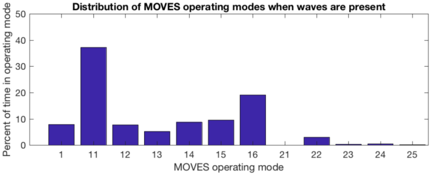


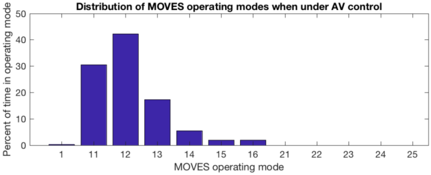
Best AV-based controller vs. strongest waves

- economy: almost half the fuel consumption
- safety: 70× less strong braking
- clean air: 5× less velocity variation
- efficiency: throughput up by 14% (but: no physical bottlenecks here)

Experiment 1: Fleet Emissions

MOVES (EPA, 2015) Modes (higher mode = more emissions)





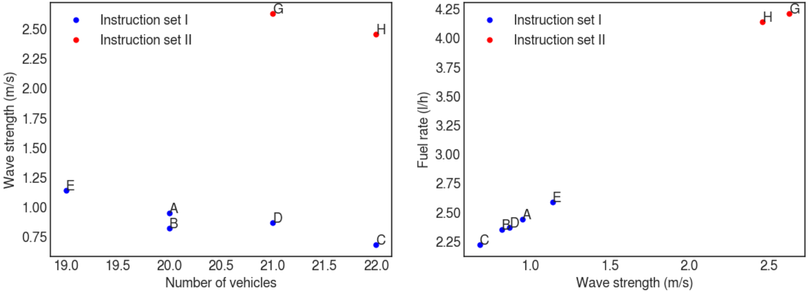
Environmental Impact of Control on Whole Fleet

Metric/Pollutant	unit	waves	control	reduction
vehicle st. dev.	m/s	3.31	0.64	81%
strong braking	1/veh/km	8.58	0.12	99%
fuel consumption	ℓ/100km	24.6	14.1	42%
carbon dioxide (CO_2)	g/mi	1246	863.1	30.7%
carbon monoxide (CO)	g/mi	2.430	1.481	39.1%
hydrocarbons (HC)	g/mi	0.010	0.005	51.5%
nitrogen oxides (NO_x)	g/mi	0.107	0.028	73.5%

Ring Road Experiment with Driver Instructions

- Instruction set I: "Safely follow the vehicle in front as if in rush hour traffic."
- Instruction set II: "As before, but in addition place an emphasis on closing the gap to the vehicle in front, whenever safety permits."

Results



- Decrease in wave strength with increasing vehicle density (less room).
- Aggressive gap-closing (II) yields wave strength (vel. stdev) 2.5 times as large as with non-aggressive driving (I). Fuel consumption 1.8 times higher.
- Driver mindset can affect emergent wave behavior substantially.

Experiment 2: Adaptive Cruise Control

Are Commercially Implemented Adaptive Cruise Control Systems String-Stable?

https://arxiv.org/abs/1905.02108

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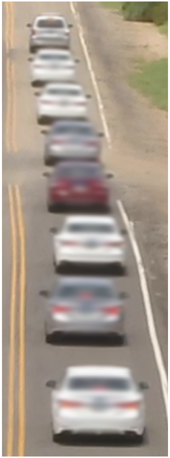
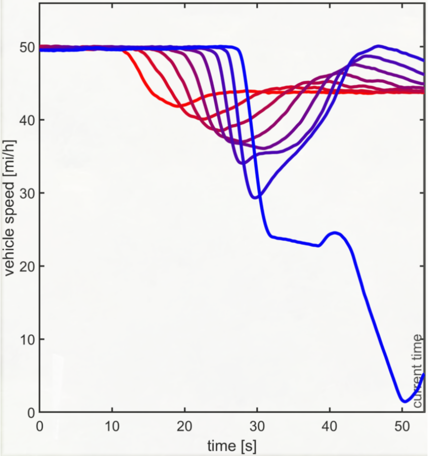
Experiment 2: Adaptive Cruise Control





- ACC systems currently available on the market may (collectively) amplify each other to produce dangerous traffic patterns.
- Here, having humans in the loop likely helps to dampen/prevent these effects (thus not reported yet on highways).

Questions/Tasks

- Assuming (a few) AVs are successful at wave dampening/suppression, then they will revert the flow back to a uniform flow state. Quantitatively compare uniform flow state with waves state.
- Hence, question: How bad are traffic waves with regards to...
  - a ...flow properties (average speed, throughput);
  - b ...energy consumption (fuel, battery)?
- Approach: Develop and analyze traffic models that reproduce waves in a principled fashion. Understand...
  - a ...impact on flow properties;
  - b ...structural interplay of traffic models and vehicle energy models.

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Overview

Key Distinction for All Traffic Models

- **First-order dynamics:** System state is vehicle positions (or density). Obtain (instantaneous) vehicle velocities from positions.
- **Second-order dynamics:** System state is vehicle positions and velocities. Model vehicle accelerations (Newton's laws of motion).

- First-order models can produce equilibrium dynamics (shock waves, traffic jams, red/green light dynamics); but ...
- Second-order dynamics needed to produce instabilities and traveling waves (phantom traffic jams). [Or: first-order with delay; not treated here]

Microscopic Models

First-order: $\dot{x}_j = V(x_{j+1} - x_j)$

Second-order:

$$\ddot{x}_j = f(x_{j+1} - x_j - \ell, \dot{x}_{j+1} - \dot{x}_j, \dot{x}_j)$$

Macroscopic Models

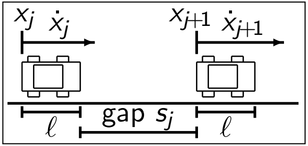
First-order: $\rho_t + (\rho U(\rho))_x = 0$

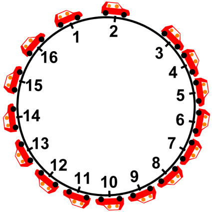
Second-order:

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

Microscopic Car-Following Models

- Vehicles at positions $x_1 < \ldots < x_N$.
- Car-following: car j affected only by $j+1$.
- Types of arrangements:
  a) Infinite road with one vehicle leading.
  b) Ring road (N follows 1): proxy for infinite road.





Second-Order Model Dynamics

- $\ddot{x}_j = f(s_j, \dot{s}_j, v_j)$,
  with gap $s_j = x_{j+1} - x_j - \ell$ and velocity difference $\dot{s}_j = \dot{x}_{j+1} - \dot{x}_j$.

Perturbations to Uniform Flow

- Equilibrium: vehicles equi-spaced with identical velocities v^{eq}.
- Linearize: $x_j = x_j^{\text{eq}} + y_j$, where y_j infinitesimal perturbation.

Car Following: String Stability

Linearized Dynamics

- $\ddot{y}_j = \alpha_1 (y_{j+1} - y_j) - \alpha_2 \dot{y}_j + \alpha_3 \dot{y}_{j+1}$,
  where $\alpha_1 = \frac{\partial f}{\partial s}$, $\alpha_2 = \frac{\partial f}{\partial \dot{s}} - \frac{\partial f}{\partial v}$, $\alpha_3 = \frac{\partial f}{\partial \dot{s}}$ (all eval. at equilibrium).

Frequency Response of Car-Following I/O Behavior

- Laplace transform ansatz $y_j(t) = c_j e^{\omega t}$, where $c_j, \omega \in \mathbb{C}$.
- Yields I/O system: $c_j = F(\omega) c_{j+1}$ with transfer function

$$F(\omega) = \frac{\alpha_1 + \alpha_3 \omega}{\alpha_1 + \alpha_2 \omega + \omega^2} \,.$$

- Re(ω): temporal growth/decay — $|F|$: growth/decay across vehicles
  Im(ω): frequency of oscillation — $\theta(F)$: phase shift across vehicles
- **Def.:** string stability means $|F(\omega)| \leq 1 \ \forall \omega \in i\mathbb{R}$.
- The model above is string stable exactly if $\alpha_2^2 - \alpha_3^2 - 2\alpha_1 \geq 0$.
- If unstable: small perturbations $\longrightarrow$ exponential growth until nonlinearities kick in $\longrightarrow$ waves, collisions, etc.

Two-Species Car-Following (Humans and AVs)

- Slightly unstable human driver model, i.e. $\alpha_2^2 - \alpha_3^2 - 2\alpha_1 < 0$.
- What changes when a few automated vehicles are added to the flow? (that drive slightly differently than humans)
  Can the few AVs stabilize traffic flow, and thus prevent traffic waves?
- Humans: $\ddot{x}_j = f(h_j, \dot{h}_j, v_j)$; AVs: $\ddot{x}_j = g(h_j, \dot{h}_j, v_j)$.
- Let AVs leave same equilibrium spacing as humans. Linearize.
- Humans: $\ddot{y}_j = \alpha_1 (y_{j+1} - y_j) - \alpha_2 u_j + \alpha_3 u_{j+1}$
  AVs: $\ddot{y}_j = \beta_1 (y_{j+1} - y_j) - \beta_2 u_j + \beta_3 u_{j+1}$
- Transfer functions: $F(\omega) = \frac{\alpha_1 + \alpha_3 \omega}{\alpha_1 + \alpha_2 \omega + \omega^2}$ and $G(\omega) = \frac{\beta_1 + \beta_3 \omega}{\beta_1 + \beta_2 \omega + \omega^2}$.
- Stability criterion with AV penetration rate γ:
  $$\boxed{|F(\omega)|^{1-\gamma} \cdot |G(\omega)|^{\gamma} \leq 1 \ \forall \omega \in i\mathbb{R}}$$
- Problem with this result: It states that any number of human-driven vehicles can be stabilized with any number of AVs, and any spatial arrangement. That cannot be true in reality.

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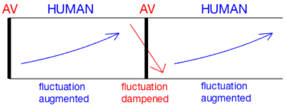
Resolution of Modeling Problem

- Linear stability only captures $t \to \infty$ behavior.
- For transient t, a small perturbation may produce a large deviation.
- Instability of human driving: perturbations grow from car to car.
- Stability of coupled system: AV(s) reduce(s) perturbation by more than amplification caused by all humans.
- Just before hitting the AV, perturbation could be amplified a lot.
- System with noise yields needed failure to remain close to equilibrium:

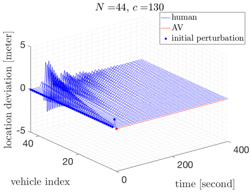
$$du_j = [\alpha_1(y_{j+1} - y_j) - \alpha_2 u_j + \alpha_3 u_{j+1}]dt + s_j dB_t$$

Amplification and decay of perturbation

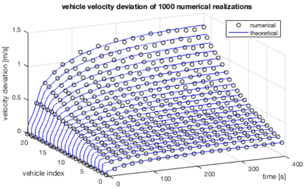


We know: 1 AV can stabilize $\approx$ 25 humans.

System response to single perturbation



With noise: system's mean deviation

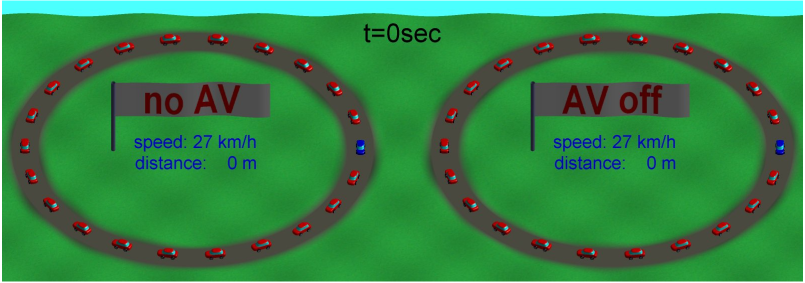


Popular Car-Following Models with Instabilities

- Intelligent driver model (IDM): $\ddot{x}_j = a\left[1-\left(\frac{\dot{x}_j}{v_0}\right)^{\delta}-\left(\frac{s_0+\tau\dot{x}_j-\dot{x}_j\dot{s}_j/(2\sqrt{ab})}{s_j}\right)^2\right]$
- Optimal velocity model (OVM): $\ddot{x}_j = a\,(V(s_j) - \dot{x}_j)$
- Follow the leader – OVM: $\ddot{x}_j = a\,(V(s_j) - \dot{x}_j) + b\frac{\dot{s}_j}{(s_j)^{\delta}}$

Simulation: FTL–OVM with 1 AV Using Local–Global Control Law

- Local: adjust velocity to safely follow lead vehicle.
- Global: choose velocity equal to estimated average speed of flow.



Second-Order Macroscopic Models

Here: Payne-Whitham Model [ARZ Model Very Similar]

$$\underbrace{\begin{pmatrix}\rho \\ u\end{pmatrix}_t + \begin{pmatrix} u & \rho \\ \frac{1}{\rho}\frac{dp}{d\rho} & u\end{pmatrix}\begin{pmatrix}\rho \\ u\end{pmatrix}_x}_{\text{hyperbolic part}} = \underbrace{\begin{pmatrix} 0 \\ \frac{1}{\tau}(U(\rho) - u)\end{pmatrix}}_{\text{relaxation term}}$$

Eigenvalues

$$\left\{ \begin{array}{l} \lambda_1 = u - c \\ \lambda_2 = u + c \end{array} \right\}$$

$$c^2 = \frac{dp}{d\rho}$$

Relaxation to Equilibrium

Consider formal limit $\tau \to 0$. Then $u \to U(\rho)$, i.e., the system reduces to the Lighthill-Whitham-Richard (LWR) model $\rho_t + (\rho U(\rho))_x = 0$.

Linear Stability Analysis

(LS) When are constant base state solutions $\rho(x,t) = \tilde{\rho}$, $u(x,t) = U(\tilde{\rho})$ stable (i.e. infinitesimal perturbations do not amplify)?

Reduced Equation

(RE) When do solutions of the 2×2 system converge (as $\tau \to 0$) to solutions of the reduced equation

$$\rho_t + (\rho U(\rho))_x = 0 \quad ?$$

Sub-Characteristic Condition

(SCC) $\lambda_1 < \mu < \lambda_2$, where $\mu = (\rho U(\rho))'$

Theorem [Whitham: Comm. Pure Appl. Math 1959]

(LS) $\Longleftrightarrow$ (RE) $\Longleftrightarrow$ (SCC)

PW Model

$$\begin{cases} \rho_t + (\rho u)_x = 0 \\ u_t + u u_x + \frac{1}{\rho} p(\rho)_x = \frac{1}{\tau}(U(\rho) - u) \end{cases}$$

Traveling Wave Ansatz

$\rho = \rho(\eta)$, $u = u(\eta)$, with self-similar variable $\eta = \frac{x - st}{\tau}$.

Then $\rho_t = -\frac{s}{\tau}\rho'$, $\quad \rho_x = \frac{1}{\tau}\rho'$, $\quad u_t = -\frac{s}{\tau}u'$, $\quad u_x = \frac{1}{\tau}u'$

and $\quad p_x = \frac{1}{\tau}c^2\rho'$, $\quad c^2 = \frac{dp}{d\rho}$

Continuity Equation

$$\rho_t + (u\rho)_x = 0$$

$$-\frac{s}{\tau}\rho' + \frac{1}{\tau}(u\rho)' = 0$$

$$(\rho(u - s))' = 0$$

$$\rho = \frac{m}{u - s}$$

$$\rho' = -\frac{\rho}{u - s}u'$$

Momentum Equation

$$u_t + u u_x + \frac{p_x}{\rho} = \frac{1}{\tau}(U - u)$$

$$-\frac{s}{\tau}u' + \frac{1}{\tau}u u' + \frac{dp}{d\rho}\frac{\rho'}{\rho} = \frac{1}{\tau}(U - u)$$

$$(u - s)u' - c^2\frac{1}{u - s}u' = U - u$$

$$u' = \frac{(u - s)(U - u)}{(u - s)^2 - c^2}$$

Jamiton Ordinary Differential Equation for $u(\eta)$

$$u' = \frac{(u-s)(U(\rho)-u)}{(u-s)^2 - c(\rho)^2} \quad \text{where} \quad \rho = \frac{m}{u-s}$$

where

$$s = \text{travel speed of jamiton}$$

$$m = \text{mass flux of vehicles through jamiton}$$

Key Point

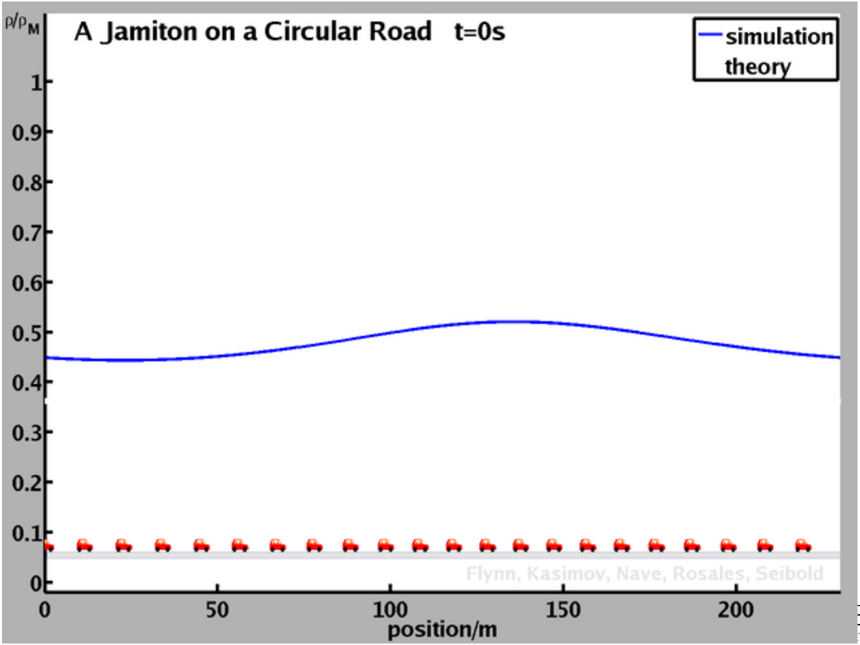
In fact, m and s can not be chosen independently:

Denominator has root at $u = s + c$. Solution can only pass smoothly through this singularity (the sonic point), if $u = s + c$ implies $U = u$.

Using $u = s + \frac{m}{\rho}$, we obtain for this sonic density ρ_S that:

$$\begin{cases} \text{Denominator} & s + \frac{m}{\rho_S} = s + c(\rho_S) \implies m = \rho_S c(\rho_S) \\ \text{Numerator} & s + \frac{m}{\rho_S} = U(\rho_S) \implies s = U(\rho_S) - c(\rho_S) \end{cases}$$

Algebraic condition (Chapman-Jouguet condition [Chapman, Jouguet (1890)]) that relates m and s (and ρ_S). Jamitons described by ZND detonation theory.



A Jamiton on a Circular Road t=0s
simulation
theory
ρ/ρ$_M$
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
Flynn, Kasimov, Nave, Rosales, Seibold

Traveling Waves in Continuity Equation

$\rho = \rho(\eta)$, $u = u(\eta)$, where $\eta = \frac{x-st}{\tau}$, yields

$$\rho_t + (u\rho)_x = 0 \Longrightarrow (\rho(u-s))' = 0$$

$$\Longrightarrow \rho(u-s) = m \Longrightarrow q = m + s\rho$$

Hence: Any traveling wave is a line segment in the fundamental diagram, whose slope s is the traveling wave speed.

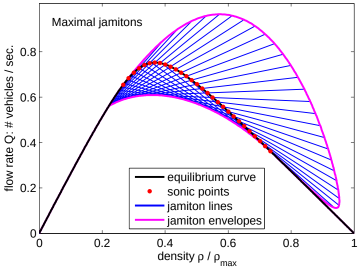
Jamiton Fundamental Diagram

Jamiton lines form set-valued region.
Jamitons can explain spread in real FD.

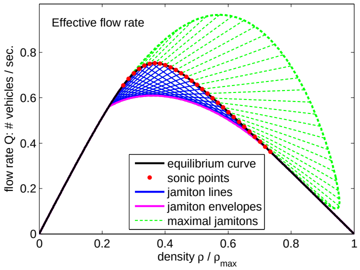
Effective Densities and Flow Rates

Averaging over full jamitons yields that effective densities/flow pairs $(\bar{\rho}, \bar{q})$ always lie below the equilibrium curve $q = Q(\rho)$.

Jamiton Fundamental Diagram



Averages over Full Jamitons



Overview

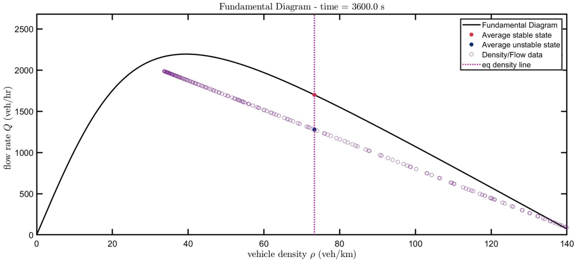
Fundamental Diagram from Microscopic Models

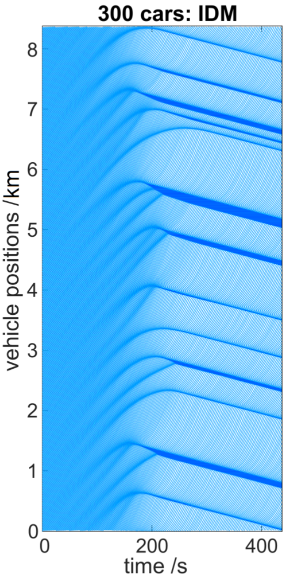
Kernel Density Estimation

Macroscopic flow quantities from trajectories.
Using Gaussian kernels $G(x) = Z^{-1}e^{-(x/h)^2}$,
define density $\rho(x,t) = \sum_j G(x - x_j(t))$
and flow rate $q(x,t) = \sum_j \dot{x}_j(t) G(x - x_j(t))$.

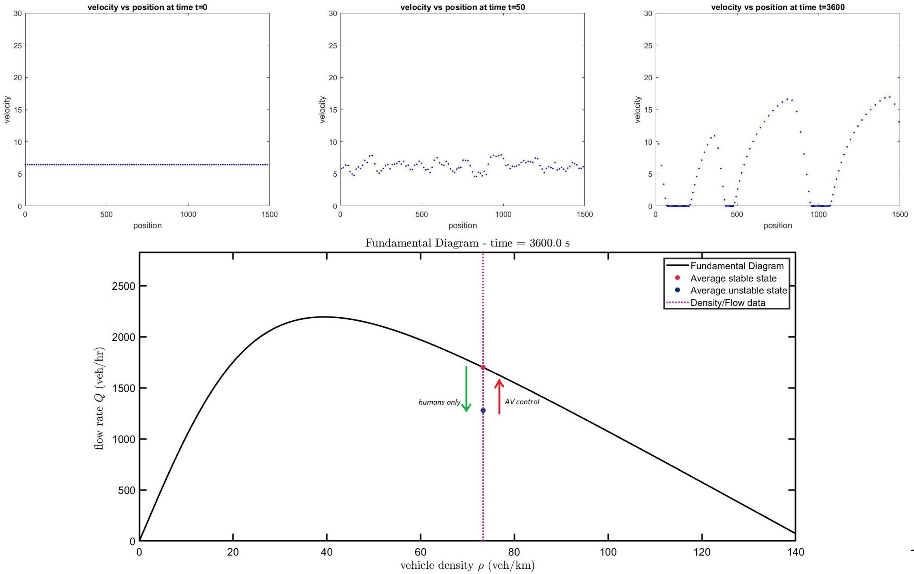
Waves in Fundamental Diagram

Data (ρ, q) lie on a line, because $\rho_t + q_x = 0$.
Average $(\bar{\rho}, \bar{q})$ lies below equilibrium curve.

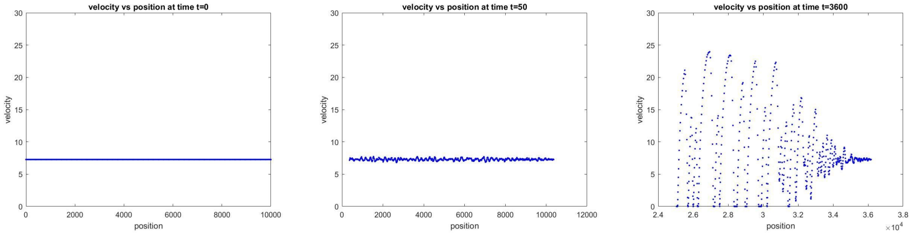


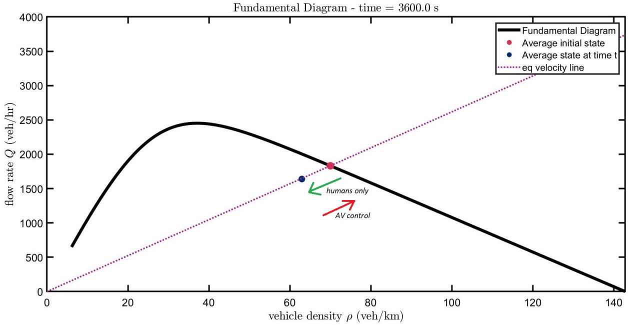


Scenario 1: Ring Road

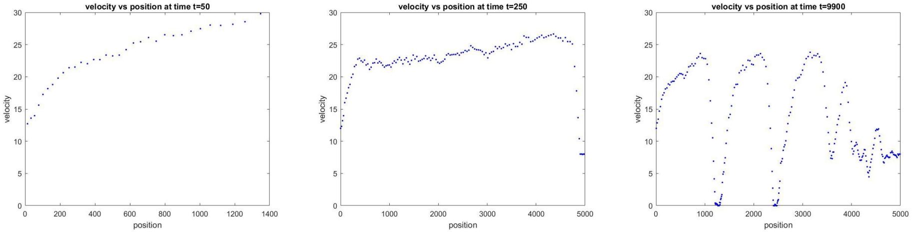


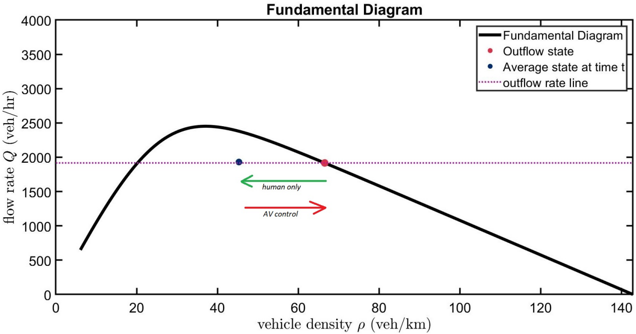
Scenario 2: First Vehicle Driving with Fixed Speed



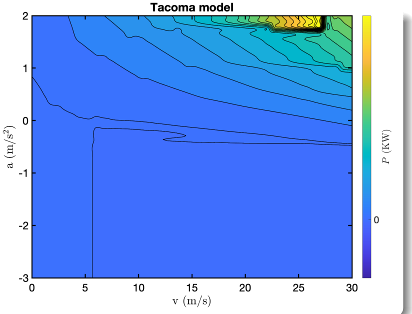


Scenario 3: Road Segment with Bottleneck at Outflow



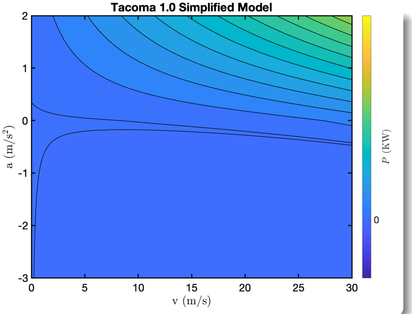


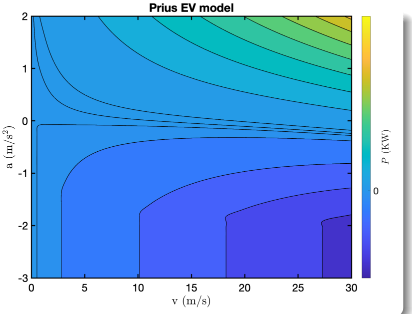
Overview



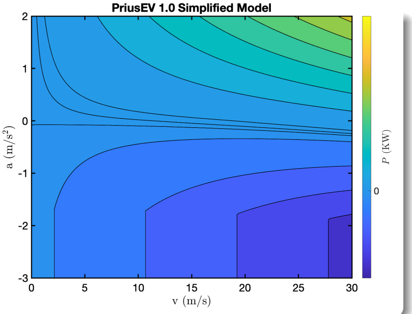
simplify →

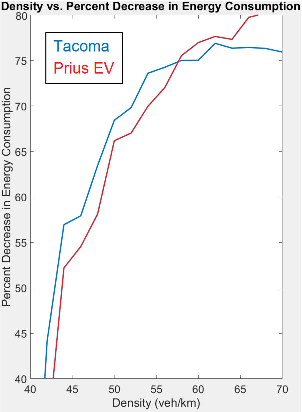
average out gear shifting

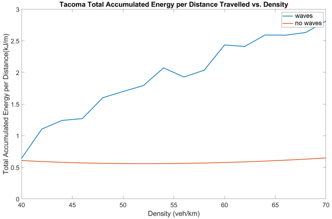


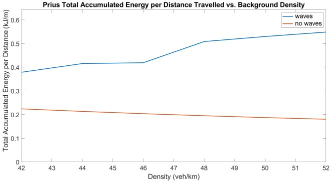


simplify →

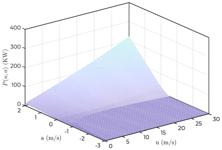




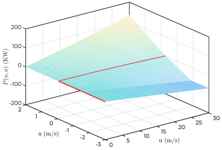




Tacoma 1.0 Simplified



PriusEV 1.0 Simple



- Idealized condition: same average density, optimal wave dampening.
- Waves increase energy demand for two reasons: (i) $P(v,\cdot)$ convex up (esp. waste energy during braking); (ii) $P(\cdot,a)$ convex up
- Impact of flow smoothing: higher savings for combustion engine; except in highly congested flow, where electric vehicle savings higher.
- Warning: High efficiency gains because our IDM waves are very strong.

Overview

Conclusions

- With vehicle automation happening, we need to understand the pitfalls and the opportunities arising from the resulting nonlinear heterogeneous system dynamics.
- Humans still dominate; far from AV-only solutions (platooning, etc.)
- Lagrangian traffic flow control: a few AVs make flow more efficient.
- There might be a free lunch: AVs will be on the road anyways.
- Explored theoretical optimal efficiency gains (achievable with perfect controllers). Easily cut energy demand of unsteady traffic in half.
- Moreover, flow efficiency gains possible (non-equilibrium flow theory reveals which flow states may result from AV-based controls).
- Challenge: Designing controllers that smooth traffic waves is easy. However, doing so in a socially acceptable way is hard.

https://ed.ted.com/lessons/what-is-phantom-traffic-and-why-is-it-ruining-your-life-benjamin-seibold

https://www.youtube.com/watch?v=CKo-v_qwJwo

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