Energy Impact of Automated Vehicles Used as Sparse Traffic Controllers

Benjamin Seibold (Temple University)

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Collaborators and Students
Nour Khoudari (PhD student, Temple)
Rabie Ramadan (postdoc, Temple)
Megan Ross (undergraduate, Temple)
Kenneth Butts (Toyota)
Alexandre Bayen (UC Berkeley)
Benedetto Piccoli (Rutgers Camden)
Jonathan Sprinkle (Univ. of Arizona)
Daniel Work (Vanderbilt), many more

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.
Overview

1. Traffic Flow Control via Autonomous Vehicles
2. Non-Equilibrium Traffic Flow Theory
3. Flow Manifestations of Traffic Waves
4. Energy Manifestations of Traffic Waves
5. Conclusions
Overview

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

Example: German highway ($v_{\text{max}} = 140$ km/h). Fuel savings: 1087 $\ell$/h. Equilibrium dynamics only (air drag reduction), no traffic waves. 

[ arxiv.org/abs/1702.07995 ]
Experiment 1: Wave Dampening via a Single AV
## Experiment: Wave Dampening via a Single AV

### 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)

### Traffic Flow Control via Autonomous Vehicles

#### Table: Performance Metrics

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

### Diagram: Velocities (vehicles, averages, and standard deviations) for Experiment A

- **Exp. start**
- **Waves start**
- **Autonomy 6.50m/s**
- **Autonomy 7.00m/s**
- **Autonomy 7.50m/s**
- **Autonomy 8.00m/s**
- **Disable Autonomy**
- **Exp. end**

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[Benjamin Seibold (Temple University)]

Energy Impact of AVs as Traffic Controllers 10/27/2020, IPAM AV Program
Experiment 1: Fleet Emissions

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

<table>
<thead>
<tr>
<th>Metric/Pollutant</th>
<th>unit</th>
<th>waves</th>
<th>control</th>
<th>reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicle st. dev.</td>
<td>m/s</td>
<td>3.31</td>
<td>0.64</td>
<td>81%</td>
</tr>
<tr>
<td>strong braking</td>
<td>1/veh/km</td>
<td>8.58</td>
<td>0.12</td>
<td>99%</td>
</tr>
<tr>
<td>fuel consumption</td>
<td>ℓ/100km</td>
<td>24.6</td>
<td>14.1</td>
<td>42%</td>
</tr>
<tr>
<td>carbon dioxide (CO₂)</td>
<td>g/mi</td>
<td>1246</td>
<td>863.1</td>
<td>30.7%</td>
</tr>
<tr>
<td>carbon monoxide (CO)</td>
<td>g/mi</td>
<td>2.430</td>
<td>1.481</td>
<td>39.1%</td>
</tr>
<tr>
<td>hydrocarbons (HC)</td>
<td>g/mi</td>
<td>0.010</td>
<td>0.005</td>
<td>51.5%</td>
</tr>
<tr>
<td>nitrogen oxides (NOₓ)</td>
<td>g/mi</td>
<td>0.107</td>
<td>0.028</td>
<td>73.5%</td>
</tr>
</tbody>
</table>
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?

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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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:
\[
\begin{align*}
\rho_t + (\rho u)_x &= 0 \\
(u + h(\rho))_t + u(u + h(\rho))_x &= \frac{1}{\tau}(U(\rho) - u)
\end{align*}
\]
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: $x_j = x_j^{eq} + y_j$, 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 \( F(\omega) = \frac{\alpha_1 + \alpha_3 \omega}{\alpha_1 + \alpha_2 \omega + \omega^2} \).

- \( \text{Re}(\omega) \): temporal growth/decay  
  \( |F| \): growth/decay across vehicles  
- \( \text{Im}(\omega) \): 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 \( \rightarrow \) exponential growth until nonlinearities kick in \( \rightarrow \) 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 \( \gamma \):
  \[
  |F(\omega)|^{1-\gamma} \cdot |G(\omega)|^\gamma \leq 1 \quad \forall \omega \in i\mathbb{R}
  \]
- 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.
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:
  \[
  du_j = \left[ \alpha_1(y_{j+1} - y_j) - \alpha_2 u_j + \alpha_3 u_{j+1} \right] dt + s_j dB_t
  \]

Amplification and decay of perturbation

System response to single perturbation

With noise: system’s mean deviation

We know: 1 AV can stabilize $\approx 25$ humans.
Popular Car-Following Models with Instabilities

- **Intelligent driver model (IDM):** \( \ddot{x}_j = a \left[ 1 - \left( \frac{\dot{x}_j}{v_0} \right)^\delta - \left( \frac{s_0 + \tau \dot{s}_j - \dot{x}_j \dot{s}_j / (2 \sqrt{ab})}{s_j} \right)^2 \right] \)

- **Optimal velocity model (OVM):** \( \ddot{x}_j = a \left( V(s_j) - \dot{x}_j \right) \)

- **Follow the leader – OVM:** \( \ddot{x}_j = a \left( V(s_j) - \dot{x}_j \right) + b \frac{\dot{s}_j}{(s_j)^\delta} \)

**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]

\[
\begin{pmatrix}
\rho \\
u
\end{pmatrix}_t + \begin{pmatrix}
u \\
\frac{1}{\rho} \frac{d\rho}{d\rho}
\end{pmatrix} \begin{pmatrix}
\rho \\
u
\end{pmatrix}_x = \begin{pmatrix}0 \\
\frac{1}{\tau} (U(\rho) - u)
\end{pmatrix}
\]

Hyperbolic part

Relaxation term

Eigenvalues

\[
\begin{align*}
\lambda_1 &= u - c \\
\lambda_2 &= u + c
\end{align*}
\]

\[c^2 = \frac{dp}{d\rho}\]

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 \( 2 \times 2 \) system converge (as \( \tau \to 0 \)) to solutions of the reduced equation \( \rho_t + (\rho U(\rho))_x = 0 \) ?

Sub-Characteristic Condition

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


\( \text{(LS)} \iff \text{(RE)} \iff \text{(SCC)} \)
Non-Equilibrium Traffic Flow Theory
Macroscopic Models: Traveling Wave Solutions

PW Model
\[
\begin{aligned}
\rho_t + (\rho u)_x &= 0 \\
u_t + uu_x + \frac{1}{\rho} p(\rho)_x &= \frac{1}{\tau}(U(\rho) - u)
\end{aligned}
\]

Traveling Wave Ansatz
\[\rho = \rho(\eta), \ u = u(\eta), \text{ with self-similar variable } \eta = \frac{x - st}{\tau}.
\]
Then \[\rho_t = -\frac{s}{\tau} \rho', \ \rho_x = \frac{1}{\tau} \rho', \ u_t = -\frac{s}{\tau} u', \ u_x = \frac{1}{\tau} u',\]
and \[p_x = \frac{1}{\tau} c^2 \rho', \ c^2 = \frac{dp}{d\rho}.
\]

Continuity Equation
\[
\begin{aligned}
\rho_t + (u\rho)_x &= 0 \\
-\frac{s}{\tau} \rho' + \frac{1}{\tau} (u\rho)' &= 0 \\
(\rho(u - s))' &= 0
\end{aligned}
\]
\[
\rho = \frac{m}{u - s} \\
\rho' = -\frac{\rho}{u - s} u'
\]

Momentum Equation
\[
\begin{aligned}
u_t + uu_x + \frac{p_x}{\rho} &= \frac{1}{\tau}(U - u) \\
-\frac{s}{\tau} u' + \frac{1}{\tau} uu' + \frac{dp}{d\rho} \frac{\rho'}{\rho} &= \frac{1}{\tau}(U - u) \\
(u - s)u' - c^2 \frac{1}{u - s} u' &= U - u
\end{aligned}
\]
\[
\frac{u'}{u - s} = \frac{(u - s)(U - u)}{(u - s)^2 - c^2}
\]
Jamiton Ordinary Differential Equation for \( u(\eta) \)

\[
u' = \frac{(u - s)(U(\rho) - u)}{(u - s)^2 - c(\rho)^2}
\]

where \( \rho = \frac{m}{u - s} \)

where

\( s = \) travel speed of jamiton

\( m = \) 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 \( \rho_S \) that:

\[
\begin{align*}
\text{Denominator} & \quad s + \frac{m}{\rho_S} = s + c(\rho_S) \quad \implies \quad m = \rho_S c(\rho_S) \\
\text{Numerator} & \quad s + \frac{m}{\rho_S} = U(\rho_S) \quad \implies \quad s = U(\rho_S) - c(\rho_S)
\end{align*}
\]

Algebraic condition (**Chapman-Jouguet condition** [Chapman, Jouguet (1890)]) that relates \( m \) and \( s \) (and \( \rho_S \)). Jamitons described by ZND detonation theory.
A Jamiton on a Circular Road \( t=0 \) s

Flynn, Kasimov, Nave, Rosales, Seibold
Traveling Waves in Continuity Equation

\[ \rho = \rho(\eta), \quad u = u(\eta), \quad \text{where} \quad \eta = \frac{x - st}{\tau}, \text{yields} \]

\[ \rho_t + (u \rho)_x = 0 \implies (\rho(u - s))' = 0 \]

\[ \implies \rho(u - s) = m \implies q = m + s\rho \]

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 \( q = Q(\rho) \).
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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 ($\rho, q$) lie on a line, because $\rho_t + q_x = 0$. Average ($\bar{\rho}, \bar{q}$) lies below equilibrium curve.
Scenario 1: Ring Road

- **Scenario 1: Ring Road with Multiple AVs**

  - **Energy Impact of AVs as Traffic Controllers**
  - **10/27/2020, IPAM AV Program 27 / 34**

  - Velocity vs position at time $t=0$, $t=50$, and $t=3600$.
  - Fundamental Diagram at time $t=3600.0$ s.

  - Key elements: Velocity, position, fundamental diagram, vehicle density, flow rate, and AV control.
Scenario 2: First Vehicle Driving with Fixed Speed

![Graphs showing velocity vs position at different times](image)

**Fundamental Diagram - time = 3600.0 s**

- **Fundamental Diagram**
- **Average initial state**
- **Average state at time t**
- **eq velocity line**
Scenario 3: Road Segment with Bottleneck at Outflow

Flow Manifestations of Traffic Waves

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Energy Manifestations of Traffic Waves

Simplified Data-Fitted Models

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Energy Impact of AVs as Traffic Controllers 10/27/2020, IPAM AV Program
• 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.
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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://www.youtube.com/watch?v=CKo-v_qwJwo