Connected and Automated Vehicles: Improving Safety and Efficiency Across the Scales

Gábor Orosz

University of Michigan, Ann Arbor
Motivation

**Connectivity** and **automation** of road vehicles may improve **safety**, **energy efficiency**, and **mobility**.
Connectivity + Automation

<table>
<thead>
<tr>
<th></th>
<th>without V2X</th>
<th>with V2X</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Human-driven Vehicle (HV)</td>
<td>Connected Human-driven Vehicle (CHV)</td>
</tr>
<tr>
<td></td>
<td>Automated Vehicle (AV)</td>
<td>Connected Automated Vehicle (CAV)</td>
</tr>
<tr>
<td>controlled by</td>
<td>controlled by</td>
<td></td>
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<tr>
<td>human driver</td>
<td>computer</td>
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Connectivity-Based Delay-Tolerant Control of Automated Vehicles: Theory and Experiments

Sándor Beregi, Sergei S. Avedisov, Chaozhe R. He, Dénes Takács, and Gábor Orosz

Connected and automated road vehicles: state of the art and future challenges

Tulga Ersal, Ilya Kolmanovsky, Neda Masoud, Necmiye Ozay, Jeffrey Scruggs, Ram Vasudevan, and Gábor Orosz

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Adaptive Cruise Control (ACC)

Simplified vehicle model

\[
\begin{align*}
\dot{h}(t) &= v_1(t) - v(t) \\
\tilde{v}(t) &= \text{sat}(u(t - \tau))
\end{align*}
\]

Desired behavior

- match velocity to preceding vehicle
- adjust velocity according to range policy

Simplest ACC algorithm

\[ u = \alpha (V(h) - v) + \beta (v_1 - v) \]

Equilibrium

\[ v_1^* = v^* = V(h^*) \]

Transfer function \( \tilde{v}_1 \rightarrow \tilde{v} \)

\[ T(s) = \frac{\beta s + \alpha \kappa}{s^2 e^{s\tau} + (\alpha + \beta)s + \alpha \kappa} \]
Adaptive Cruise Control (ACC)

Plant stability

![Diagram showing plant stability with stable and unstable conditions]
Adaptive Cruise Control (ACC)

Plant stability

\[ s^2 e^{s\tau} + (\alpha + \beta)s + \alpha \kappa = 0 \quad \Rightarrow \quad s_1, s_2, \ldots, s_\infty \]

\[ \text{Re}(s_k) < 0, \quad \forall k \in \mathbb{N} \]

Stability chart

\[ \tau = 0.6[s] \]
Adaptive Cruise Control (ACC)

String stability

![Diagram showing AV and HV with parameters s, l, h, and s_1.]

- **String stable**
  - Two graphs showing oscillations.
  - One graph with blue and red lines indicating stable behavior.

- **String unstable**
  - Another graph with blue and red lines indicating unstable behavior.
Adaptive Cruise Control (ACC)

String stability

\[ |T(j\omega)| < 1, \ \forall \omega > 0 \]

Critical delay / time headway

\[ \tau_{cr} = \frac{t_h}{2} \]

Stability chart

\[ \tau = 0.6[s] \]
Adaptive Cruise Control (ACC) - Experiments

15 [mi/hr]

30 [mi/hr]

20 [mi/hr]

10 [mi/hr]

Acceleration

Constant Speed

Braking

$AV \quad v \quad HV \quad v_1$

$s \quad \ell \quad h \quad s_1$
Adaptive Cruise Control (ACC) - Experiments

15 [mi/hr]

30 [mi/hr]

20 [mi/hr]

10 [mi/hr]

start

finish

speed, \( v \) [m/s]

accel. \( a \) [m/s²]

headway, \( h \) [m]

0 30 60 90 120 150 time, \( t \) [s]

0 35 time, \( t \) [s]
Adaptive Cruise Control (ACC) - Experiments

- Speeds: 10 [mi/hr], 20 [mi/hr], 30 [mi/hr], 15 [mi/hr]
- Graphs showing speed, acceleration, and headway over time.
Adaptive Cruise Control (ACC) - Experiments

String instability index

\[ C_S = \int_{f_0}^{f_{end}} \text{ReLu} \left( \frac{G(f)}{G_1(f)} - 1 \right) \, df \]
Adaptive Cruise Control (ACC) - Experiments

String instability index

\[ C_S = \int_{f_0}^{f_{\text{end}}} \text{ReLu} \left( \frac{G(f)}{G_1(f)} - 1 \right) \, df \]
Adaptive Cruise Control (ACC)

Connected Cruise Control (CCC)

Cooperative Adaptive Cruise Control (CACC)
Connected Cruise Control (CCC)

Dynamics of connected vehicle systems with delayed acceleration feedback
Jin I. Ge*, Gábor Orosz
Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

CrossMark

Motif-Based Design for Connected Vehicle Systems in Presence of Heterogeneous Connectivity Structures and Time Delays
Linjun Zhang and Gábor Orosz

Application of Predictor Feedback to Compensate Time Delays in Connected Cruise Control
Tamás G. Molnár, Wubing B. Qin, Tamás Insperger, and Gábor Orosz

Consensus and disturbance attenuation in multi-agent chains with nonlinear control and time delays
Linjun Zhang*1 and Gábor Orosz
Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48105, USA
Connected Cruise Control (CCC)

CCC algorithm – going beyond the line of sight

\[ u = \alpha (V(h) - v) + \beta_1 (v_1 - v) + \beta_2 (v_2 - v) \]

\[ \begin{align*}
V & \rightarrow v_{\text{set}} \\
\kappa & \rightarrow h_{\text{stop}} \\
t_h & = 1/\kappa
\end{align*} \]
Connected Cruise Control (CCC)

Link transfer functions

\[ T_{ij}(s) \]

Head-to-tail transfer function

\[ G_{02}(s) = T_{01}(s)T_{12}(s) + T_{02}(s) \]

Head-to-tail string stability

\[ |G_{02}(j\omega)| < 1, \quad \forall \omega > 0 \]

CCC algorithm – going beyond the line of sight

\[ u = \alpha (V(h) - v) + \beta_1(v_1 - v) + \beta_2(v_2 - v) \]

Without connectivity

\[ |G_{02}(j\omega)| \]

amplification, \[ |T_{ij}(\omega)| \]

angular frequency, \( \omega \) [rad/s]
Connected Cruise Control (CCC)

Link transfer functions

$T_{ij}(s)$

Head-to-tail transfer function

$G_{02}(s) = T_{01}(s)T_{12}(s) + T_{02}(s)$

Head-to-tail string stability

$|G_{02}(j\omega)| < 1, \ \forall \omega > 0$

CCC algorithm – going beyond the line of sight

$u = \alpha (V(h) - v) + \beta_1(v_1 - v) + \beta_2(v_2 - v)$

With connectivity

---

v_{set} \quad \text{time headway} \quad t_h = 1/\kappa

h_{stop} \quad h

\begin{align*}
\beta_{02} &\geq 1 \\
\beta_{01} &\geq 1
\end{align*}

---

$T_0, T_{12}, G_{02}$

amplification, $|T_{02}|$

angular frequency, $\omega$ [rad/s]
Human Driver - Experiments

- Acceleration
- Constant Speed
- Braking

Human-driven vehicle

Graph showing acceleration over time.
Adaptive Cruise Control (ACC) - Experiments

- Acceleration
- Constant Speed
- Braking

Automated Vehicle

[Diagram showing the process with AV, HV, and their corresponding states (v, v1, v2, s, l, h, s1), and a graph showing acceleration over time.]
Connected Cruise Control (CCC) - Experiments

- Acceleration
- Constant Speed
- Braking

Connected Automated Vehicle

![Diagram of connected vehicles and their movements](image)

![Graph of acceleration over time](image)

- CAV $v$
- HV $v_1$
- CHV $v_2$

$s$, $\ell$, $h$, $s_1$
Experiments in Mixed Traffic

8.6 miles = 13.5 km
Experiments in Mixed Traffic

Energy consumption (per unit mass)

\[ w_i = \int_0^T \text{ReLU}(\dot{v}_i(\theta)) v_i(\theta) d\theta \]
Experiments in Mixed Traffic

7% energy saving by connectivity
19% energy saving by connectivity

<table>
<thead>
<tr>
<th></th>
<th>$w_1 [J/kg]$</th>
<th>$w_2 [J/kg]$</th>
<th>$w_3 [J/kg]$</th>
<th>$w_4 [J/kg]$</th>
<th>$w_5 [J/kg]$</th>
<th>$w_6 [J/kg]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp #1</td>
<td>86</td>
<td>93</td>
<td>100</td>
<td>79</td>
<td>77</td>
<td>72</td>
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<tr>
<td>Exp #2</td>
<td>90</td>
<td>88</td>
<td>97</td>
<td>100</td>
<td>96</td>
<td>87</td>
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<tr>
<td>Exp #3</td>
<td>83</td>
<td>84</td>
<td>100</td>
<td>94</td>
<td>91</td>
<td>81</td>
</tr>
<tr>
<td>Exp #4</td>
<td>80</td>
<td>76</td>
<td>100</td>
<td>84</td>
<td>85</td>
<td>77</td>
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Connectivity can Enhance the Benefits of Automation

How can we leverage connectivity in large scale traffic?
Connectivity can Enhance the Benefits of Automation
Traffic jams cost time, fuel, money, increase pollution

V2X connectivity – can help!

US39 South near Dearborn, Michigan

I96 near Ann Arbor, Michigan
Connectivity may Help to Improve Traffic Efficiency Even for Lean Penetration of Connectivity

Connected Traffic Control (CTC)
- Measure effect on traffic behind

Connected Cruise Control (CCC)
- Anticipate/predict traffic ahead

V2X

CHV  HV  HV  HV  CAV  HV  HV  HV  HV  CHV
Traffic Forecasting using Vehicle-to-Vehicle Communication

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Delayed Lagrangian continuum models for on-board traffic prediction
Tamás G. Molnár, Devesh Upadhyay, Michael Hopka, Michiel Van Nieuwstadt, Gábor Orosz

On-Board Traffic Prediction for Connected Vehicles: Implementation and Experiments on Highways
Tamás G. Molnár, Xunbi A. Ji, Sanghoon Oh, Deñes Takács, Michael Hopka, Devesh Upadhyay, Michiel Van Nieuwstadt, and Gábor Orosz

2022 American Control Conference (ACC)
Atlanta, USA, June 8-10, 2022
We Recorded Data in Real Traffic Conditions

Experiments with connected human-driven vehicles

Natural driving no platooning, not necessarily same lane

Trajectory data in congestions
GPS Trajectory Data Obtained via Connectivity

- Trajectories are similar, shifted copies of each other
- Congestion waves propagate in time and space (5-6 m/s)
Main features of V2X data:
- Propagation of traffic in time
- Propagation of traffic in space
- String instability

How to directly utilize V2X data for traffic prediction and control?
**Goal:** predict upcoming slowdowns

**Benefit:** optimized operation of our vehicle using prediction

**Method:** V2X-connectivity reveals what is ahead → tells what may happen to us later
Predict the ego’s future motion from lead’s past data

**Connectivity-based prediction:** real-time on-board individualized

Different from routing apps (location-based, few minutes delay)
Predictions Rely on Congestion Wave Propagation

- Congestion waves propagate backwards along the road
- Simplest prediction: copy and shift the lead’s trajectory
- More sophisticated models improve the accuracy
Prediction horizon depends on speed and distance.
Prediction horizon depends on speed and distance
Prediction horizon depends on speed and distance

Predictions can be Updated in Real Time
Prediction horizon depends on speed and distance
Prediction horizon depends on speed and distance

Predictions can be Updated in Real Time

Prediction horizon depends on speed and distance
Predictions can be Updated in Real Time

Prediction horizon depends on speed and distance

- **ego** lead
- **V2V**
- **lead**
- **ego** lead

Prediction horizon depends on speed and distance.
Traffic Models are Needed for Predictions

Car-following behavior:

\[ X(n, t) = X(n + 1, t - t_g) - d_{st} \]
\[ v(n, t) = v(n + 1, t - t_g) \]

Nominal traffic model:

**Input**: position and speed of lead

\[ X_{k+1} = AX_k + Bu_k + \xi, \quad \xi \sim \mathcal{N}(0, Q) \]
\[ y_k = CX_k + \eta, \quad \eta \sim \mathcal{N}(0, R) \]

**State**: position and speed of vehicles between lead and ego

**Output**: position and speed of ego
First We Estimate the Present State of Traffic

- Simulate traffic between lead and ego over the past, up to present
- Use traffic memory to correct the model with Kalman filter

\[
\hat{X}_{k|k-1} = A\hat{X}_{k-1|k-1} + Bu_{k-1}
\]
\[
P_{k|k-1} = AP_{k-1|k-1}A^T + Q
\]
\[
M_k = P_{k|k-1}C^T(CP_{k|k-1}C^T + R)^{-1}
\]
\[
\hat{X}_{k|k} = \hat{X}_{k|k-1} + M_k(y^m_k - C\hat{X}_{k|k-1})
\]
\[
P_{k|k} = (I - M_kC)P_{k|k-1}
\]
Simulate traffic between lead and ego into the future
Use nominal model, no correction

Predict
\[
\dot{X}_{k|k-1} = AX_{k-1|k-1} + Bu_{k-1} \\
P_{k|k-1} = AP_{k-1|k-1}A^T + Q
\]
Predictions Match the Collected Data

- Simulate traffic between lead and ego into the future
- Use nominal model, no correction

Predict

\[
\hat{X}_{k|k-1} = A\hat{X}_{k-1|k-1} + Bu_{k-1}
\]

\[
P_{k|k-1} = AP_{k-1|k-1}A^T + Q
\]
Similar Accuracy is Achieved when using LSTM
The Method was Tested in Real Traffic
The Method was Tested in Real Traffic
Energy-efficient Reactive and Predictive Connected Cruise Control

Minghao Shen, Student Member, IEEE, Robert Austin Dollar, Member, IEEE, Tamas G. Molnar, Member, IEEE, Chaozhe R. He, Member, IEEE, Ardalan Vahidi, Senior Member, IEEE, Gábor Orosz Senior Member, IEEE
Connectivity can Enable Traffic Control via CAVs

Connected Traffic Control (CTC)

Virtual Rings on Highways: Traffic Control by Connected Automated Vehicles

Tamás G. Molnár, Michael Hopka, Devesh Upadhyay, Michiel Van Nieuwstadt, and Gábor Orosz

Connected Cruise and Traffic Control for Pairs of Connected Automated Vehicles

Sicong Guo®, Gábor Orosz®, Senior Member, IEEE, and Tamás G. Molnár®, Member, IEEE
Undesired human response causes instability

\[ u_{HV} = \alpha_h (V_h(h) - \nu) + \beta_h (v_L - \nu) \]

\[ \dot{h}(t) = v_L(t) - v(t) \]

\[ \dot{v}(t) = u(t - \tau) \]
Smooth Driving Mitigates Congestion

$u_{HV} = \alpha_h(V_h(h) - v) + \beta_h(v_L - v)$

$u_{AV} = \alpha(V(h) - v) + \beta(v_L - v)$

Automated vehicles can drive smoother…

…but may be outnumbered by unstable drivers
Traffic Control Requires High Penetration of Automation

\[ u_{HV} = \alpha_h (V_h(h) - v) + \beta_h (v_L - v) \]
\[ u_{AV} = \alpha (V(h) - v) + \beta (v_L - v) \]

Large penetration of automation is needed to mitigate congestions.

Can connectivity help?
Automated vehicles can drive smoother…

…but may be outnumbered by unstable drivers
Even Low Penetration of Connectivity is Beneficial

Connectivity helps to smoothen traffic

Stability may be achievable, degree of instability decreases
Energy consumption (per unit mass)

\[ w_i = \int_0^T \text{ReLU}(\dot{v}_i(\theta)) v_i(\theta) d\theta \]

Energy is saved

Beneficial both for CHV and CAV

Connected Traffic Control (CTC)

Even Low Penetration of Connectivity is Beneficial
Even Low Penetration of Connectivity is Beneficial

\[ u_{CAV} = \alpha (V(h) - v) + \beta (v_L - v) + \beta_B (v_B - v) \]

Connectivity helps to smoothen traffic

Stability may be achievable, degree of instability decreases
What about Combining CCC and CTC → Cooper Pairs in Traffic

\[ u_0 = \alpha_0 (V_0(h_0) - v_0) + \beta_0 (v_1 - v_0) + \beta_{0,N+1} (v_{N+1} - v_0) \]

\[ u_{N+1} = \alpha_{N+1} (V_{N+1}(h_{N+1}) - v_{N+1}) + \beta_{N+1} (v_{N+2} - v_{N+1}) + \beta_{N+1,0} (v_0 - v_{N+1}) \]
Human Drivers are String Unstable

100% HV

speed, \( v \) (m/s)

0 10 20 30

0 100 200 300

time, \( t \) (s)
Large Penetration of AVs can Smoothen Traffic

5% AV

speed, $v$ (m/s)

0 10 20 30

0 100 200 300
time, $t$ (s)
Large Penetration of AVs can Smoothen Traffic

10% AV

![Diagram showing the impact of AV penetration on traffic flow]

- Speed, $v$ (m/s)
- Time, $t$ (s)

AVs: Autonomous Vehicles
HV: Human-driven Vehicles
Large Penetration of AVs can Smoothen Traffic

20% AV
Large Penetration of AVs can Smoothen Traffic

100% AV

Graph showing speed (m/s) vs. time (s) for AVs and HVs.
Human Drivers are String Unstable
Low Penetration of CAV can Smoothen Traffic
Low Penetration of CAV can Smoothen Traffic
Low Penetration of CAV can Smoothen Traffic

10% AV

Without Connectivity

10% CAV

With Connectivity
Low Penetration of CAV can Smoothen Traffic

20% AV

Without Connectivity

With Connectivity

20% CAV

speed, $v$ (m/s)

time, $t$ (s)
Low Penetration of CAV can Smoothen Traffic

Without Connectivity

100% AV

With Connectivity

10% CAV
Low Penetration of CAV can Smoothen Traffic

\[
\Gamma_i = \frac{\max_{t \geq 0} |v_i(t) - v_i(0)|}{\max_{t \geq 0} |v_L(t) - v_L(0)|}
\]

\[
\bar{\Gamma} = \frac{1}{100} \sum_{i=0}^{99} \Gamma_i
\]

Connectivity can really make a difference!
Bridging the Connectivity Gap with Infrastructure

TRAFFIC CONTROL

CV
connected vehicle

V2I
roadside unit

4G/5G

CAT
connected automated truck

V2I
roadside unit

4G/5G

CV
connected vehicle

TRAFFIC PREDICTION

CV
connected vehicle

V2I
roadside unit

4G/5G

CV
connected vehicle

CCAT

CMDOT
Michigan Department of Transportation

NAVISTAR

commsignia

Ford
Bridging the Connectivity Gap with Infrastructure

[Map showing various roads and intersections like 9 mile Rd, 7 mile Rd, 5 mile Rd, Ann Arbor Rd, Ford Rd, Michigan 12, Interstate 94, etc.]

[Graph showing speed over time with current time, speed prediction, actual speed, and prediction horizon indicated]
Because Traffic has a Memory

Cheers!
Questions ?