Autonomous Vehicles and Connected Systems: Market Adoption and Flow Implications

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Northwestern University
Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- Throughput Analysis: Simulation Results
- Lane Changing in Connected Environment: Game Theory
- Takeaways, Limitations and Challenges
WHAT IS A DRIVERLESS CAR?

Federal National Highway Traffic Safety Administration (NHTSA): Four Levels of Automation

**Preliminary Statement of Policy Concerning Automated Vehicles**

**Level 0 (No automation)**
The human is in complete and sole control of safety-critical functions (brake, throttle, steering) at all times.

**Level 1 (Function-specific automation)**
The human has complete authority, but cedes limited control of certain functions to the vehicle in certain normal driving or crash imminent situations. Example: electronic stability control

**Level 2 (Combined function automation)**
Automation of at least two control functions designed to work in harmony (e.g., adaptive cruise control and lane centering) in certain driving situations.
Enables hands-off-wheel and foot-off-pedal operation.
*Driver still responsible for monitoring and safe operation and expected to be available at all times to resume control of the vehicle.* Example: adaptive cruise control in conjunction with lane centering

**Level 3 (Limited self-driving)**
Vehicle controls all safety functions under certain traffic and environmental conditions.
Human can cede monitoring authority to vehicle, which must alert driver if conditions require transition to driver control.
*Driver expected to be available for occasional control.* Example: Google car

**Level 4 (Full self-driving automation)**
Vehicle controls all safety functions and monitors conditions for the entire trip.
The human provides destination or navigation input but is not expected to be available for control during the trip. *Vehicle may operate while unoccupied.* Responsibility for safe operation rests solely on the automated system
## Implications of Each Level: User, Market and Society

*Kornhauser, 2014*

<table>
<thead>
<tr>
<th>Level</th>
<th>&quot;Less&quot;</th>
<th>Value Proposition</th>
<th>Market Force</th>
<th>Societal Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &quot;55 Chevy&quot;</td>
<td>Zero</td>
<td>Zero</td>
<td>Zero</td>
<td>Zero</td>
</tr>
<tr>
<td>1 &quot;Cruise Control&quot;</td>
<td>Infinitesimal</td>
<td>Some Comfort</td>
<td>Infinitesimal</td>
<td>Infinitesimal</td>
</tr>
<tr>
<td>2 &quot;CC + Emergency Braking&quot;</td>
<td>Infinitesimal</td>
<td>Some Safety</td>
<td>Small; Needs help From “Flo &amp; the Gecko” (Insurance Industry)</td>
<td>“20+%” fewer accidents; less severity; fewer insurance claims</td>
</tr>
<tr>
<td>3 &quot;Texting Machine&quot;</td>
<td>Some</td>
<td>Liberation (some of the time/places); much more Safety</td>
<td>Consumers Pull, TravelTainment Industry Push</td>
<td>Increased car sales, many fewer insurance claims, Increased VMT</td>
</tr>
</tbody>
</table>
The concept is not new…

GM's Futurama exhibit at the 1939 World’s Fair in NYC

"abundant sunshine, fresh air [and] fine green parkways" upon which cars would drive themselves.
The concept is not new…
But now it is here, there and everywhere...

2015 SELF DRIVING CARS
**SAFETY FIRST: What Causes Crashes?**

**Table 1. Driver-, Vehicle-, and Environment-Related Critical Reasons**

<table>
<thead>
<tr>
<th>Critical Reason Attributed to</th>
<th>Number</th>
<th>Estimated Percentage* ± 95% conf. limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers</td>
<td>2,046,000</td>
<td>94% ±2.2%</td>
</tr>
<tr>
<td>Vehicles</td>
<td>44,000</td>
<td>2% ±0.7%</td>
</tr>
<tr>
<td>Environment</td>
<td>52,000</td>
<td>2% ±1.3%</td>
</tr>
<tr>
<td>Unknown Critical Reasons</td>
<td>47,000</td>
<td>2% ±1.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2,189,000</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Percentages are based on unrounded estimated frequencies (Data Source: NMVCCS 2005–2007)

Drivers Do!
Autonomous vehicle technologies reduce/eliminate human error

### Table 2. Driver-Related Critical Reasons

<table>
<thead>
<tr>
<th>Critical Reason</th>
<th>Estimated (Based on 94% of the NMVCCS crashes)</th>
<th>Percentage* ± 95% conf. limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recognition Error</td>
<td>845,000</td>
<td>41% ±2.2%</td>
</tr>
<tr>
<td>Decision Error</td>
<td>684,000</td>
<td>33% ±3.7%</td>
</tr>
<tr>
<td>Performance Error</td>
<td>210,000</td>
<td>11% ±2.7%</td>
</tr>
<tr>
<td>Non-Performance Error (sleep, etc.)</td>
<td>145,000</td>
<td>7% ±1.0%</td>
</tr>
<tr>
<td>Other</td>
<td>162,000</td>
<td>8% ±1.9%</td>
</tr>
<tr>
<td>Total</td>
<td>2,046,000</td>
<td>100%</td>
</tr>
</tbody>
</table>

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Connected Vehicles: Basic Concepts
Connected Vehicles Technology

Drivers

Connected Vehicles technology helps drivers with these decisions.

Free-Flow

Car-Following
Connected Vehicles Technology

Drivers: Dynamic Mobility Applications

Queue Warning

1. Host Vehicle receives data and provides driver with imminent queue warning
2. Vehicles broadcast their rapid changes in speed, acceleration, position, etc.
3. Queue condition forms
4. Driver provides sufficient time to brake safely, change lanes, or even modify route

Speed Harmonization

1. Vehicles slowing down at recurrent bottleneck broadcast speed, location, etc.
2. TMC traffic management center identifies impending congestion and initiates speed harmonization plan for upstream vehicles
3. TMC relays appropriate speed recommendations to upstream vehicles
4. Upstream vehicles implement (or alert drivers to) the recommended speed

Cooperative Adaptive Cruise Control

Without CACC:
- Irregular braking and acceleration
- Longer headways
- Lower throughput
- Risk of rear-end collisions

CACC Enabled:
- Coordinated speeds
- Minimized headways
- Higher throughput
- Reduced rear-end collisions

1. Lead vehicle broadcasts location, heading, and speed
2. CACC-enabled following vehicles automatically adjust speed, acceleration, and following distance
3. Any speed or acceleration perturbations by lead vehicle can be instantly accounted for by following vehicles utilizing V2V communication

Source: Federal Highway Administration (FHWA), INFLO ConOps Report, 2012
**Connectivity**

Connected systems (internet of everything)

- Ad-hoc networks
- Peer-to-Peer (Neighbor)
- Receive only
- Isolated

**Automated**

- Fully manual Level 0
- Fully automated Level 4

**INTELLIGENCE RESIDES ENTIRELY IN VEHICLE**

**Coordinated**

- Real-time info
- Asset tracking
- Electronic tolling

**Cooperative Driving**

- Optimized flow
- Routing
- Speed harmonization

**Autonomous Vehicles**

**Smart Highways**

**INTELLIGENCE RESIDES ENTIRELY IN VEHICLE**
Coordination through connectivity and automation: Continuous-flow at-grade intersections
Two Sets of Questions:

1. Adoption Factors

- What factors affect purchase and use decisions of autonomous vehicles?
- Will people use these differently from conventional cars?
- Will new mobility service alternatives (e.g. hybrid transit) emerge in connection with these vehicles?
- How do we incorporate the implications of autonomous vehicle adoption in our planning models?
- Are current models adequate to consider these aspects?
Two Sets of Questions:

2. Traffic Flow/System Implications

• What are the implications of connectivity and/or automated functions on how we model driver behavior and traffic?

• How do we model the communications aspects (of connected systems) jointly with the traffic flow (e.g. to support operational control design)?

• What are the implications of automation vs. connectivity on traffic system performance in terms of
  
  SAFETY
  THROUGHPUT ("Capacity")
  STABILITY (⇒ Safety)
  FLOW BREAKDOWN (Reliability)
  SUSTAINABILITY (Greenhouse gases, energy)

• What is the sensitivity to relative market penetration on impact on mixed traffic performance?
Who will buy?

- WILL CLASSIC ROGERS’ ADOPTION CURVE HOLD?
KEY ADOPTION FACTORS

• ABILITY TO DRIVE
• TRUST
• BENEFIT PERCEPTION
  – Safety
  – Mobility
  – Efficiency (time saving, constraint reduction)
• AFFORDABILITY
• Ability to drive
YOU and DRIVING

• THOSE WHO CANNOT DRIVE
• THOSE WHO PREFER NOT TO DRIVE
• THOSE WHO PREFER TO DRIVE
• THOSE WHO LOVE TO DRIVE
• Ability to drive
• TRUST
Age

Time value for parents

Safety value for parents

Cohort Effect: Increasing trust

Cohort Effect: Increasing need

Safety value for self

Time value for children

Age
TWO KEY ASPECTS

• AUTONOMOUS CAR AS MOBILITY TOOL
  – Greater safety, efficiency, etc...
  – Enables multitasking, short vs. longer spans

• AS ROBOTIC ASSISTANT
  – Go shop, pick up kids– all mobility chores imposed by auto-centric suburban lifestyle
  – For small businesses– go deliver, pick up supplies...
ADOPTION PROPENSITY

MONEY CONSTRAINED

Just as well...
LOW PROPENSITY

GADGET? TOY?
CONVENIENCE?
SAFETY?

Role for Policy?
Discounts, Incentives
Payment plans...

High Value
Can Afford
HIGH PROPENSITY

TIME CONSTRAINED
ADOPTION PROPENSITY

MONEY CONSTRAINED

Stay healthy!
LOW PROPENSITY

Role for Policy?
Discounts, Incentives
Family plans
Payment plans...

TIME VALUE?
CONVENIENCE?
SAFETY?

? 

High Value
Can Afford
HIGH PROPENSITY

HEALTH CONSTRAINED
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- Throughput Analysis: Simulation Results
- Takeways, Limitations and Challenges
An Incremental View

- Driverless vehicles have different performance characteristics, and enable different (higher) service levels for a given infrastructure.
- System performance dependent on specific technological features and market penetration; flow modeling (supply side) largely capable of capturing these interactions and impacts.
- Changes in performance captured through usual LOS attributes: travel time, reliability; and some less usual ones: comfort, perceived safety, availability (waiting time), in addition to cost.
- Travel behavior models, including present-day activity-based models, capture responses to these attributes in terms of traveler choices of destination, modes, routes, etc...
- We can iterate these to achieve mutually consistent state (equilibrium).
Demand Models (Activity and Travel Behavior)

Activity choices:
- engagement
- duration
- sequencing and chaining
- with whom, etc...

Travel choices:
- destination
- mode
- trip timing
- path choice

Performance Models (flow simulation)

Transportation System Attributes:
- performance measures
- travel time
- reliability
- availability
- comfort/convenience
- safety
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• Travel behavior models, including present-day activity-based models, capture responses to these attributes in terms of traveler choices of destination, modes, routes, etc...
• We can iterate these to achieve mutually consistent state (equilibrium).
• Technology features as vehicle attributes influencing vehicle type choice, in same way as fuel type, or performance features.
Demand Models (Activity and Travel Behavior)

**MOBILITY CHOICES**
- Vehicle type choice
  
  (Degree of Autonomy)
- Mobility program choice

Activity choices
- engagement
- duration
- sequencing and chaining
- with whom, etc...

Travel choices
- destination
- mode
- trip timing
- path choice

Performance Models (flow simulation)

Transportation System Attributes
- performance measures
- travel time
- reliability
- availability
- comfort/convenience
- safety

DEMAND (FLOWS) V

TECHNOLOGY T
Driverless vehicles impact activity patterns at the individual and household levels in ways that go well beyond current ABM capabilities.

**TWO KEY ASPECTS:**

- **AUTONOMOUS CAR AS MOBILITY TOOL**
  - Greater safety, efficiency, etc...
  - Enables multitasking, short vs. longer spans
- **AS ROBOTIC ASSISTANT**
  - Go shop, pick up kids— all mobility chores imposed by auto-centric suburban lifestyle
  - For small businesses— go deliver, pick up supplies...

**Demand-side:**

- Implications for vehicle use/sharing within household
- “Chauffeur” features of waiting and/or showing up when needed
- Additional trips and VMT (deadheading), remote parking...
- Sequencing and routing

**Supply-side:**

- Vehicle availability/waiting time attribute
Less Incremental II

**Major Mobility Supply Shifts**

- Driverless vehicles will enable new forms of mobility supply
- New forms of car sharing with greater convenience may reduce the motivation for individual ownership
- Car-sharing marketplaces may emerge—driverless Uber, reducing cost and uncertainty of sharing model
- The realm between personal transportation and public mobility can widen considerably to include various hybrid forms
- What will become of public transit as we know it? Driverless, personalized at low density, more efficient and accessible at higher density...
- Some of these trends beginning to emerge today (e.g. Helsinki’s goal of public personal urban mobility).
ACTIVITY SYSTEM and MOBILITY CHOICES

Demand Models (Activity and Travel Behavior)
- Activity choices
  - engagement
  - duration
  - sequencing and chaining with whom, etc...
- Travel choices
  - destination
  - mode
  - trip timing
  - path choice

Performance Models (flow simulation)

Transportation System Attributes
- performance measures
- travel time
- reliability
- availability
- comfort/convenience
- safety

NEW MOBILITY INDUSTRY SUPPLY OPTIONS

DEMAND (FLOWS) V

TECHNOLOGY T
Are Tools Adequate?

- Existing state-of-the-art tools could address *incremental scenario*
  - Flow modeling aspects require additional calibration as technology prototypes appear; interaction between driverless and other vehicles biggest challenge, but traffic modeling community is rising to the task.
  - More uncertainty on behavior side, though incremental scenarios could be explored under selected assumptions.
Are Tools Adequate?

• Existing model structures fail under *Less Incremental Scenario I* features:
  - robotic assistant/chauffeur features,
  - within household shared use,
  - role of information...
  
  will stress even most advanced model structures beyond limit of applicability.

• Development requires going back to basics of travel/activity behavior research, combining qualitative insight with experimental methods (e.g. virtual gaming environments).
Are Tools Adequate?

• New mobility supply options under *Less Incremental Scenario II* are not within scope of any existing models.

• There are no models in planning practice that can predict emergence of new modes and forms of mobility.

• Typically provided exogenously to the models, in the form of scenarios to be analyzed.

• Existing models (ABM and supply-side) not up to the task of modeling full implications of these new mobility supply scenarios.
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- Takeways, Limitations and Challenges
Work in collaboration with recent PhD graduate Alireza Talebpour

*Currently Assistant Professor at Texas A&M University*
Acceleration Framework

- No Automation Not Connected
- No Automation Connected
- Self-Driving Not Connected
# Acceleration Framework

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>No Automation Not Connected</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>No Automation Connected</td>
<td>Probabilistic</td>
<td></td>
<td>High</td>
<td>High</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Self-Driving Not Connected</td>
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</table>

- The car-following model of Talebpour, Hamdar, and Mahmassani (2011) is used.
  - Probabilistic
  - Recognizes two different driving regimes:
    - Congested
    - Uncongested
  - Consider crashes endogenously
### Acceleration Framework

<table>
<thead>
<tr>
<th>No Automation</th>
<th>No Automation</th>
<th>Self-Driving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connected</td>
<td>Not Connected</td>
<td>Not Connected</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Active V2V Communications</th>
<th>Inactive V2V Communications</th>
<th>Active V2I Communications</th>
<th>Inactive V2I Communications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Acceleration Behavior:</td>
<td>Deterministic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Perception of Surrounding Traffic Condition:</td>
<td>Accurate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Reaction Time:</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Safe Spacing:</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• High-Risk maneuvers:</td>
<td>Very Unlikely</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **The Intelligent Driver Model** (Treiber, Hennecke, and Helbing, 2000) is used.
### Acceleration Framework

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Communications Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active V2V</td>
<td>Inactive V2V</td>
</tr>
<tr>
<td>Active V2I</td>
<td>Inactive V2I</td>
</tr>
</tbody>
</table>

- Sources of information: drivers’ perception and road signs
- Behavior is modeled similarly to the “No Automation Not Connected”
### Acceleration Framework

<table>
<thead>
<tr>
<th>No Automation Not Connected</th>
<th>No Automation Connected</th>
<th>Self-Driving Not Connected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active V2V Communications</strong></td>
<td><strong>Inactive V2V Communications</strong></td>
<td><strong>Active V2I Communications</strong></td>
</tr>
<tr>
<td><strong>Inactive V2I Communications</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **TMC can detect individual vehicle trajectories**
  - Speed harmonization
  - Queue warning

- **Depending on the availability of V2V Communications:**
  - Active V2V Communications: IDM
  - Inactive V2V Communications: Talebpour, Hamdar, and Mahmassani.
Acceleration Framework

- No communication between vehicle and TMC
- Depending on the availability of V2V Communications:
  - Active V2V Communications: IDM
  - Inactive V2V Communications: Talebpour, Hamdar, and Mahmassani
• On-board sensors are simulated:
  • SMS Automation Radars (UMRR-00 Type 30) with 90m±2.5% detection range and ±35 degrees horizontal Field of View (FOV).
• Speed should be low enough so that the vehicle can react to any event outside of the sensor range ($v_{\text{max}}$) (Reece and Shafer, 1993 and Arem, Driel, Visser, 2006).

\[
v_{\text{max}} = \sqrt{-2a_n^{\text{decc}} \Delta x}
\]

\[
a_n(t) = \min\left(a_n^{d}(t), k(v_{\text{max}} - v_n(t)) \right)
\]

\[
a_n^{d}(t) = k_a a_{n-1}(t - \tau) + k_v (v_{n-1}(t - \tau) - v_n(t - \tau)) + k_d (s_n(t - \tau) - s_{\text{ref}})
\]
Connected Vehicles Technology Communication

- It is essential to consider the V2V/V2I communications when modeling a connected environment.
- Connectivity through the vehicular ad hoc network (VANET) is a key element.
- Several studies focused on connectivity in a VANET,
  - Jin et al. (2011)
  - Ajeer et al. (2011)
  - Durrani et al. (2010)
Connected Vehicles Technology
Communication

- Most of these studies,
  - Assume homogenous Poisson distribution for vehicles along a road segment.
  - Consider road segments as one-dimensional objects.
  - Assume normal distribution for speed.

- It is essential to study the connectivity of VANET by considering
  - Non-homogenous distribution for vehicles along a road segment.
  - Road segments as two-dimensional objects.

- Existence of a communication link between two nodes depends on,
  - Wireless technology
  - Transmission power and rate
  - Distance and geographical location
  - Signal propagation and interference
Communication Network
Dynamic Nature of Vehicular Movements

Based on NGSIM Data
Communication Network
Percolation

• There are many instances in which
  a fluid spreads through a medium,
  a disease spreads among people,
  information spreads in social networks, and
  a liquid penetrates into a porous material.

• Broadbent and Hammersley (1957) introduced the “percolation theory” to model these instances.

• There are two models, Discrete Percolation and Continuum Percolation

• Design question: how to form clusters of communicating vehicles, with a “leader” communicating with the infrastructure (V2I) and other groups, and transmitting information within the group?
Clustering Algorithm
What is a cluster?

- Each cluster consists of,
  - One cluster head
  - Several cluster members

- Assumption: cluster members can only communicate with the cluster head (1-hop communication between cluster members).

- A cluster head can communicate with cluster members and other cluster heads from other clusters.

Having stable clusters is the key to reducing signal interference.

This study incorporated driving history and driver heterogeneity, in addition to the usual distance and speed measures into VANET clustering algorithms.
V2V Communications Model
Clustering

A clustering algorithm based on Affinity Propagation (Hassanabadi et al., 2014 and Frey and Dueck, 2007) is used for clustering.

Model Parameters:

- $s(i, k)$: similarity between $i$ and $k$ indicates how well $k$ can be $i$’s exemplar.

\[
s(i, k) = -\|x_i - x_k\| - \|x^i - x^K\|
\]
V2V Communications Model
NS3 Implementation

Network Simulator 3 (NS3) is a discrete-event communication network simulator.

Dedicated Short-Range Communication (DSRC) Protocol is the standard protocol for V2V communications. DSRC in 5.9GHz spectrum.

DSRC interface uses 7 non-overlapping channels (Xu et al., 2012):
- A control channel with 1000m range.
- Six service channels with 30-400m range.

DSRC uses
- The control channel to send safety packets.
- Service channels to send non-safety packets (e.g. Clustering information)
V2V Communications Model
NS3 Implementation – Clustering Frequency

Packet size = 50 byte: Location, speed, acceleration
Packet Forwarding Overhead = 10 ms (Koizumi et al., 2012)
Effective Transmission range = 5m
Biggest Cluster Size = 8

Effective Transmission range = 10m
Biggest Cluster Size = 93

Effective Transmission range = 20m
Biggest Cluster Size = 216

DSRC in 5.9GHz spectrum.
V2V Communications Model
NS3 Implementation – Packet Delivery

Effect of Packet Delivery Rate on Clustering

- PDR = 50%
- PDR = 70%
- PDR = 80%
- PDR = 90%
- PDR = 100%
V2V Communications Model
NS3 Implementation – Packet Delivery

Effect of Packet Delivery Rate on Clustering

- PDR = 50%
- PDR = 70%
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- PDR = 90%
- PDR = 100%
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Stability Analysis

• Local Stability vs. String Stability

Car-following models: fifty years of linear stability analysis – a mathematical perspective.
Transportation Planning and Technology
Stability Analysis

A car-following model can be formulated as:

\[
\begin{align*}
\dot{x}_n &= v_n \\
\dot{v}_n &= f(s_n, \Delta v_n, v_n)
\end{align*}
\]

Empirical observations suggest that there exists an equilibrium speed-spacing relationship:

\[
f(s^*, 0, V(s^*)) = 0, \ \forall s^* > 0
\]

A platoon of infinite vehicles is string stable if a perturbation from equilibrium decays as it propagates upstream.
Stability Analysis

String Stable Regime  Unstable Oscillatory Regime  Unstable Collision Regime
Stability Analysis

Following the definition of string stability, the following criteria guarantees the string stability of a heterogeneous traffic stream (Ward, 2009):

\[
\sum_{n} \left[ \frac{f_{v}^{n^2}}{2} - f_{\Delta v}^{n} f_{v}^{n} - f_{s}^{n} \right] \left[ \prod_{m \neq n} f_{s}^{m} \right]^{2} < 0
\]

where

\[
f_{s}^{n} = \left. \frac{\partial f \left( s_n, \Delta v_n, v_n \right)}{\partial s_n} \right|_{(s^*, 0, V(s^*))}
\]

\[
f_{v}^{n} = \left. \frac{\partial f \left( s_n, \Delta v_n, v_n \right)}{\partial v_n} \right|_{(s^*, 0, V(s^*))}
\]

\[
f_{\Delta v}^{n} = \left. \frac{\partial f \left( s_n, \Delta v_n, v_n \right)}{\partial \Delta v_n} \right|_{(s^*, 0, V(s^*))}
\]
Stability Analysis
Heterogeneous Traffic Flow

- Parameters of regular vehicles are adjusted to create a very unstable traffic flow.

- As the number of connected vehicles increases, stability of the heterogeneous traffic flow increases.
Stability Analysis
Heterogeneous Traffic Flow

- Parameters of regular vehicles are adjusted to create a very unstable traffic flow.
- As the number of automated vehicles increases, stability of the heterogeneous traffic flow increases.
Stability Analysis
Heterogeneous Traffic Flow

At high market penetration rates, the effect of autonomous vehicles on stability is more pronounced than the effect of connected vehicles.
Stability Analysis
Heterogeneous Traffic Flow

• Parameters of regular vehicles are adjusted to create a very unstable traffic flow.

• Low market penetration rates of automated vehicles do not result in significant stability improvements.

• At low market penetration rates of automated vehicles,

\[ stability \sim \hat{a} \cdot MPR_C + \hat{b} \]

Market penetration rate of connected vehicles
Stability Analysis
Simulation Segment – Ring Road

- 200 vehicles with 40 meters initial spacing.
- To create perturbation:
  One vehicle is slowed down to $v = 1 \, m/s$
  with maximum deceleration ($-8 \, m/s^2$).
  Speed is kept at $1 \, m/s$ for 50 s.
Stability Analysis
Ring Road Analysis

No Automation
Not Connected
No Automation
Connected
Self-Driving
Not Connected
Stability Analysis
Ring Road Analysis

No Automation
Connected

Market Penetration Rates of Connected Vehicles:
10% 50% 90%

Self-Driving
Not Connected

Market Penetration Rates of Autonomous Vehicles:
10% 50% 90%
A one-lane highway with an infinite length is simulated.

String Stability as a Function of Reaction Time and Platoon Size is investigated.

---

**Regular**

**10% Connected**

**90% Connected**

**10% Automated**

**90% Automated**

- **Oscillation Regime**
- **Collision Regime**
Oscillation and collision thresholds increase as platoon size decreases.

Oscillation and collision thresholds increase as market penetration rate increases.

At high market penetration rates, Autonomous vehicles have more positive effect on both oscillation and collision thresholds compared to connected vehicles.
Stability Analysis
Summary

The presented acceleration framework is string stable.

Analytical investigations show that string stability can be improved by the addition of connected and automated vehicles.

- Improvements are observed at low market penetration rates of connected vehicles (unlike automated vehicles).

- At high market penetration rates, automated vehicles have more positive impact on stability compare to connected vehicles.

Simulation results revealed that

- Oscillation and collision thresholds increase as platoon size decreases.

- Oscillation and collision thresholds increase as market penetration rate increases.

- Automated vehicles have more positive impact on stability compare to connected vehicles.
Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- Throughput Analysis: Simulation Results
- Takeways, Limitations and Challenges
The average breakdown flow in a series of simulations is considered as the bottleneck capacity.
THROUGHPUT and SPEED-DENSITY RELATION
SENSITIVITY ANALYSIS – MIXED ENVIRONMENT

10% R – 0% C – 90% A  
10% R – 20% C – 70% A  
10% R – 40% C – 50% A  
10% R – 50% C – 40% A  
10% R – 70% C – 20% A  
10% R – 90% C – 0% A
• Low market penetration rates of autonomous and connected vehicles do not result in a significant increase in bottleneck capacity.

• Autonomous vehicles have more positive impact on capacity compare to connected vehicles.

• Capacities over 3000 veh/hr/lane can be achieved by using autonomous vehicles.
Conclusion (Traffic flow aspects)

The presented acceleration framework is string stable; greater autonomous vehicle penetration increases stability (faster decay of perturbations).

**Connected Vehicles / Autonomous vehicles:**

- Low penetration rate increases the scatter in fundamental diagram.
- High penetration rate reduces the scatter in fundamental diagram.
- Capacity increases as market penetration rate increases.

From eliminating/delaying breakdown formation stand point:

*Autonomous Vehicles are more effective than Connected Vehicles*
Important Caveat

There are many different ways of implementing the technologies, especially with regard to driving and flow control.

Simulation testbeds can help evaluate alternatives and examine implications.
Lane-Changing Framework

It is assumed that V2V can provide information about the nature of lane-changing maneuvers:

Discretionary lane-changing vs. Mandatory lane-changing

A game-theoretical approach is adopted with the following pure strategies:

- Lag vehicle: Accelerate, Decelerate, Change Lane
- Target Vehicle: Change Lane, Do not Change Lane
Lane-Changing Framework
Inactive V2V Communications

Without information, drivers are uncertain about the nature of other drivers’ lane-changing maneuvers.

Two-person non-zero-sum non-cooperative game under incomplete information.

“Harsanyi Transformation” is used to solve the game with incomplete information:

- “Harsanyi Transformation” transforms the lag vehicle’s incomplete information about the nature of each lane-changing maneuver into imperfect information about the move by nature.

- “Nature” as a player chooses the type of each lane-changing maneuver.
  - Lane-changing is mandatory with probability $p$ and discretionary with probability $(1-p)$
**Lane-Changing Framework**

**Inactive V2V Communications**

**Discretionary lane-changing game in normal form**

<table>
<thead>
<tr>
<th>ACTION</th>
<th>Target Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_1$ (Change Lane)</td>
</tr>
<tr>
<td>$B_1$ (Accelerate)</td>
<td>$(P_{11}, R_{11})$</td>
</tr>
<tr>
<td></td>
<td>$(P_{12}, R_{12})$</td>
</tr>
<tr>
<td>$B_2$ (Decelerate)</td>
<td>$(P_{21}, R_{21})$</td>
</tr>
<tr>
<td></td>
<td>$(P_{22}, R_{22})$</td>
</tr>
<tr>
<td>$B_3$ (Change Lane)</td>
<td>$(P_{31}, R_{31})$</td>
</tr>
<tr>
<td></td>
<td>$(P_{32}, R_{32})$</td>
</tr>
</tbody>
</table>

**Mandatory lane-changing game in normal form**

<table>
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<td></td>
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</tr>
</tbody>
</table>
Lane-Changing Framework
Inactive V2V Communications

<table>
<thead>
<tr>
<th>ACTION</th>
<th>Target Vehicle</th>
<th>( A_1^M A_2^D )</th>
<th>( A_1^M A_2^D )</th>
<th>( A_1^M A_2^D )</th>
<th>( A_1^M A_2^D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1 ) (Accelerate)</td>
<td>( P_{11}, Q_{11} )</td>
<td>( (P_{11}, pP_{11} + (1-p)P_{21}) )</td>
<td>( (Q_{11}, pQ_{11} + (1-p)R_{11}) )</td>
<td>( (P_{12}, pP_{12} + (1-p)P_{21}) )</td>
<td>( (Q_{12}, pQ_{12} + (1-p)R_{12}) )</td>
</tr>
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<td>( B_2 ) (Decelerate)</td>
<td>( P_{21}, Q_{21} )</td>
<td>( (P_{21}, pP_{21} + (1-p)P_{22}) )</td>
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<td>( P_{31}, Q_{31} )</td>
<td>( (P_{31}, pP_{31} + (1-p)P_{32}) )</td>
<td>( (Q_{31}, pQ_{31} + (1-p)R_{31}) )</td>
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<td>( (Q_{32}, pQ_{32} + (1-p)R_{32}) )</td>
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Lane-Changing Framework
Active V2V Communications

With information, drivers are certain about the nature of other drivers’ lane-changing maneuvers.

Two-person non-zero-sum non-cooperative game under complete information.
## Lane-Changing Framework

### Payoff Functions

#### Payoff matrix of the target vehicle

<table>
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<tbody>
<tr>
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</tr>
<tr>
<td>$B_1$ (Accelerate)</td>
<td>$\eta_1 \cdot Acc^{C}<em>{\text{Target}} + \eta_2 \cdot \Delta V + \varepsilon</em>{11}$</td>
<td>$0 + \varepsilon_{12}$</td>
</tr>
<tr>
<td>$B_2$ (Decelerate)</td>
<td>$\eta_1 \cdot Acc^{C}<em>{\text{Target}} + \eta_2 \cdot \Delta V + \varepsilon</em>{21}$</td>
<td>$0 + \varepsilon_{22}$</td>
</tr>
<tr>
<td>$B_3$ (Change Lane)</td>
<td>$\eta_2 \cdot \Delta V + \varepsilon_{31}$</td>
<td>$0 + \varepsilon_{32}$</td>
</tr>
</tbody>
</table>

#### Payoff matrix of the lag vehicle

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<tbody>
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</tr>
<tr>
<td>$B_1$ (Accelerate)</td>
<td>$\eta_3 \cdot Acc^{C}<em>{\text{Target}} + \delta</em>{11}$</td>
<td>$\eta_3 \cdot Acc^{C}<em>{\text{Lead}} + \delta</em>{12}$</td>
</tr>
<tr>
<td>$B_2$ (Decelerate)</td>
<td>$\eta_4 \cdot Acc^{C}<em>{\text{Target}} + \delta</em>{21}$</td>
<td>$\eta_4 \cdot Acc^{C}<em>{\text{Lead}} + \delta</em>{22}$</td>
</tr>
<tr>
<td>$B_3$ (Change Lane)</td>
<td>$\eta_1 \cdot Acc^{C}<em>{\text{Target}} + \eta_2 \cdot \Delta V + \delta</em>{31}$</td>
<td></td>
</tr>
</tbody>
</table>

- $Acc^{C}_{\text{Target}}$: Acceleration to prevent collision for the lag vehicle considering the target vehicle as the leader.
- $Acc^{C}_{\text{Lead}}$: -3.05 m/s²
- $\Delta V$: Speed difference between the old leader and the new leader
Lane-Changing Framework Calibration – Method of Simulated Moments

Start

**Vector of Moments**
For all combination of $\theta$ and $\beta$ and all lane-changing instances in the dataset calculate the vector of moments:

$$m_{kT}(\theta, \beta) = \frac{1}{T} \sum_{t=1}^{T} \left[ 1(\alpha_t = k) - \tilde{P}(k|x, f, \beta) \right]$$

End

$$(\hat{\theta}, \hat{\beta}) = \text{argmin}_{\theta, \beta} m_{kT}(\theta, \beta)' \times m_{kT}(\theta, \beta)$$

**Monte-Carlo Simulation**

**Initialization**
Draw from $N(\mu, \sigma)$ and Calculate the Pay-off Functions.

$$u_i(a, x, \theta, \epsilon) = f_i(a, x, \theta, \epsilon) + \epsilon(a)$$

**Nash Equilibria**
Find the entire set of Nash equilibria using Gambit.

**Probability of Selecting Actions**

$$\lambda(\omega, \Omega(u), \beta) = e^{\beta \gamma(\omega, u)}$$

$$\sum_{\omega' \in \Omega(u)} e^{\beta \gamma(\omega', u)}$$

Calculate $\tilde{P}(a|x, f, \beta)$
Lane-Changing Framework
Calibration Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_1$</td>
<td>-0.750</td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>0.875</td>
</tr>
<tr>
<td>$\eta_3$</td>
<td>-0.750</td>
</tr>
<tr>
<td>$\eta_4$</td>
<td>0.125</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Mean Absolute Error (MAE)  0.383

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_1$</td>
<td>-0.875</td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>0.375</td>
</tr>
<tr>
<td>$\eta_3$</td>
<td>-0.625</td>
</tr>
<tr>
<td>$\eta_4$</td>
<td>0.25</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Mean Absolute Error (MAE)  0.059
Lane-Changing Framework Simulation – Fictitious Play

Initialization
Driver A decides to change lane

Decision Making

Decision Time (DT) ~ N(μ, σ)
T = 0

Select Strategy Based on other driver’s decision

Observe and Update Experience Based on the game outcome

T = T + 1

Outcome Stable?

No

T < DT

Yes

Execute Strategies
Lane-Changing Framework Simulation Segment

3.5 Miles
Lane-Changing Framework
Simulation Results

Simulated Period

Loop Detector Data

MOBIL

Gap-Acceptance Model

Game Theory Based Model
ARE WE THERE YET?  WHO IS READY?

1. Technology is here and now; “Big Tech” and “New Tech” is in the lead– ready to market within 3-5 years.

2. Automotive players– wide range (“waiting on standards”)
   • Connectivity in vehicles here and now;
   • Driver-assist features already in high-end vehicles;
   • Semi-autonomous in 3~5 yrs.
   • Fully-autonomous: Special uses (freight, internal transit) by 2020

3. System Integrators: more hype than deployment; not quite there yet.

4. Insurance, Legal: surprisingly nimble

5. LEAST READY: Government agencies; biggest hurdles on system aspects, public sector side

6. Many challenges ahead, and many more opportunities
We Love Feedback

Questions/Comments

Email: masmah@northwestern.edu

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