How to Get There from Here: Fundamental Research Opportunities in Autonomous Vehicles, Connected travelers and the Internet of Things

Hani Mahmassani
Northwestern University
Gartner’s Hype Cycle for Emerging Technologies, 2015

Source: Gartner (August 2015)
Outline

- Background: Autonomous Vehicles, Connected Systems
- Three Research Questions
- Autonomous Vehicles: Adoption Factors, System Planning Models
- Flow Implications:
  - Joint modeling of VANET and traffic flow
  - Safety, Stability, Throughput
- Takeways, Limitations and Challenges
The concept is not new...
But now it is here, there and everywhere...

2015 SELF DRIVING CARS
Connected Vehicles Technology

Drivers

Connected Vehicles technology helps drivers with these decisions.
Connected Vehicles Technology

Drivers: Dynamic Mobility Applications

Queue Warning

1. Host Vehicle receives data and provides driver with imminent queue warning
2. Queue condition forms
3. Driver provided 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 relays appropriate speed recommendations to upstream vehicles
3. 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

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

Automation

- Fully manual Level 0
- Fully automated Level 4

- INTELLIGENCE RESIDES ENTIRELY IN VEHICLE

Coordinated
- Optimized flow
- Routing
- Speed harmonization

Connected
- Real-time info
- Asset tracking
- Electronic tolling

Cooperative Driving

Smart Highways

INTELLIGENCE and INTERDEPENDENCE

INTELLIGENCE RESIDES ENTIRELY IN VEHICLE
Coordination through connectivity and automation: Continuous-flow at-grade intersections
Extreme Connectivity: Internet of Things

Why is this relevant to transportation?

Seamless connectivity

Transportation delivers physical mobility in a virtually connected mobile environment.
IoT and the City: Leveraging connectivity in urban mobility
IoT and the City: Integrating multimodal transport options
IoT and the City: Complex Urban Operations
IoT and Mobility: Opportunities

FOR INDIVIDUAL USERS
  • Enhanced User Experience
  • Telemobility
  • Connected Life

FOR SYSTEM OPERATORS
  • Greater efficiencies
  • Smart Cities

FOR THIRD PARTIES
  • UNBOUNDED OPPORTUNITIES!
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Three Sets of Questions:

1. Adoption Factors and Implications for Systems Planning

• 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?
Three 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?
Three Sets of Questions:

3. How do we get there?

- What are the challenges in developing and implementing platforms for integrating connected capabilities across multiple systems and sectors?
- What would it take for smart cities to actually happen (beyond individual apps and individual sectors)?
- Are municipal/state governments actually capable of the necessary leadership?
- Is there a market-based pathway towards this goal?
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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
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…
SUBSTITUTION OR COMPLEMENTARITY?

Possible Hypotheses

- Substitute, no other change
- Substitute, free up time, money (individual level) and improve safety and congestion (for society)
- Start using car for activities previously either not done, postponed or chained
- New uses of mobility tools, major reorganization of activity patterns, especially for caregivers (of young people, elderly)
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

Demand (FLOWS) V

Technology T
Less Incremental I
Major Activity Shifts and Mobility Use

• 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
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 models.

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 are 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
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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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>
<th>No Automation Not Connected</th>
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<th>Self-Driving Not Connected</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Acceleration Behavior: Probabilistic</td>
<td>• Perception of Surrounding Traffic Condition: Subjective</td>
<td></td>
</tr>
<tr>
<td>• Reaction Time: High</td>
<td>• Safe Spacing: High</td>
<td></td>
</tr>
<tr>
<td>• Safe Spacing: High</td>
<td>• High-Risk maneuvers: Possible</td>
<td></td>
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- 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>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>• Perception of Surrounding Traffic Condition:</td>
<td>Accurate</td>
</tr>
<tr>
<td>• Reaction Time:</td>
<td>Low</td>
<td>• Reaction Time:</td>
<td>Low</td>
</tr>
<tr>
<td>• Safe Spacing:</td>
<td>Low</td>
<td>• Safe Spacing:</td>
<td>Low</td>
</tr>
<tr>
<td>• High-Risk maneuvers:</td>
<td>Very Unlikely</td>
<td></td>
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</table>

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

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

- No Automation Not Connected
- No Automation Connected
- Self-Driving Not Connected

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- 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.
AcceleraDon Framework

No AutomaDon
Not Connected

Self-Driving
Not Connected

No AutomaDon
Connected

Active V2V Communications
Active V2I Communications

Inactive V2V Communications
Inactive V2I Communications

• 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 ($v_{max}$) (Reece and Shafer, 1993 and Arem, Driel, Visser, 2006).

$$v_{max} = \sqrt{-2a_n^{decc} \Delta x}$$

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

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

• It is essential to consider the V2V/V2I communications when modeling a
c 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?
Communication Network
Connectivity: Constant Transmission Power

Effective Transmission range = 5m
Biggest Cluster Size = 8

Effective Transmission range = 10m
Biggest Cluster Size = 93

Effective Transmission range = 20m
Biggest Cluster Size = 216
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.

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

Effect of Packet Delivery Rate on Clustering

- PDR = 50%
- PDR = 70%
- PDR = 80%
- PDR = 90%
- PDR = 100%

Graph showing the effect of different packet delivery rates on clustering.
V2V Communications Model
NS3 Implementation – Packet Delivery

Effect of Packet Delivery Rate on Clustering

- PDR = 50%
- PDR = 70%
- PDR = 80%
- PDR = 90%
- PDR = 100%
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:

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

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

String Stable Platoon

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

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

where

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

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

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

Market penetration rate of connected vehicles

Automated, Connected, and Regular Vehicles
Stability Analysis
Simulation Segment – Ring Road

• 200 vehicles with 40 meters initial spacing.
• To create perturbation:
  One vehicle is slowed down to \( v = 1 \text{ m/s} \) with maximum deceleration \((-8 \text{ m/s}^2)\).
  Speed is kept at \( 1 \text{ m/s} \) 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%
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.
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.
Further Work and Caveats

More recent work: lane-changing framework for connected and autonomous vehicles based on Game Theory

Talebpour, Mahmassani and Hamdar, TR Part C, 2015)

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.

Impacts on travel behavior potentially even more challenging, and important!
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Connectivity Implications for data

- ALL MORE: scope (items), detail, frequency, quantity
  - First-line critical uses
    - Safety-related
    - Motion-enabling
    - Navigation
  - Second-line important uses
    - Flow optimization
    - Information and control
  - Third-line potential uses
    - Seemingly unrelated uses
    - User experience
    - Marketing
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
Will it happen?

- Smart Cities, and Connected vehicle systems will not happen by fiat, through top-down big plan
- System is too complex, too fragmented, too many owners, jurisdictions, etc...
- System is too dynamic, will not wait for the final design to materialize, be tested, revised, stabilized, etc...
- It will happen through more or less loose coupling of smart apps, developed by entrepreneurial entities, and/or agencies with specific needs
- Opportunity is in facilitating data sharing, transparency, access across apps—this is as much culture as it is technology
- More likely to happen first in places like Dubai and Singapore.
1. Autonomous vehicle technology is here and now, and road-ready
2. Connectivity and IoT dramatically increase opportunity for user, system, and third parties
3. Transportation and mobility industries undergoing major disruptive influences: technology, players, concepts
4. Biggest hurdles on system aspects, public sector side
5. Initial market within 3 yrs, more by 2020, full blown by 2030
6. Many challenges ahead, and many more opportunities
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