Modeling Driver Behavior in a Connected Environment
Integration of Microscopic Traffic Simulation and Telecommunication Systems

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Everything is getting connected and users are at the center of this web of connectivity.
Smart Cities Vision

Image Powered by Intel
Automated vs. Connected

Vehicle Operation

- No Automation
- Function Specific Automation
- Combined Function Automation
- Limited Self-Driving Automation
- Full Self-Driving Automation

CONNECTIVITY

- Improve drivers’ strategic and operational decisions.

Vehicle-to-Vehicle (V2V) Communications

- Increase drivers’ situational awareness.
- Improve drivers’ operational decisions.

Vehicle-to-Infrastructure (V2I) Communications

- Improve drivers’ strategic decisions.
Automated vs. Connected

Vehicle Operation

- No Automation
- Function Specific Automation
- Combined Function Automation
- Limited Self-Driving Automation
- Full Self-Driving Automation

Connectivity

- Enhance self-contained sensing capabilities through real-time messaging.

Vehicle-to-Vehicle (V2V) Communications
- Improve vehicles’ operational decisions.

Vehicle-to-Infrastructure (V2I) Communications
- Improve vehicles’ strategic decisions.
Applications for Connectivity

Vehicle-to-Vehicle (V2V) Communications
- Emergency Break Light Warning
- Forward Collision Warning
- Intersection Movement Assist
- Blind Spot and Lane Change Warning

Vehicle-to-Infrastructure (V2I) Communications
- Speed Harmonization
- Intelligent Traffic Signals
- Enable Traveler Information
- Transit Connection
- Incident Management
- Eco-Routing
- Smart Parking
- AFV Charging Stations

Image Source: Lexus and Mercedes
Motivation

Connected Vehicles technology and Vehicle Automation are two emerging technologies that will change the driving environment and consequently drivers’ behavior.

- Improvements in drivers’ strategic and operational decisions are expected.
- Improvements in mobility, safety, reliability, emissions, and comfort are expected.

However, the extent of these improvements are unknown.
Framework

Traffic

- Car-following
- Lane-Changing

Telecommunications

- Clustering

Connected

Automated

Regular
Outline

Image Source: Volvo, Lexus, and USDOT
## Acceleration Framework

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

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- **Acceleration Behavior:** Probabilistic
- **Perception of Surrounding Traffic Condition:** Subjective
- **Reaction Time:** High
- **Safe Spacing:** High
- **High-Risk maneuvers:** Possible

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

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The Intelligent Driver Model (Treiber, Hennecke, and Helbing, 2000) is used.

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

## Acceleration Framework

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

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NORTHWESTERN UNIVERSITY
• 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

Active V2V Communications | Inactive V2V Communications
---|---
Active V2I Communications | Inactive V2I Communications
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\(^1\) and Arem, Driel, Visser, 2006\(^2\)).

\[
\begin{align*}
    v_{max} &= \sqrt{-2a_{n}^{d,ecc} \Delta x} \\
    a_n(t) &= \min\left(a_n^d(t), k(v_{max} - v_n(t))\right) \\
    a_n^d(t) &= k_a a_{n-1}(t - \tau) + k_v (v_{n-1}(t - \tau) - v_n(t - \tau)) + k_d (s_n(t - \tau) - s_{ref})
\end{align*}
\]

The average breakdown flow in a series of simulations is considered as the bottleneck capacity.
Throughput Analysis
Sensitivity Analysis – Connected Vehicles

0% MPR

10% MPR

50% MPR

70% MPR

90% MPR

100% MPR
Throughput Analysis
Sensitivity Analysis – Automated Vehicles

0% MPR

10% MPR

50% MPR

70% MPR

90% MPR

100% MPR
Throughput Analysis
Simulation Results

• Low market penetration rates of automated and connected vehicles do not result in a significant increase in bottleneck capacity.

• Automated vehicles have more positive impact on capacity compared to connected vehicles.

• Capacities over 3000 veh/hr/lane can be achieved by using automated vehicles.
Throughput Analysis
Summary

Connected Vehicles / Automated 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.

Automated vehicles have more positive impact on capacity compared to connected vehicles.
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 instability of a heterogeneous traffic flow (Ward, 2009):

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

where

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

Stability Analysis
Heterogeneous Traffic Flow

At high market penetration rates, the effect of automated vehicles on stability is more significant than 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,

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

Automated, Connected, and Regular Vehicles
Stability Analysis
Simulation Results

A one-lane highway with an infinite length is simulated.

String Stability as a Function of Reaction Time and Platoon Size is investigated.
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 compared 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 compared to connected vehicles.
Outline

Image Source: Volvo, Lexus, and USDOT
V2V Communications Model

Background

Algorithms can be categorized into two groups,

- **Topological methods**
  
  Use network topology to select nodes.
  
  Network topology changes rapidly; therefore, **Topological date should be transmitted at a high rate**

- **Statistical methods**
  
  Use local measures (e.g. transmission distance).

**Topological methods are more accurate.**

- Clustering algorithms can be used to reduce the amount of required data transmission.

Image Source: USDOT
V2V Communications Model

Background – What is a Cluster?

Each cluster consists of,

- **One** cluster head
- **Several** cluster members

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 reduce signal interference.**
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.

\[
s(i, k) = -\|x_i - x_k\| - \|x^i - x^k\|
\]

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%

NS3 Implementation – Packet Delivery
SPD-HARM Simulation
Definition

Speed Harmonization
- Dynamically adjusts and coordinates maximum speed limit based on
  Prevailing traffic state
  Road surface condition
  Weather

Objectives
- Avoid or delay flow breakdown by reducing speed variance
- Smooth out shock waves
- Improve flow quality and throughput
- Reduce delay and improve reliability
- Safety?
SPD-HARM Simulation
Shockwave Detection

Distance vs. TIME graph with wavelet transform highlighted.
SPD-HARM Simulation
Speed Limit Selection Algorithm

Based on Allaby et al. (2007) a reactive decision tree is used.

SPD-HARM Simulation
Study Segments

Hypothetical Segment

Chicago

Image Source: Google Maps
SPD-HARM Simulation
Results: Hypothetical Segment

0% Compliance  10% Compliance  90% Compliance

Flow (Veh/h) vs Density (Veh/km)
Flow (Veh/h) vs Speed (km/h)
Flow (Veh/h) vs Time (minute)
CO2 vs Time (minute)
SPD-HARM Simulation
Results: Chicago
Concluding Remarks

An integration of a traffic simulation framework and a wireless communication simulation framework is presented.

Under the assumptions of this study, mobility will improve and emissions will decrease by the addition of connected and automated vehicles.

- Automated vehicles are more effective compared to connected vehicles.

Simulating the flow of information is essential to study the effects of connected and automated vehicles on mobility, safety, and emissions.
What is Next?

There is a lot more room for improvement.
There are a lot of elements to add.
New measures are required and we need to apply new data collection procedures.

Image Source: USDOT