RESEARCH THAT MOVES YOU

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Smart, Connected, Intelligent Mobility Networks: Why Is it Different This Time?

Hani S. Mahmassani
Northwestern University

NSF Workshop on Control of Networked Transportation Systems
July 8-9, 2019; Philadelphia, PA, USA
CAV systems are likely to be major game changers in traffic, mobility, and logistics. No longer a question of if, but of when, in what form, at what rate, and through what kind of evolution path.
SEVEN Factors Affecting Future Urban Mobility

• **Personal**— mobile computing and communication technologies capable of engaging travelers and exchanging information anywhere and anytime, best manifested through the ubiquitous smartphone;

• **Connected**— promising a future surface transport fleet that is seamlessly connected with each other and with the infrastructure;

• **Automated**— to varying degrees in different operational environments, towards eventual full automation (NHTSA Levels 4 and 5);

• **Shared**— continuation of trend towards emerging mobility services such as ridesharing, ride-hailing (e.g. Uber) and on-demand delivery, which, powered by automation and connectivity, is poised to transform personal and freight mobility;

• **Electric**— greater adoption of electric and plug-in hybrid vehicles in both person and freight movement can significantly reduce carbon impact

• **Social**— social media that provides new opportunities to track, understand and influence human behavior towards more efficient transportation use.

• **Non-motorized**— or motor-assisted forms of individual mobility, from walking to bicycling and mini electric scooters, there has been a resurgence in non-automotive mobility.
Intelligent Transportation Systems

Convergence of location, telecommunication and automotive technologies for better transportation system safety, efficiency, and user convenience.
Drinking From A Fire Hose:  Real-time Data And Transportation Decision-making

Hani S. Mahmassani
The University of Texas at Austin

UCTC Student Conference, Irvine, CA
February 2001
**CONVENTIONAL WORLD**

- Steady - state
- Equilibrium
- Static
- Data poor
- Uncertainty about past/ current events
- Component level
- Long lead time between solution and implementation
- Limited “accountability” of decisions
- “A priori” solutions

**ITS ENVIRONMENT**

- Time varying
- Evolutionary paths
- Dynamic
- Data rich
- Known past/current events (to varying degrees)
- System level
- Immediate action
- Performance monitoring and feedback
- Real-time adaptive strategies
1994 to 2019

25 YEARS--
DEPLOYMENT OF A LOT OF
TECHNOLOGY

NOT AS MUCH INTELLIGENCE
But navigation services are freely available to users on any smartphone—in most cities of the world.

Most with real-time travel time information at least on major arterials.

Some even with prediction.

Though in nearly all cases limited to individual, uncoordinated (“selfish”) routing.
Multimodal mobility at the push of a button

Soon to include urban air mobility services
INTELLIGENT VEHICLE-HIGHWAY SYSTEMS

ITS 0.9 Vehicles
Highway infrastructure

ITS 1.0 Buses, trains, multimodal services
Urban mobility

ITS 2.0 = CS 2.0 CONNECTED SYSTEMS

FOCUS: THE USER
Mobility as an APP in seamless connected environment
TWO MAIN AREAS FOR DEVELOPING TRANSPORTATION SYSTEM INTELLIGENCE

Realization I
Monitor the state of the system at all times, provides basis to intervene and apply control actions in real-time.

State estimation and prediction, Online optimization

Realization II
Eliminate or reduce individual human error, and the system will operate more efficiently.

Autonomous and Connected Vehicles
CONNECTED VEHICLE SYSTEMS
VEHICLE TO VEHICLE COMMUNICATION

V2X—VEHICLE TO PEDESTRIAN/BICYCLE/E-SCOOTER COMMUNICATION

VEHICLE TO INFRASTRUCTURE COMMUNICATION

PED/BIKE TO INFRASTRUCTURE COMMUNICATION

CONNECTED MOBILITY SYSTEMS
The connected vehicle is already a mainstream reality

60%

Cellular penetration in new light vehicles sales by 2021

Source: Qualcomm®
The connected vehicle is already a mainstream reality.
Vision for always-connected vehicle
Requires new levels of connectivity and intelligence

Heterogeneous connectivity
- Vehicle-to-Everything communications
- Connected infotainment
- Wireless EV charging
- Real-time navigation

On-device intelligence
- Intuitive instrumentation
- Immersive multimedia
- Augmented reality
- Always-on sensing

Source: Qualcomm®
Overcoming the challenges of V2X communications

**V2X Challenges**

- **High relative speeds**
  Leads to significant Doppler shift / frequency offset

- **High node densities**
  Random resource allocation results in excessive resource collisions

- **Time synchronization**
  Lack of synchronization source when out-of-coverage

**C-V2X Solutions**

- **Enhanced signal design**
  E.g. increasing # of ref signal symbols to improve synchronization and channel estimation

- **Enhanced transmission structure**
  Transmit control and data on the same sub-frame to reduce in-band emissions

- **More efficient resource allocation**
  New methods using sensing and semi-persistent resource selection

- **Allow utilization of GPS timing**
  Enhancements to use satellite (e.g. GNSS) when out-of-coverage

Source: Qualcomm
C-V2X increases reaction time over 802.11p/DSRC

For improved safety use cases - especially at high-speeds, e.g. highway

- Reaction time: ~9.2 sec
- Braking distance: ~2.5 sec
- C-V2X range: >450 m
- 802.11p range: ~225 m

LTE ~8 dB higher link budget due to single carrier waveform, coding gain, longer transmission time and higher Tx power

Safer driving experience
- Increased driver reaction time

Support for high speeds
- Relative speeds up to 500 km/h

Increased situational awareness
- Gather data from further ahead

Source: Qualcomm
5G will build upon and enhance C-V2X

New 5G platform will augment/complement C-V2X—no ‘rip and replace’

- **4G LTE**: Continue to evolve and provide ubiquitous coverage as 5G is rolled out
- **C-V2X**: C-V2X direct and network communications
- **5G**: Bring new capabilities for C-V2X network communications and augment C-V2X direct communications over time

Multi-mode vehicle with simultaneous connectivity across 4G LTE, C-V2X and 5G

Source: Qualcomm
Simple Taxonomy of ITS Applications

**Conventional ITS**: Transportation Management

**Emerging**: Multimodal, user-customized

Augments facility-based sensors; improves demand estimation and predictive strategies

**ITS**: Traveler information systems (ATIS)

**Next Gen**: Personalized, social, gamified to maximize response and impact
Connectivity

- Connected systems (internet of everything)
- Ad-hoc networks
- Peer-to-Peer (Neighbor)
- Receive only
- Isolated

Automation

- Fully manual Level 0
- Fully automated Level 5

INTELLIGENCE RESIDES ENTIRELY IN VEHICLE
Gap Analysis Structure
(NUTC, 2018 for FHWA study)

FOUR KEY MODELING COMPONENTS

Demand Effects:
Household and Firms
Activity and Travel
Choices

Supply Changes:
Mobility as a Service
Shared Fleet Operations

Operational
Performance:
Flow Modeling and
Control Strategies

Network
Integration:
Traveler Assignment
Multi-Agent Behavior
Interactions
Equilibration
Fully-autonomous vehicles (AVs) expected to accelerate existing trends toward shared urban mobility

AVs eliminate cost and performance limitations associated with human drivers

Allow mobility services to compete with personal vehicles in terms of cost and quality of service (i.e. short wait times)

**Mobility as a service (MaaS)**—Everyone has access to portfolio of services for different purposes—multiple public transit modes, shared bikes, shared fleet of private vehicles, rides on demand...

Expect to see a wide-variety of **AV fleet business models**
AV Fleet Business Models for Mobility Service

Potential Variants

AV Fleet Business Model Decisions

Hyland and Mahmassani (TRR, 2017)

Strategic Decisions

- Pricing
  - Variable (e.g. Marginal Cost)
  - Fixed
- Reservation Time-frame
  - Advanced Requests
  - Immediate Requests
- Shared Rides
  - Sharing
  - No Sharing
- Reservation Type
  - Point-to-Point
  - Hourly
- Vehicles
  - Heterogeneous
  - Homogeneous
- Fleet Size Elasticity
  - Variable/Elastic
  - Fixed
- Vehicle Fuel-Type
  - Electric
  - Conventional Gasoline

Tactical Decisions

- Vehicle Repositioning
- Diverting En-route Vehicles
- Request Hold before Assignment
OUR APPROACH

INTEGRATED TRAFFIC-TELECOM SIMULATION PLATFORM
Predictive Control Application in a CAV Environment: Shockwave Detection and Speed Harmonization

Based on Amr ElFar’s PhD Dissertation (2019)
What is a Traffic Shockwave?

• Traffic shockwaves reflect a transition from the free-flow traffic state to the congested state
  – can create potentially unsafe situations to drivers
  – increase travel time
  – significantly reduce highway throughput

• Traditional detection approach is to track changes in speed and density over space and time
  – Density is difficult to measure on freeways (occupancy as a proxy)
  – Locating the start of the shockwave is inaccurate (depends on the number and location of installed road sensor)

• Connectivity offers new opportunities for better detection of shockwaves.
  – Detailed vehicle trajectories offer deeper insights into traffic interactions that leads to shockwave formation
Traffic Shockwave Illustration
Speed Harmonization

**Control Strategy**

- **Centralized**
  - Central traffic management
  - V2I

- **Decentralized**
  - Fleet-oriented control
  - V2V

**Traffic Monitoring**

- Estimating Traffic Properties
  - CAV Trajectories
  - Mean Speed
  - Speed Standard Deviation

- Tracking Traffic Dynamics
  - Early Shockwave Detection

**Traffic State Prediction**

- Traffic Properties
- Shockwave formations

- Machine Learning Technique
  - Logistic Regression
  - Neural Networks
  - Random Forests

- Prediction Model Type
  - Offline Models
  - Online Models

- Congestion start time
- Congestion location

- Updated speed limit
- CAV IDs to be updated
- Broadcasting Strategy (V2V, V2I)

Transport Facility

- Road geometry
- Demand Patterns
- CAV MPRs

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Prediction Methodology

Objective: identify shockwave formation and propagation based on the speed variation of individual vehicles available through connected vehicles technology

1. Segment a road facility into smaller sections (e.g. 200 ft)
2. Estimate traffic properties from CAV generated data in those sections
3. Monitor the changes in traffic properties across sections (mean speed, speed standard deviation)
4. Identify formation and propagation of shockwaves
At low market penetrations, SSD could not be estimated for some time steps because there were not any connected vehicles detected.

For market penetrations that are larger than 30%, SSD could be estimated for all time steps.
Building the Predictive Models

- Temporally and spatially lagged models
  - current values of the dependent variable is predicted using lagged (past values) of explanatory variables – when current values of explanatory variables are used, it predicts the future state
  - spatially lagged because traffic disruption starts downstream of a target segment
  - Actual vehicle trajectories to build models (NGSIM)

\[ y_{ts} = v(t-1)s + v(t-1)(s+1) + ssd(t-1)(s+1) \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_{ts} )</td>
<td>Traffic State</td>
</tr>
<tr>
<td></td>
<td>Binary: the state of traffic whether congested or uncongested as identified using the travel time index (TTI) with a threshold above 1.7 (LA Congestion).</td>
</tr>
<tr>
<td>( v(t-1)s )</td>
<td>Lagged Mean Speed in Current Section</td>
</tr>
<tr>
<td></td>
<td>Continuous: the average speed of individual vehicles in the current section, lagged 10, 20, or 30 seconds</td>
</tr>
<tr>
<td>( v(t-1)(s+1) )</td>
<td>Lagged Mean Speed in Downstream Section</td>
</tr>
<tr>
<td></td>
<td>Continuous: the average speed of individual vehicles in the next downstream section, lagged 10, 20, or 30 seconds</td>
</tr>
<tr>
<td>( ssd(t-1)(s+1) )</td>
<td>Lagged Speed Standard Deviation in Downstream Section</td>
</tr>
<tr>
<td></td>
<td>Continuous: the speed standard deviation of individual vehicles in the next downstream section, lagged 10, 20, or 30 seconds</td>
</tr>
</tbody>
</table>
Methodology

Types of Predictive Models

- **Offline models**
  - built using historical data and updated whenever new data is available or when necessary (e.g. major infrastructure changes)

- **Online models**
  - built using historical data and updated (re-trained) regularly using real-time information on prevailing traffic conditions

Machine Learning Specifications

- **Binary logistic regression**
  - cut-off probability above 50%

- **Random Forest**
  - 500 trees

- **Neural Networks**
  - One hidden layer
Model Accuracy Measures

• Three accuracy measures
  – **Overall accuracy**: the percentage of traffic states correctly predicted
  – **Congested state prediction accuracy**: the percentage of the congested states correctly predicted
  – **Uncongested state prediction accuracy**: the percentage of the uncongested states correctly predicted
## Offline Models (Partial MPR)

<table>
<thead>
<tr>
<th>Model</th>
<th>CV</th>
<th>Overall Accuracy</th>
<th>Congested State Prediction Accuracy</th>
<th>Uncongested State Prediction Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Forest 10s</td>
<td>30%</td>
<td>91%</td>
<td>95%</td>
<td>80%</td>
</tr>
<tr>
<td>Random Forest 10s</td>
<td>50%</td>
<td>92%</td>
<td>95%</td>
<td>82%</td>
</tr>
<tr>
<td>Random Forest 10s</td>
<td>100%</td>
<td>93%</td>
<td>95%</td>
<td>85%</td>
</tr>
<tr>
<td>Random Forest 20s</td>
<td>30%</td>
<td>86%</td>
<td>92%</td>
<td>70%</td>
</tr>
<tr>
<td>Random Forest 20s</td>
<td>50%</td>
<td>88%</td>
<td>93%</td>
<td>73%</td>
</tr>
<tr>
<td>Random Forest 20s</td>
<td>100%</td>
<td>90%</td>
<td>94%</td>
<td>77%</td>
</tr>
</tbody>
</table>

- Higher accuracy at higher MPRs -> **improved SSD estimates**
- Similar patterns for other ML algorithms
Congestion Prediction Conclusion

• Two types of predictive models were developed
  – Offline models; built using historical data only
  – Online models; updated in real-time
• Overall prediction accuracy 86% - 94%
• The models can be used for partially connected traffic streams
Control Strategy Application: Predictive Speed Harmonization in a Connected Environment with Centralized Control
Predictive Speed Harmonization in a Connected Environment with Centralized Control

Freeway Segment
- Road geometry
- Demand Patterns
- CAV Trajectories

Speed Control
Central Speed Selection and Broadcasting
- Updated speed limit
- CAV IDs to be updated

Traffic Monitoring
Central System - V2I
- Section mean speeds
- Section speed standard deviations
- Shockwave formations

Congestion Prediction
Central Model
- Congestion start time
- Congestion location
System Differentiation

The system is different from traditional speed harmonization systems in four key areas:

1. It solely relies on connected vehicles to collect traffic information – no need for road sensors
2. Uses machine learning to predict traffic congestion (up to 93% accuracy)
3. The system identifies the location of congestion anywhere on a freeway segment - not constrained by infrastructure sensors
4. General formulation selects optimal speed limits and broadcasting distance to maximize traffic speed
Design Parameters

• **Prediction horizon**: duration over which congestion is predicted to happen
  – affects prediction accuracy

• **Broadcasting distance**: the distance between the predicted congestion location and the point at which CAVs receive updated speed limits before reaching congestion
  – affects the transition smoothness of traffic

• **Set of potential speed limits** for traffic upstream of congestion
  – affects the effectiveness of the strategy
Case Studies

• Multiple operational scenarios of a 2-lane freeway segment (5 Km) with one on-ramp

• Volumes: 3000 vph main lanes, 500 vph on-ramp
Congestion Prediction

- Utilize the same machine learning model introduced earlier

\[ y_{ts} = v(t-1)s + v(t-1)(s+1) + ssd(t-1)(s+1) \]

- Training data was generated using simulated trajectories for 2-lane highway with one on-ramp at various demand levels (1000 - 4000 vphl)

<table>
<thead>
<tr>
<th>Model</th>
<th>Prediction Horizon</th>
<th>Overall Accuracy</th>
<th>Congested State Prediction Accuracy</th>
<th>Uncongested State Prediction Accuracy</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous study - Elfar et al (10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logistic</td>
<td>10s</td>
<td>93%</td>
<td>96%</td>
<td>85%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>Logistic</td>
<td>20s</td>
<td>91%</td>
<td>95%</td>
<td>79%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>Random Forest</td>
<td>10s</td>
<td>93%</td>
<td>95%</td>
<td>85%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>Random Forest</td>
<td>20s</td>
<td>90%</td>
<td>94%</td>
<td>77%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>Neural Network</td>
<td>10s</td>
<td>89%</td>
<td>97%</td>
<td>68%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>Neural Network</td>
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<td>90%</td>
<td>95%</td>
<td>78%</td>
<td>NGSIM</td>
</tr>
<tr>
<td>This study</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Random Forest</td>
<td>10s</td>
<td>99%</td>
<td>95%</td>
<td>99%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Random Forest</td>
<td>20s</td>
<td>98%</td>
<td>90%</td>
<td>99%</td>
<td>Simulation</td>
</tr>
<tr>
<td>Random Forest</td>
<td>30s</td>
<td>97%</td>
<td>87%</td>
<td>99%</td>
<td>Simulation</td>
</tr>
</tbody>
</table>
Activating SPDHRM reduces the severity and length of traffic shockwaves (improves safety)

Note: Using conventional Decision-tree approach for setting speed limit values
Activating SPDHRM improves traffic stability and performance
Activating SPDHRM increases overall speed and reduces its variation.
Connectivity improves the performance of SPDHRM

Higher CV market penetration:

1. Improves congestion prediction
2. Improves speed compliance rate
Automated vehicles stabilize traffic without SPDHRM due to the robotic nature of its driving behavior.

SPDHRM further improves traffic performance by controlling speed of connected vehicles.
SPDHRM has virtually no impact on traffic in high automation conditions

- SPDHRM is not activated as the high market penetration of AVs prevents congestion
The system’s design parameters need to be fine-tuned for optimal results

<table>
<thead>
<tr>
<th>Broadcasting Distance (m)</th>
<th>Average Travel Time (sec)</th>
<th>Average Speed (km/h)</th>
<th>StdDev Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>233</td>
<td>75</td>
<td>16</td>
</tr>
<tr>
<td>1000</td>
<td>229</td>
<td>80</td>
<td>9</td>
</tr>
<tr>
<td>1500</td>
<td>237</td>
<td>76</td>
<td>13</td>
</tr>
<tr>
<td>2000</td>
<td>235</td>
<td>77</td>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prediction Horizon (sec)</th>
<th>Average Travel Time (sec)</th>
<th>Average Speed (km/h)</th>
<th>StdDev Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>236</td>
<td>75</td>
<td>14</td>
</tr>
<tr>
<td>20</td>
<td>229</td>
<td>80</td>
<td>9</td>
</tr>
<tr>
<td>30</td>
<td>230</td>
<td>76</td>
<td>15</td>
</tr>
</tbody>
</table>

Two ways to choose parameters:
• Scenario-analysis (field or simulations)
• Optimization
Optimization-based Formulation for Predictive SPDHRM at the Individual Vehicle Level

\[
\max \sum_{t=t_0}^{t_0+\tau_{oh}} \sum_{v \in V} DT_{tv}(u^m_{v5})
\]

\[
u_{min} \leq u^m_{v5} \leq u_{max}, \quad \forall v \in V^{us}
\]

\[
u^m_{v5} = 5 \times u_{v}, \quad \forall v \in V^{us}
\]

\[
u_{v} \text{ integer,} \quad \forall v \in V^{us}
\]

- \(t\): time step
- \(t_0\): current time step
- \(\tau_{oh}\): optimization horizon
- \(v\): vehicle id
- \(V\): set of all vehicle ids in targeted segment
- \(V^{us}\): set of vehicles ids upstream of congestion location
- \(DT_{tv}\): distance traveled by vehicle \((v)\) at time step \((t)\) as a function of speed limits (simulation)
- \(u^m_{v5}\): decision variable - updated speed for vehicle \((v)\) as a multiple of 5
- \(u_{v}\): decision variable - updated speed for vehicle \((v)\)
- \(u_{min}\): min speed limit on highway
- \(u_{max}\): max speed limit on highway

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General formulation is computationally infeasible at the individual vehicle level

- Microsimulation is the only way to predict distance travelled by vehicles while capturing the interactions of different driving behaviors and control strategies

- Major limitation of this formulation
  - Microsimulation is computationally intensive and time consuming
  - Microsimulation-based optimization needs to run the simulation a large number of times to find optimal solution

- Solution: reformulate to reduce number of decision variables
  - Finite reduced sets of speeds and distances

\[
\begin{align*}
  u & \in U = \{u_{\text{min}}, (u_{\text{min}} + 5), \ldots, u_{\text{max}}\} \\
  d & \in D = \{500, 1000, 1500\}
\end{align*}
\]
Performance Comparison

Optimization-based vs. Decision-Tree Speed Control

\[
\max_{t_0 + t_{oh}} \sum_{t=t_0} \sum_{v \in V} DT_{tv}(u, d)
\]

\[u \in U = \{55, 60, 65, ..., 100\} \text{ km/h}\]

\[d \in D = \{500, 1000, 1500\} \text{ m}\]
Optimization-based speed control further reduces the severity and length of traffic shockwaves.

Optimal limit selection from a wider set of speeds and optimal broadcasting distance leads to smooth transition of upstream flow.
Optimization-based speed control further improves the stability of traffic

Smooth transition in speed limits improves stability of traffic
Optimization-based speed control further improves the overall traffic speed.

The optimization formulation maximizes speed.
Increasing optimization horizon beyond 30 seconds (3x monitoring time-step) does not significantly improve performance

<table>
<thead>
<tr>
<th>Optimization Horizon (seconds)</th>
<th>Average Travel Time (sec)</th>
<th>Average Speed (km/h)</th>
<th>StdDev Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>232</td>
<td>75</td>
<td>16</td>
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<tr>
<td>20</td>
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<tr>
<td>30</td>
<td>221</td>
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</tr>
<tr>
<td>40</td>
<td>222</td>
<td>86</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>220</td>
<td>81</td>
<td>9</td>
</tr>
</tbody>
</table>

- Increasing prediction horizon significantly slows down simulation
What to keep in mind for a real-world application of optimization-based control?

• Additional layer of prediction when estimating distance traveled – more prone to prediction errors
  • advancements in traffic microsimulation models and reinforced learning techniques minimize errors

• Computationally intensive and time consuming due to running a large number of simulations
  • Parallelization
  • Optimize traffic simulator for speed
  • Reduce number of potential decision variables to test (fastest)
Centralized SPDHRM Conclusion

• Activating the SPDHRM system improves traffic stability, speed, and reduces travel time
• The system performance improves at higher market penetrations of CAVs
• The optimization-based control strategy further improves the performance of the system
Control Strategy Application: Predictive Speed Harmonization in a Connected Environment with Decentralized Control
Predictive Speed Harmonization in a Connected Environment with **Decentralized Control**

- **Freeway Segment**
  - CAV Fleet Trajectories

- **Speed Control**
  - Individual Vehicle Speed Selection
    - Updated speed limit
    - Activation location
  - Congestion start time
  - Congestion location downstream of vehicle

- **Traffic Monitoring**
  - Individual Vehicles - V2V
  - Fleet Size and Communication Range
  - Downstream traffic mean speeds
  - Downstream traffic speed standard deviations
  - Shockwave formations ahead

- **Congestion Prediction**
  - Single or Multiple (Fleet-based) Models
Decentralized SPDHRM improves traffic stability and performance
Decentralized SPDHRM increases overall speed and reduces its variation.
Connectivity improves the performance of decentralized SPDHRM

Higher CV market penetration:

1. Improves congestion prediction
2. Improves speed
3. Improves effectiveness

Note: This case assumes one single fleet (same prediction model, all CV data shared)
Decentralized SPDHRM improves performance under low automation

- Automated vehicles stabilizes traffic without SPDHRM due to the robotic nature of its driving behavior
- SPDHRM further improves traffic performance by controlling speed of connected vehicles

This case assumes one single fleet
Virtually no impact on traffic in high automation conditions

- SPDHRM is not activated as the high market penetration of AVs prevents congestion.

This case assumes one single fleet.
Decentralized SPDHRM Conclusion

• Activating the decentralized system reduces the severity of traffic shockwaves, improves stability of traffic, increases overall traffic speed, and reduces travel time
• Having multiple prediction models (fleet-based models) reduces the effectiveness of the strategy
• Successful application of the decentralized system requires standardization of data collection among vehicles and the ability to communicate with vehicles from other fleets to improve prediction range and accuracy
KEY TAKEAWAYS: HOW IS IT DIFFERENT THIS TIME?

1. Transportation and mobility industries undergoing major disruptive influences: technology, players, concepts.

2. Forces transforming mobility systems – no longer dependent on public infrastructure investment. Connectivity through C-V2X (Advanced LTE, 5G) rather than DSRC.

3. Emergence and growing role for shared mobility fleets (autonomous Uber-like services and variants), though private ownership not likely to go away.

4. Change driven by direct user adoption of products and services, not agency sanctioning and procurement.

5. Advances in AI, computational optimization, distributed control, etc.-- driven and deployed by large technology companies.

6. Connectivity and automation—generate orders of magnitude more data and data opportunities; from micro to system level, in very large quantities. Prediction and learning enable effective operation and control.

7. Automation: All about replacing human functions, including responses and behaviors, by sensors, machine learning, AI and optimal control. Fundamental knowledge and analytics built around modeling human capabilities, limitations and choices remains essential.

8. Transportation agencies: Embrace change, rethink how to best accomplish mission.
Selected Research Challenges

1. The behavior question: what will people do? Adoption of new technologies and services, usage, satisfaction, happiness...
2. Algorithms for real-time shared autonomous fleet operations under different business models, at scale.
3. Integrated dynamic network modeling frameworks for urban and regional-level impact evaluation and system design: multi-player games with cooperative/competitive agents.
4. System operation and management through personalized information/incentives towards efficient and sustainable mobility; role of prediction, behavioral science.
5. Flow management in mixed traffic environments; machine learning, real-time control.
6. Data management in connected environment— from micro scale interventions to macro level assessment.
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