# RESEARCH *THAT MOVES YOU*

**Northwestern University Transportation Center**

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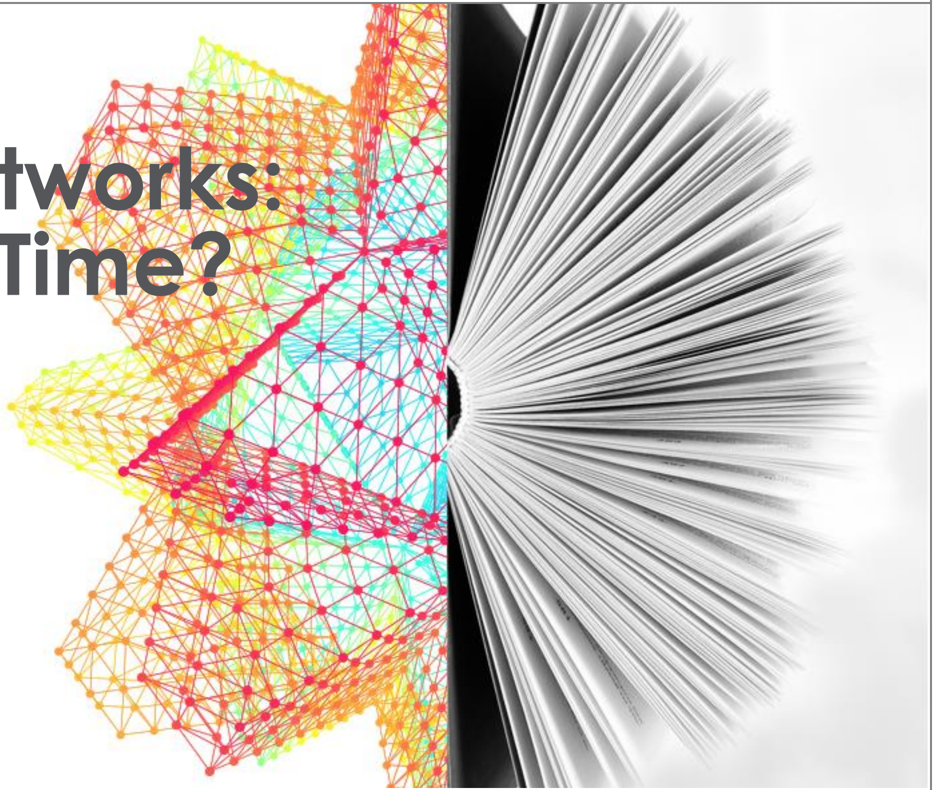
Data. Changes. Everything.

# 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

# Autonomous and Connected Vehicles

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 | ITS ENVIRONMENT |
| --- | --- |
| - Steady - state | - Time varying |
| - **Equilibrium** | - **Evolutionary paths** |
| - Static | - Dynamic |
| - **Data poor** | - **Data rich** |
| - Uncertainty about past/ current events | - Known past/current events (to varying degrees) |
| - **Component level** | - **System level** |
| - Long lead time between solution and implementation | - Immediate action |
| - **Limited "accountability" of decisions** | - **Performance monitoring and feedback** |
| - "A priori" solutions | - Real-time adaptive strategies |

1994

to

2019

**25 YEARS--**
**DEPLOYMENT OF A LOT OF *TECHNOLOGY***

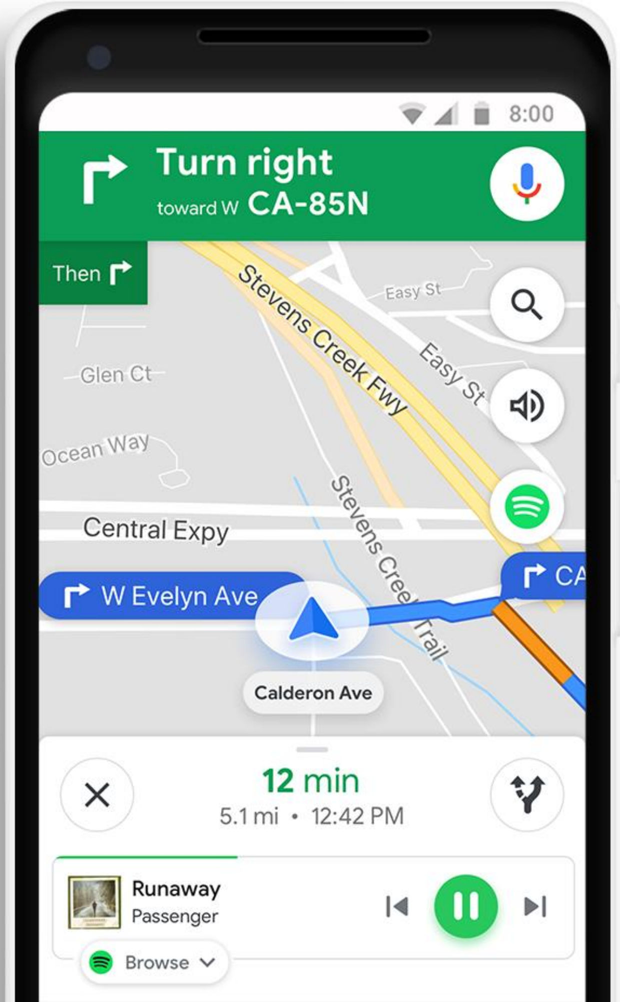
**NOT AS MUCH *INTELLIGENCE***

## 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

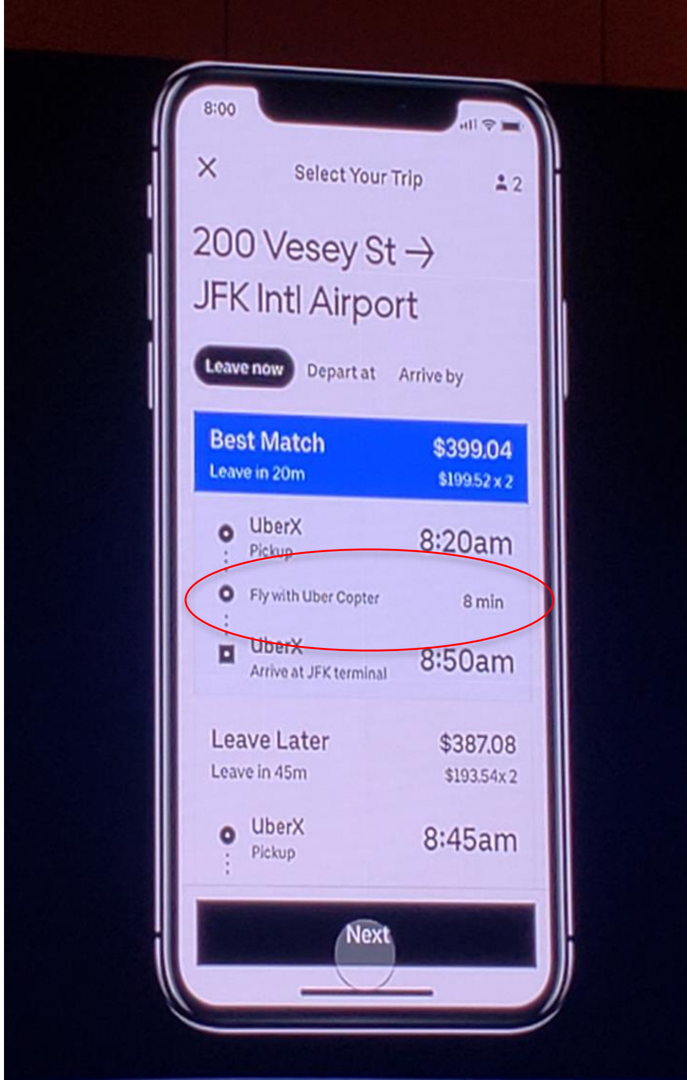
Some even with prediction

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


INTELLIGENT *TRANSPORTATION* SYSTEMS

**ITS 1.0**

Buses, trains, multimodal services
Urban mobility

**ITS 2.0 = CS 2.0**

*CONNECTED* SYSTEMS

Digital 6th Sense


**FOCUS: THE USER**

Mobility as an APP in seamless connected environment

# TWO MAIN AREAS FOR DEVELOPING TRANSPORTATION SYSTEM INTELLIGENCE

**Realization I**

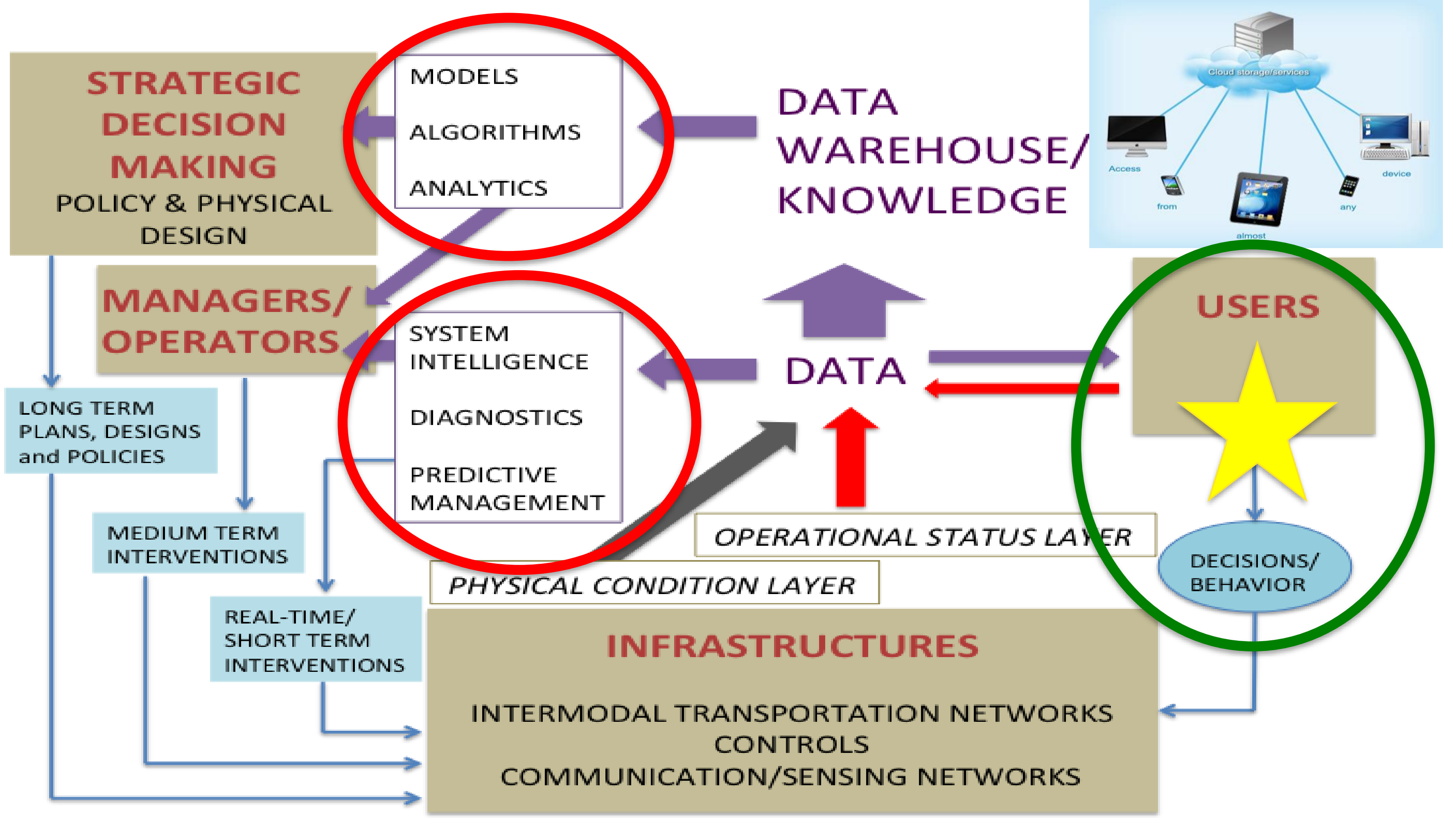
Monitor the state of the system at all times, provides basis to intervene and apply control actions in real-time.

*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*

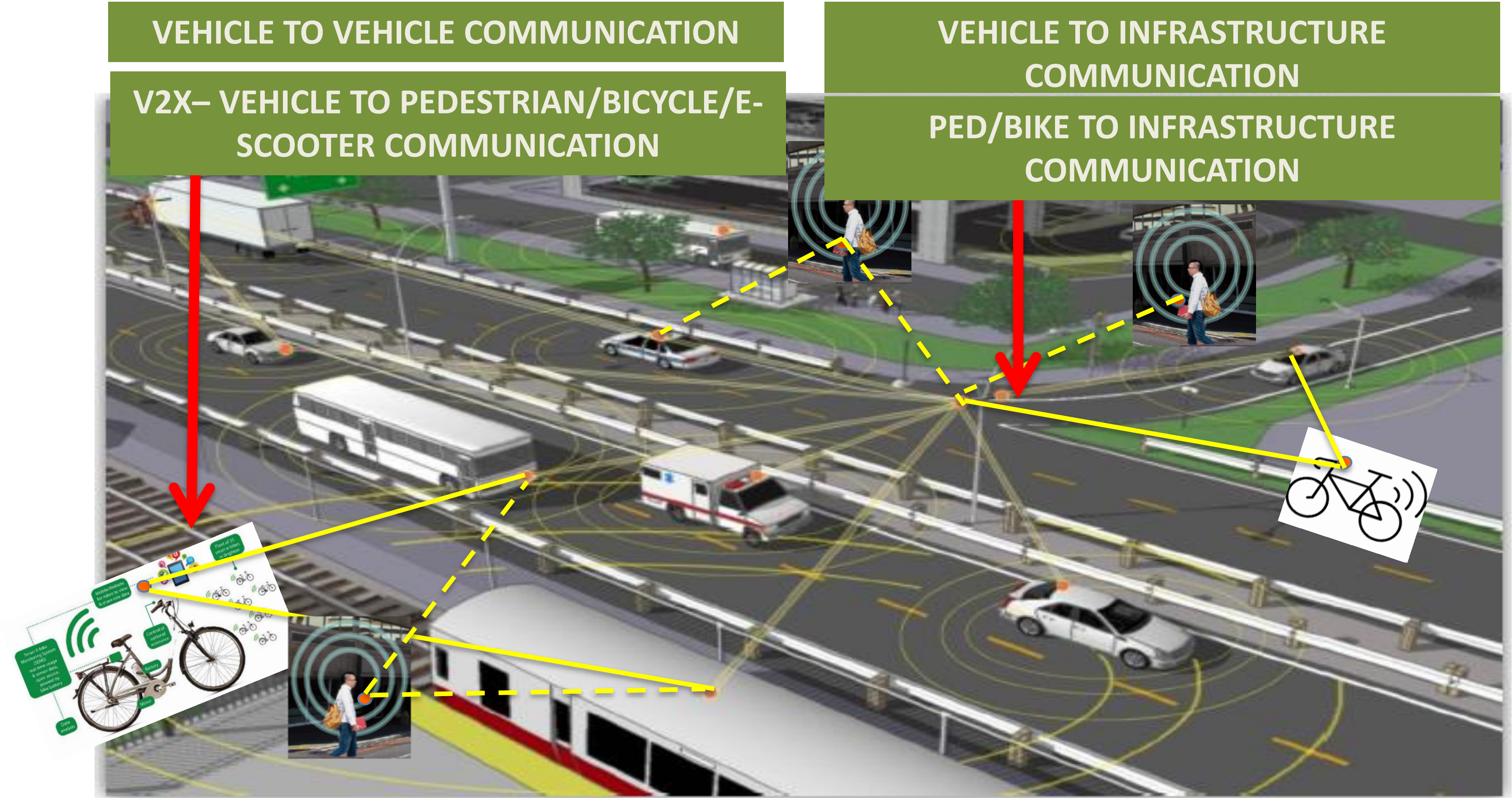

STRATEGIC DECISION MAKING
POLICY & PHYSICAL DESIGN
MODELS
ALGORITHMS
ANALYTICS
DATA WAREHOUSE/ KNOWLEDGE
Cloud storage/services
Access
from
almost
any
device
MANAGERS/ OPERATORS
SYSTEM INTELLIGENCE
DIAGNOSTICS
PREDICTIVE MANAGEMENT
DATA
USERS
LONG TERM PLANS, DESIGNS and POLICIES
MEDIUM TERM INTERVENTIONS
REAL-TIME/ SHORT TERM INTERVENTIONS
OPERATIONAL STATUS LAYER
PHYSICAL CONDITION LAYER
DECISIONS/ BEHAVIOR
INFRASTRUCTURES
INTERMODAL TRANSPORTATION NETWORKS
CONTROLS
COMMUNICATION/SENSING NETWORKS

VEHICLE TO VEHICLE COMMUNICATION

VEHICLE TO INFRASTRUCTURE COMMUNICATION

# CONNECTED VEHICLE SYSTEMS

U.S. Department of Transportation




# CONNECTED MOBILITY SYSTEMS

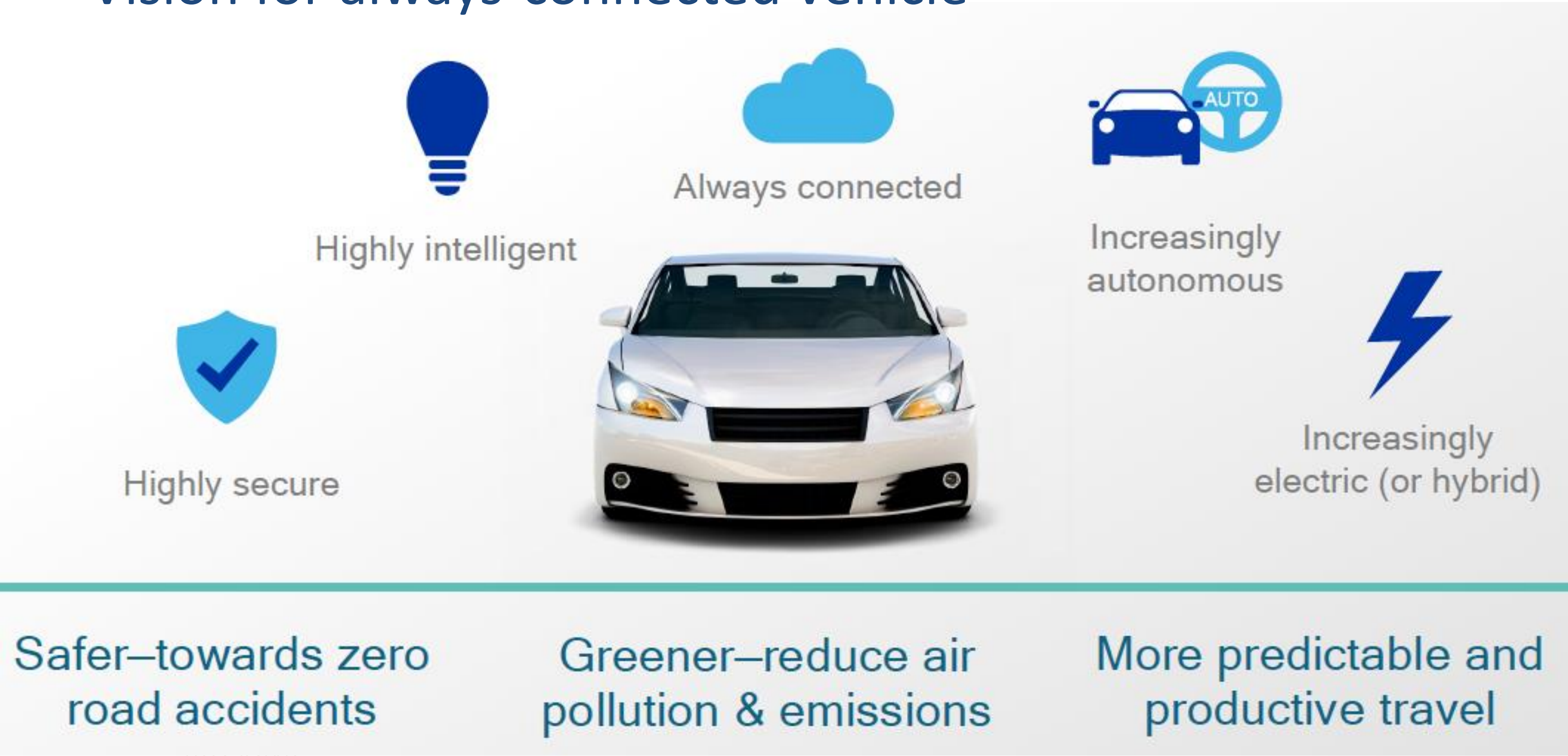
# The connected vehicle is already a mainstream reality

60%

Cellular penetration in new light vehicles sales by 2021[1]

Source: QUALCOMM

# Vision for always-connected vehicle




Source: QUALCOMM

# 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
- Bluetooth
- Wi-Fi / Hotspot
- Cellular 3G/4G/5G
- Always-on telematics
- CAN / Ethernet / Powerline

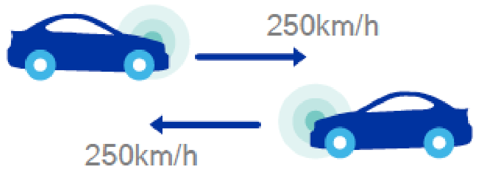
## On-device intelligence

- Intuitive instrumentation
- Immersive multimedia
- Augmented reality
- Always-on sensing
- Computer vision
- Intuitive security
- Machine learning



Source: QUALCOMM

# Overcoming the challenges of V2X communications

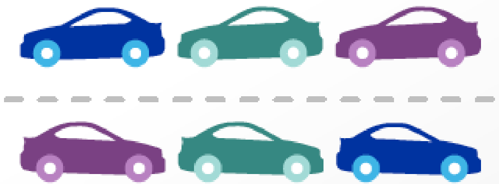



## V2X Challenges

### High relative speeds
Leads to significant Doppler shift / frequency offset

## C-V2X Solutions

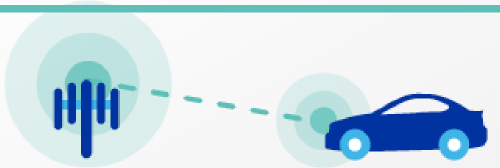
### Enhanced signal design
E.g. increasing # of ref signal symbols to improve synchronization and channel estimation



### High node densities
Random resource allocation results in excessive resource collisions

### 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



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

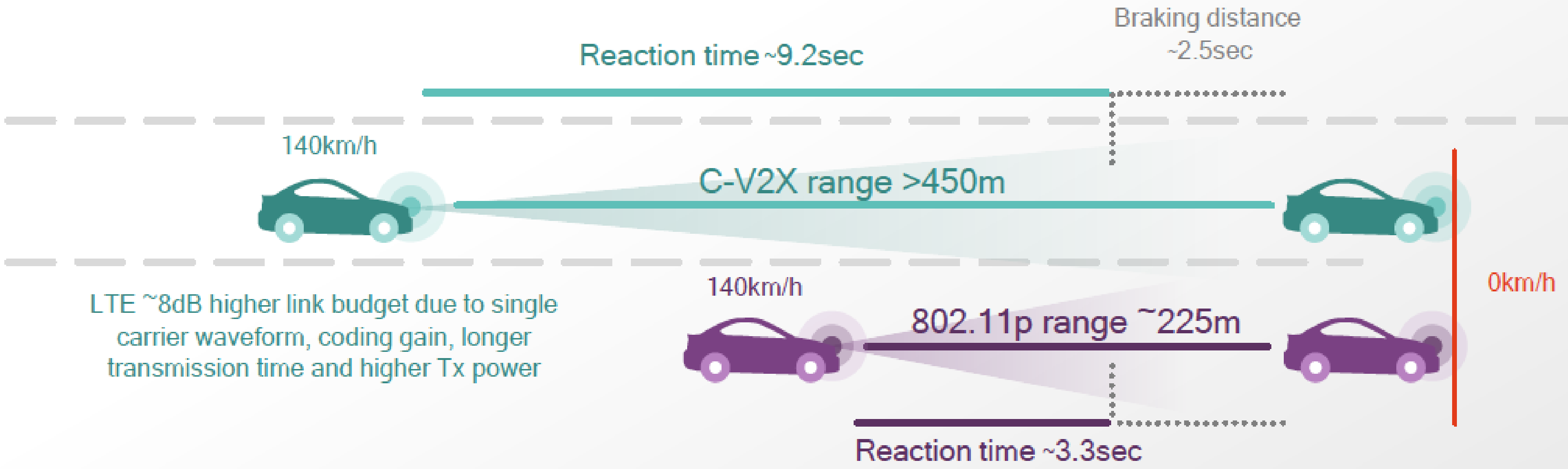
### Allow utilization of GPS timing
Enhancements to use satellite (e.g. GNSS) when out-of-coverage



Source: QUALCOMM

# C-V2X increases reaction time over 802.11p/DSRC

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




### Safer driving experience

Increased driver reaction time

### Support for high speeds

Relative speeds up to 500km/h

### Increased situational awareness

Gather data from further ahead

09/23/2009

Source: QUALCOMM

# 5G will build upon and enhance C-V2X

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

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

**4G LTE** — Continue to evolve and provide ubiquitous coverage as 5G is rolled out

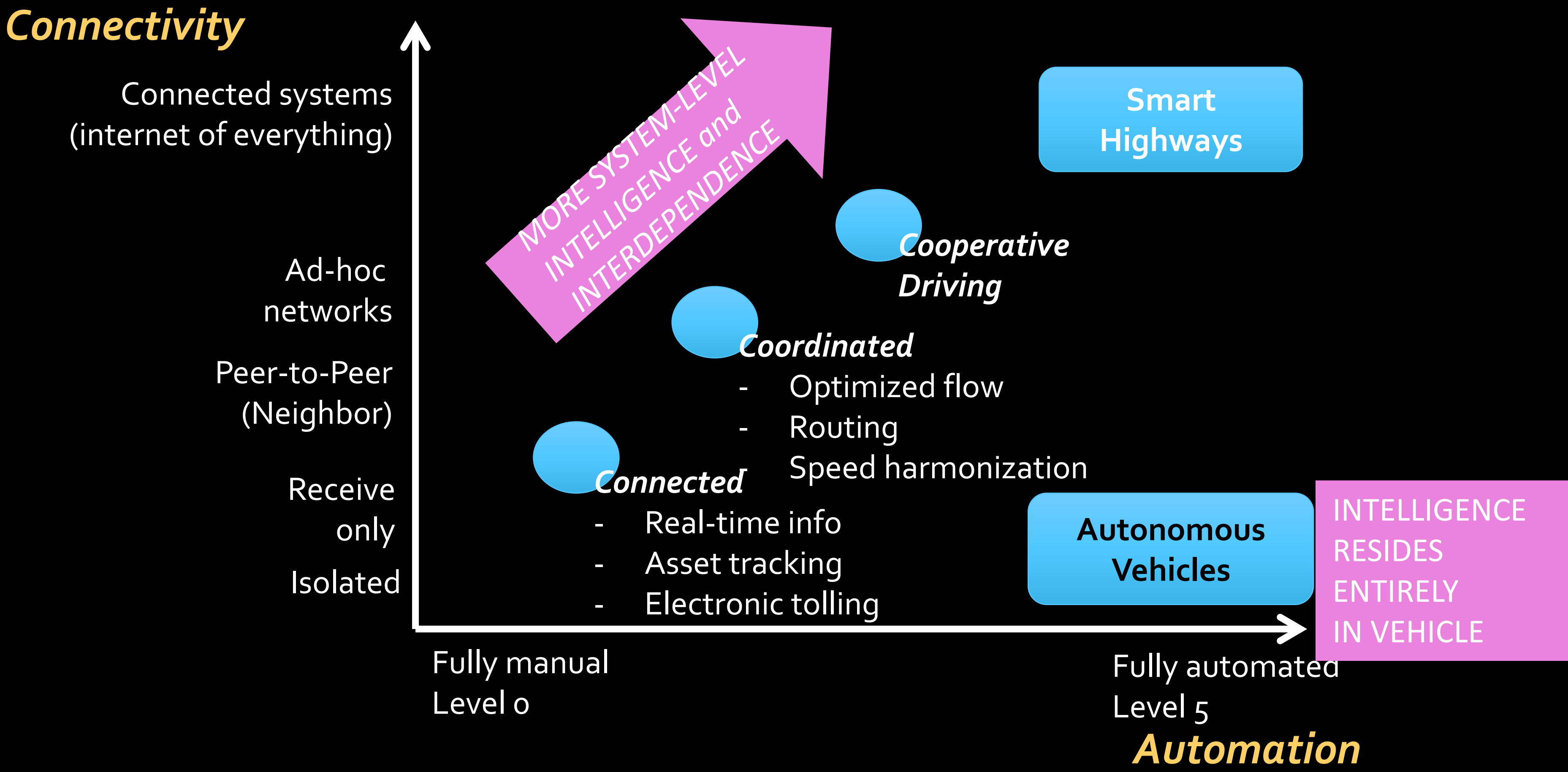
**C-V2X** — C-V2X direct and network communications

**5G** — Bring new capabilities for C-V2X network communications and augment C-V2X direct communications over time

Source: QUALCOMM

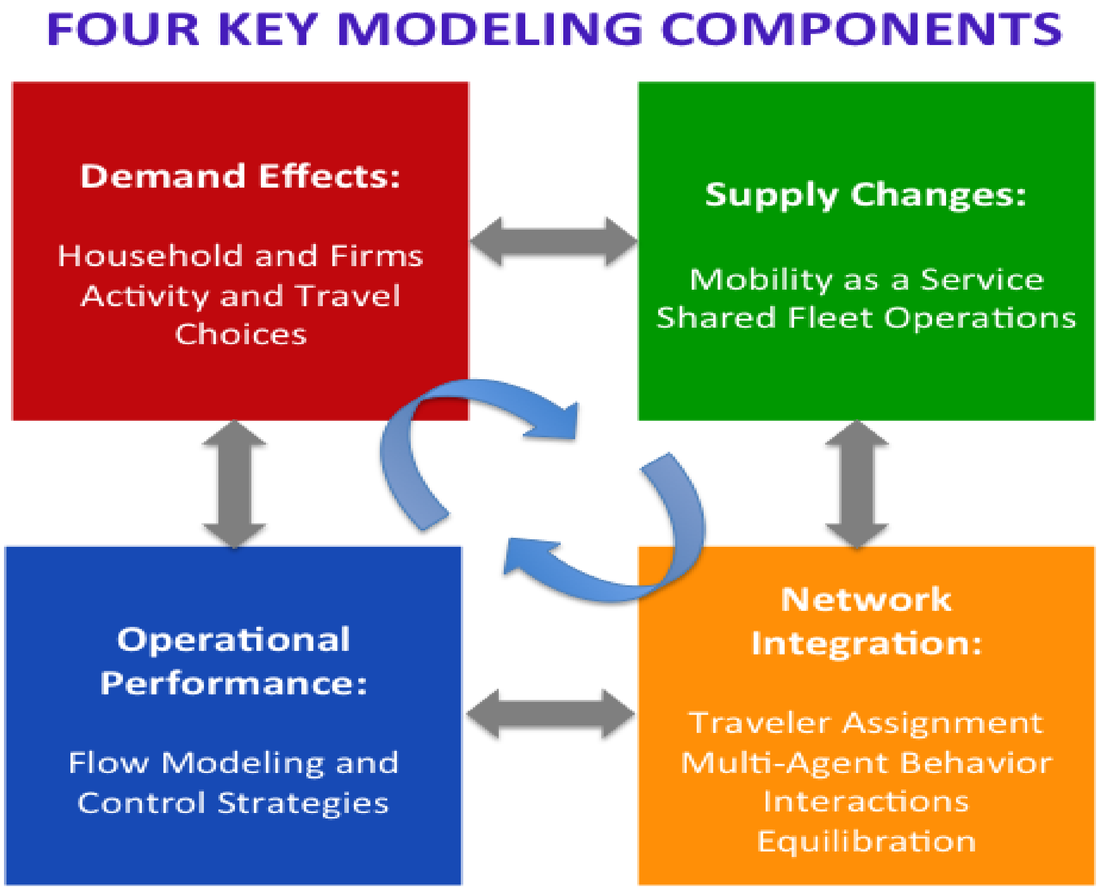
# Simple Taxonomy of ITS Applications

| | SENSING FACILITIES | SENSING PARTICLES |
|---|---|---|
| **INTERVENTION FACILITIES** | Conventional ITS Transportation Management | Augments facility-based sensors; improves demand estimation and predictive strategies |
| **INTERVENTION PARTICLES** | ITS: Traveler information systems (ATIS)<br>Emerging: Multimodal, user-customized | **Next Gen:**<br>Personalized, social, gamified to maximize response and impact |


Connectivity
Connected systems
(internet of everything)
Ad-hoc
networks
Peer-to-Peer
(Neighbor)
Receive
only
Isolated
MORE SYSTEM-LEVEL
INTELLIGENCE and
INTERDEPENDENCE
Smart
Highways
Cooperative
Driving
Coordinated
- Optimized flow
- Routing
- Speed harmonization
Connected
- Real-time info
- Asset tracking
- Electronic tolling
Autonomous
Vehicles
INTELLIGENCE
RESIDES
ENTIRELY
IN VEHICLE
Fully manual
Level 0
Fully automated
Level 5
Automation

# Gap Analysis Structure

*(NUTC, 2018 for FHWA study)*



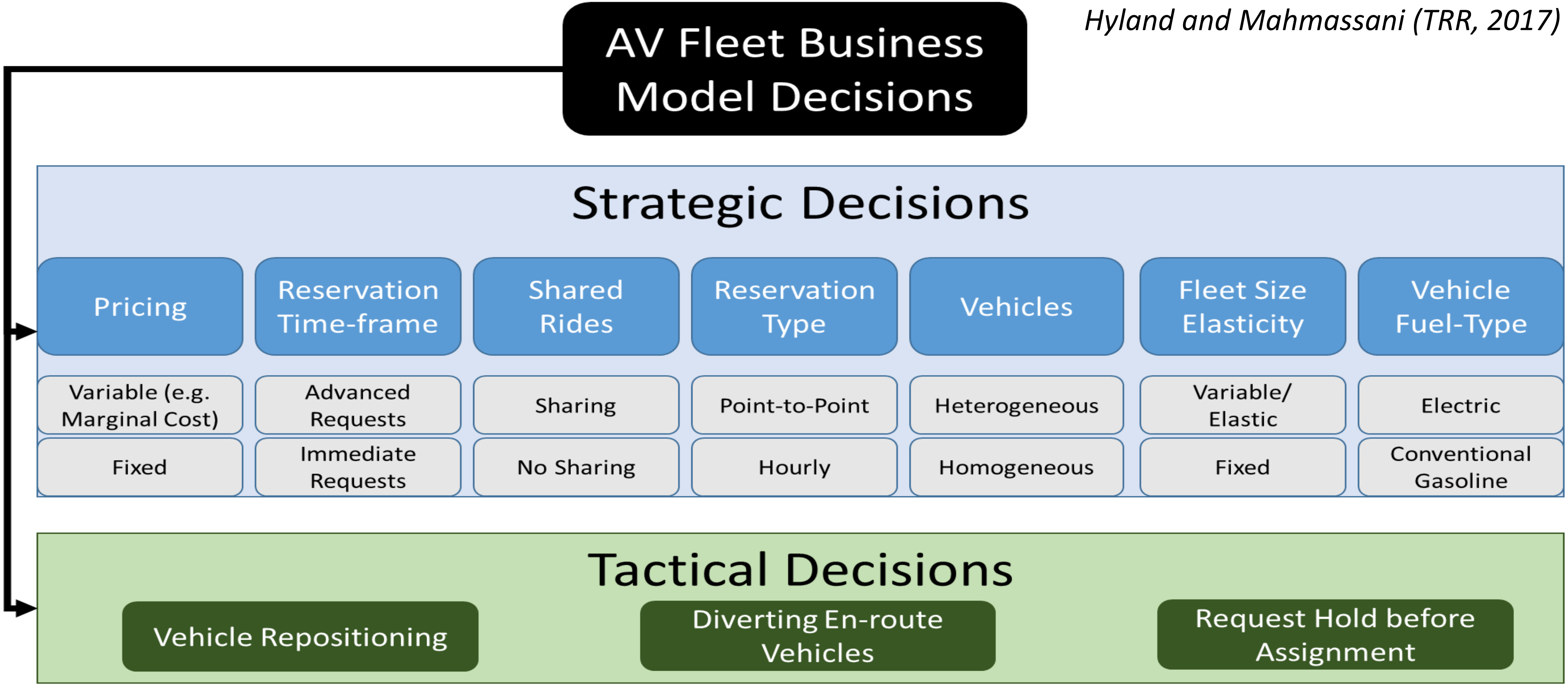
# Mobility Service Delivery Models

- 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**

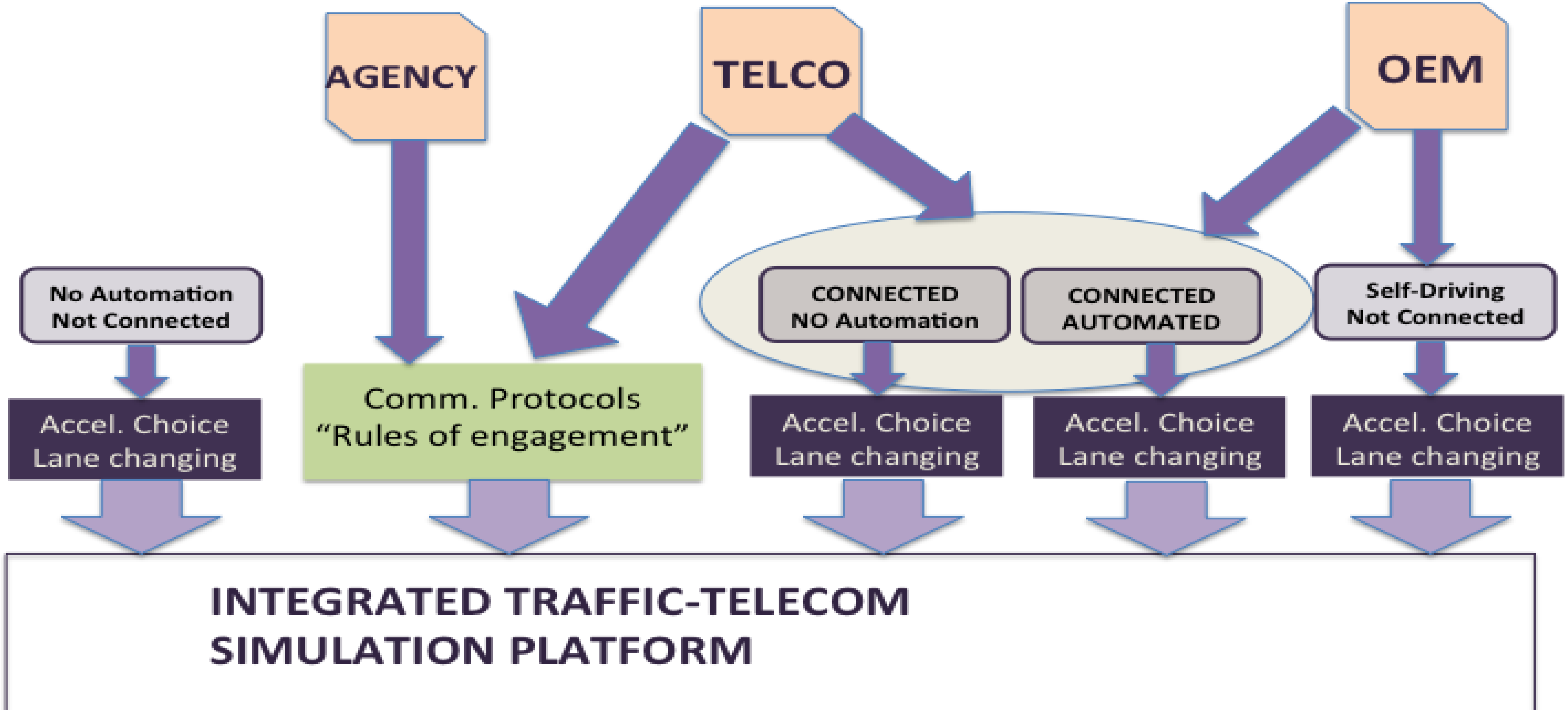
# AV Fleet Business Models for Mobility Service

## Potential Variants

*Hyland and Mahmassani (TRR, 2017)*



# OUR APPROACH



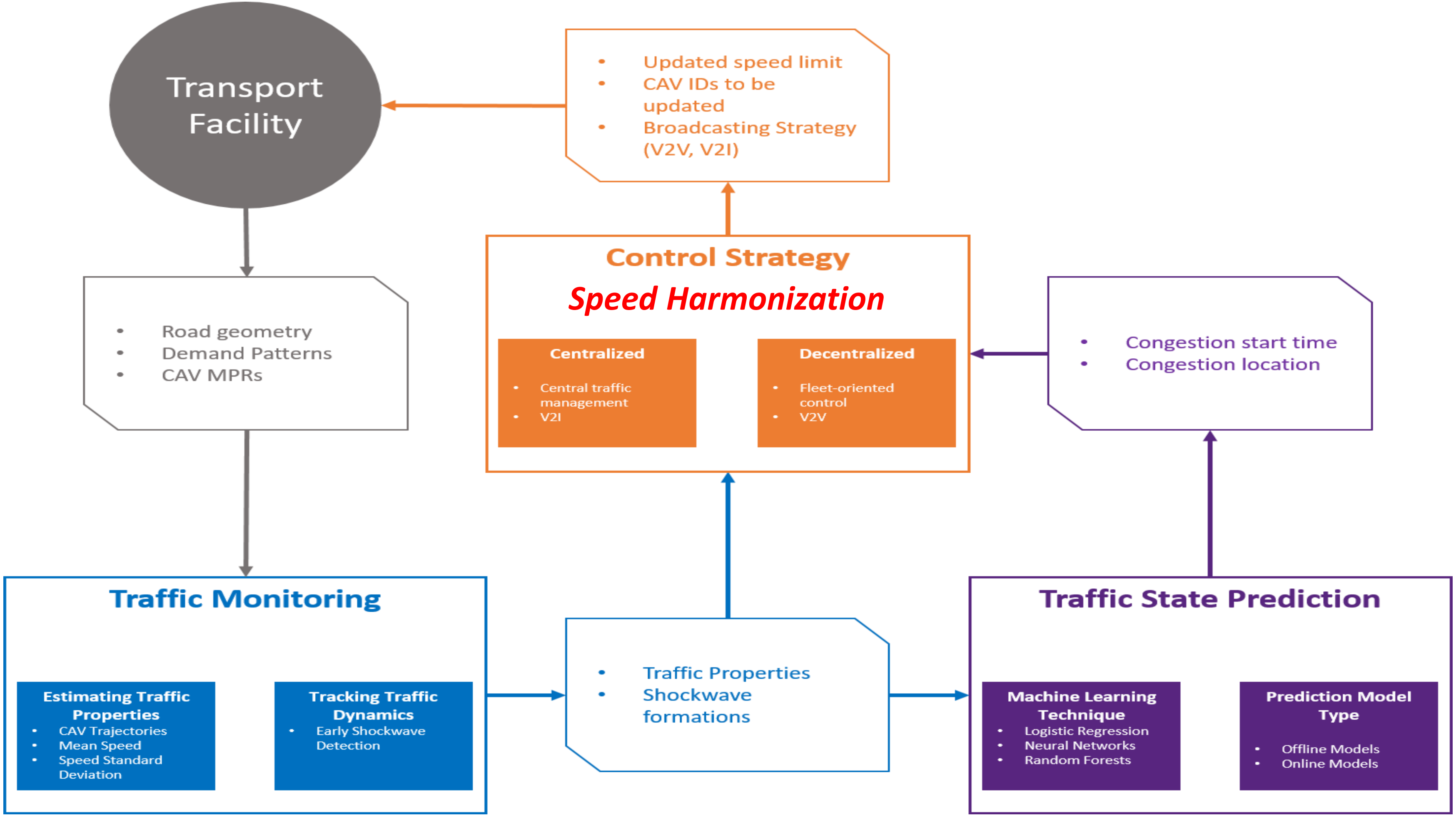
# Predictive Control Application in a CAV Environment : Shockwave Detection and Speed Harmonization

*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

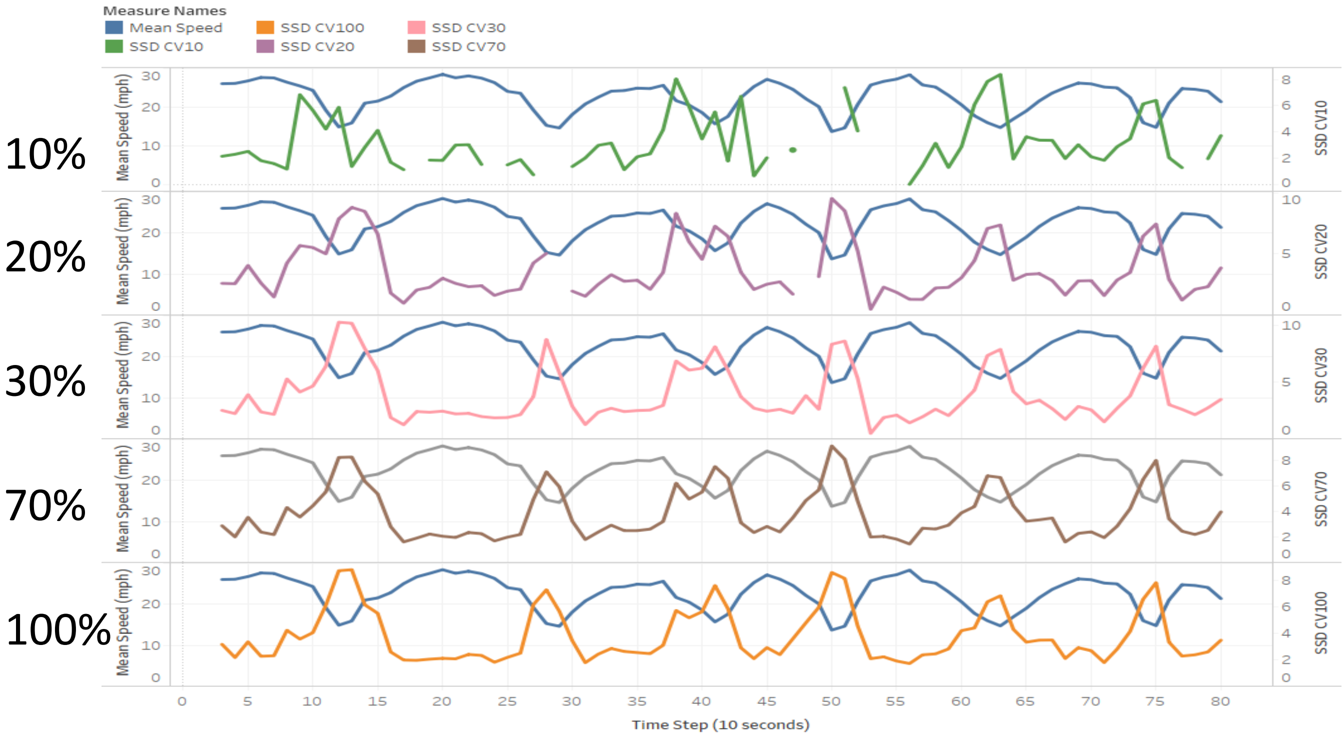

Transport Facility
Updated speed limit
CAV IDs to be updated
Broadcasting Strategy (V2V, V2I)
Road geometry
Demand Patterns
CAV MPRs
Control Strategy
Speed Harmonization
Centralized
Central traffic management
V2I
Decentralized
Fleet-oriented control
V2V
Congestion start time
Congestion location
Traffic Monitoring
Estimating Traffic Properties
CAV Trajectories
Mean Speed
Speed Standard Deviation
Tracking Traffic Dynamics
Early Shockwave Detection
Traffic Properties
Shockwave formations
Traffic State Prediction
Machine Learning Technique
Logistic Regression
Neural Networks
Random Forests
Prediction Model Type
Offline Models
Online Models

# 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

# Speed Standard Deviation Waves with Partial Connectivity




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)

$$y_{ts} = v_{(t-1)s} + v_{(t-1)(s+1)} + ssd_{(t-1)(s+1)}$$

| Variable | | Description |
|---|---|---|
| | Dependent Variable | |
| $y_{ts}$ | Traffic State | 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). |
| | Explanatory Variables | |
| $v_{(t-1)s}$ | Lagged Mean Speed in Current Section | Continuous: the average speed of individual vehicles in the current section, lagged 10, 20, or 30 seconds |
| $v_{(t-1)(s+1)}$ | Lagged Mean Speed in Downstream Section | Continuous: the average speed of individual vehicles in the next downstream section, lagged 10, 20, or 30 seconds |
| $ssd_{(t-1)(s+1)}$ | Lagged Speed Standard Deviation in Downstream Section | Continuous: the speed standard deviation of individual vehicles in the next downstream section, lagged 10, 20, or 30 seconds |

# 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)

| Model | CV | Overall Accuracy | Congested State Prediction Accuracy | Uncongested State Prediction Accuracy |
|---|---|---|---|---|
| Random Forest 10s | 30% | 91% | 95% | 80% |
| Random Forest 10s | 50% | 92% | 95% | 82% |
| Random Forest 10s | 100% | 93% | 95% | 85% |
| Random Forest 20s | 30% | 86% | 92% | 70% |
| Random Forest 20s | 50% | 88% | 93% | 73% |
| Random Forest 20s | 100% | 90% | 94% | 77% |

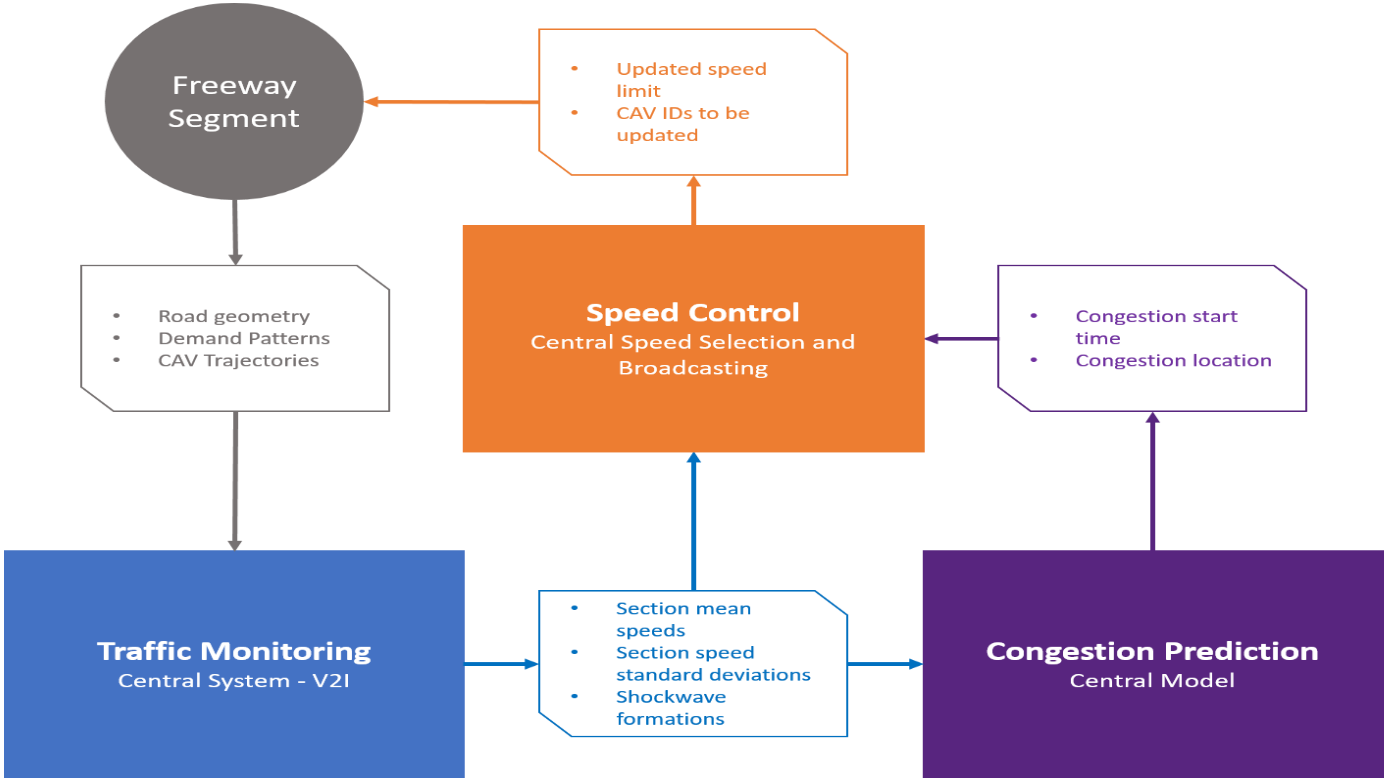
- Higher accuracy at higher MPRs -> **improved SSD estimates**
- Similar patterns for other ML algorithms

# 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



# System Differentiation

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

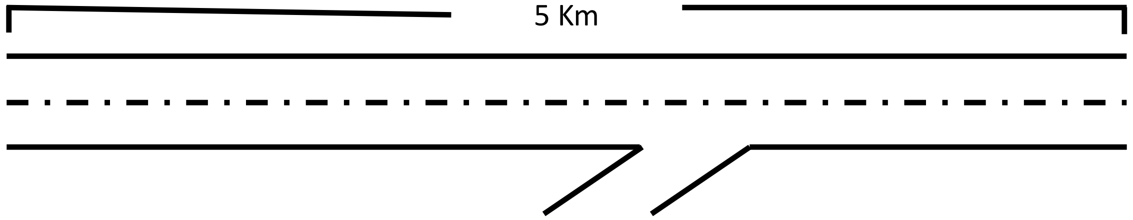
1. It solely relies on connected vehicles to collect traffic information – no need for road sensors
2. Uses machine learning to predict traffic congestion (up to 93% accuracy)
3. The system identifies the location of congestion anywhere on a freeway segment - not constrained by infrastructure sensors
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



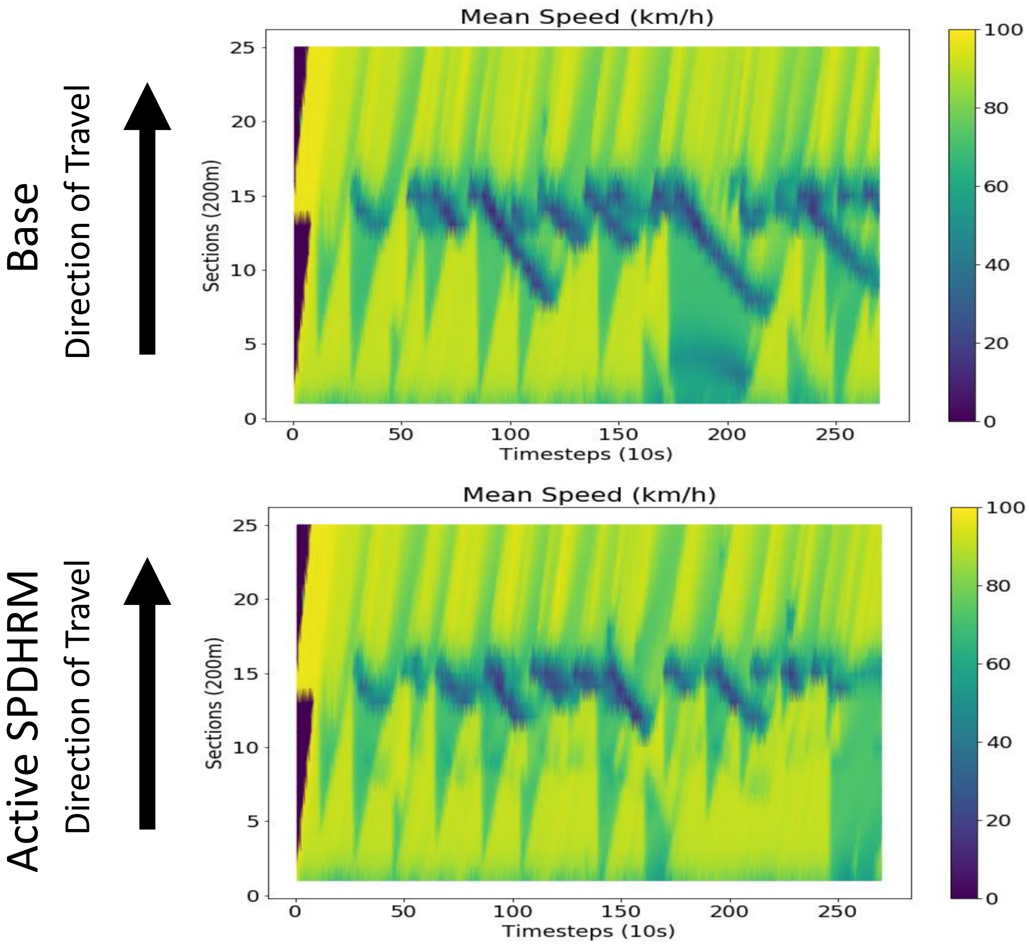
# Congestion Prediction

- 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)

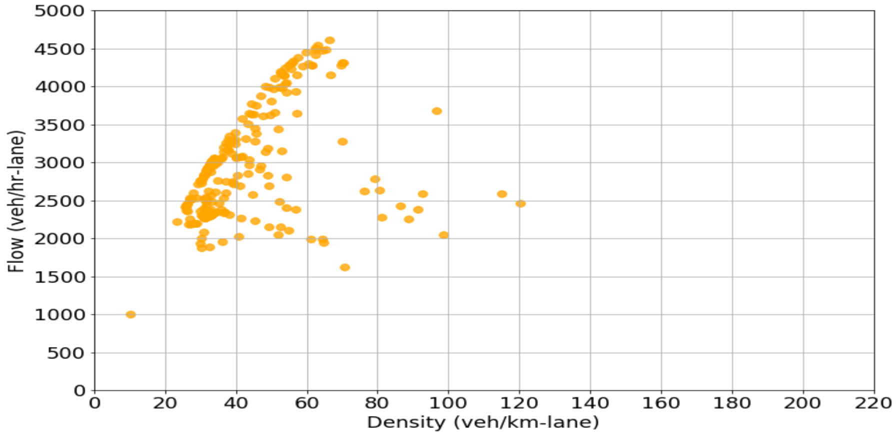
| Model | Prediction Horizon | Overall Accuracy | Congested State Prediction Accuracy | Uncongested State Prediction Accuracy | Data Source |
|---|---|---|---|---|---|
| *Previous study - Elfar et al (10)* | | | | | |
| Logistic | 10s | 93% | 96% | 85% | NGSIM |
| Logistic | 20s | 91% | 95% | 79% | NGSIM |
| Random Forest | 10s | 93% | 95% | 85% | NGSIM |
| Random Forest | 20s | 90% | 94% | 77% | NGSIM |
| Neural Network | 10s | 89% | 97% | 68% | NGSIM |
| Neural Network | 20s | 90% | 95% | 78% | NGSIM |
| *This study* | | | | | |
| Random Forest | 10s | 99% | 95% | 99% | Simulation |
| Random Forest | 20s | 98% | 90% | 99% | Simulation |
| Random Forest | 30s | 97% | 87% | 99% | Simulation |



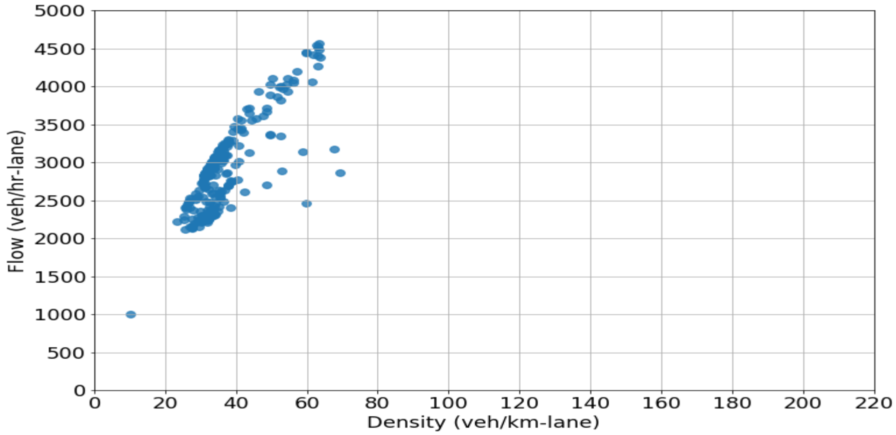

Activating SPDHRM reduces the severity and length of traffic shockwaves (improves safety)

Note: Using conventional Decision-tree approach for setting speed limit values

Base

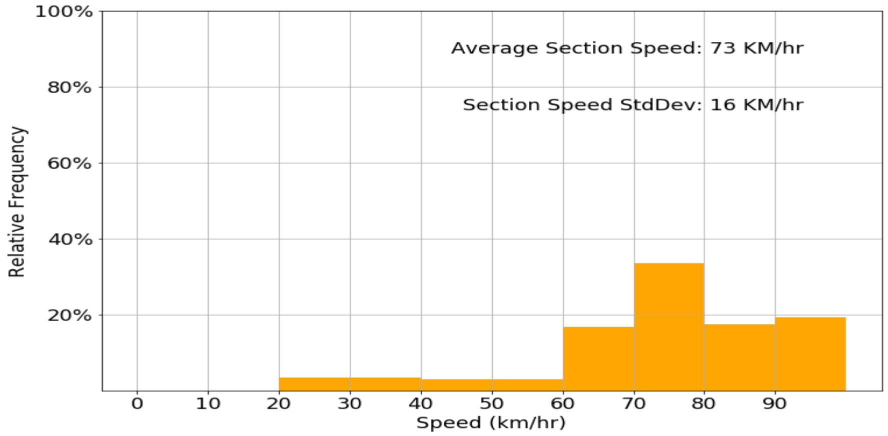



Active SPDHRM

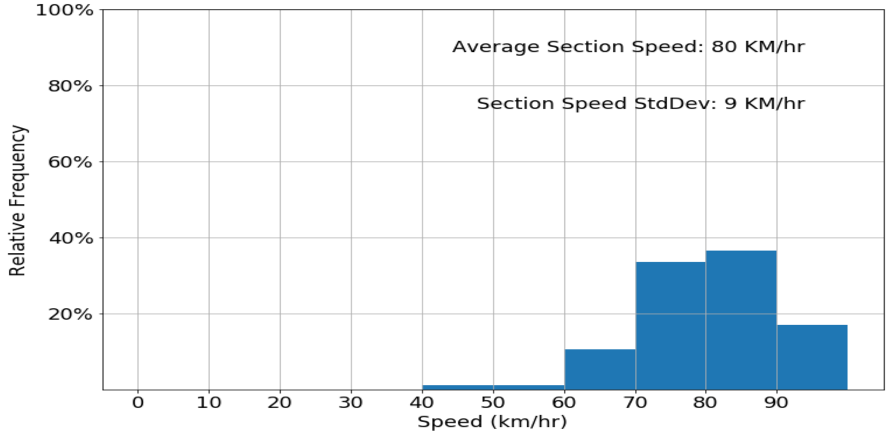



Activating SPDHRM improves traffic stability and performance

Base

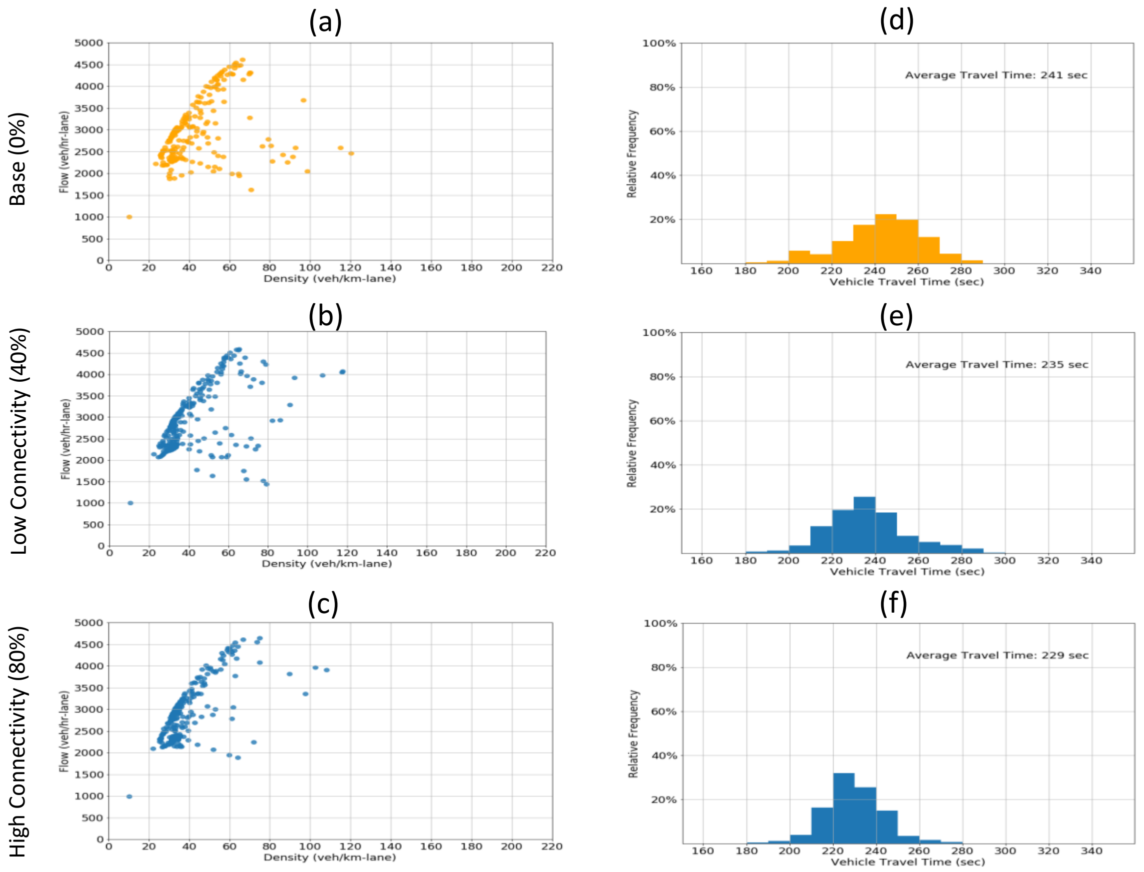



Active SPDHRM




Activating SPDHRM increases overall speed and reduces its variation

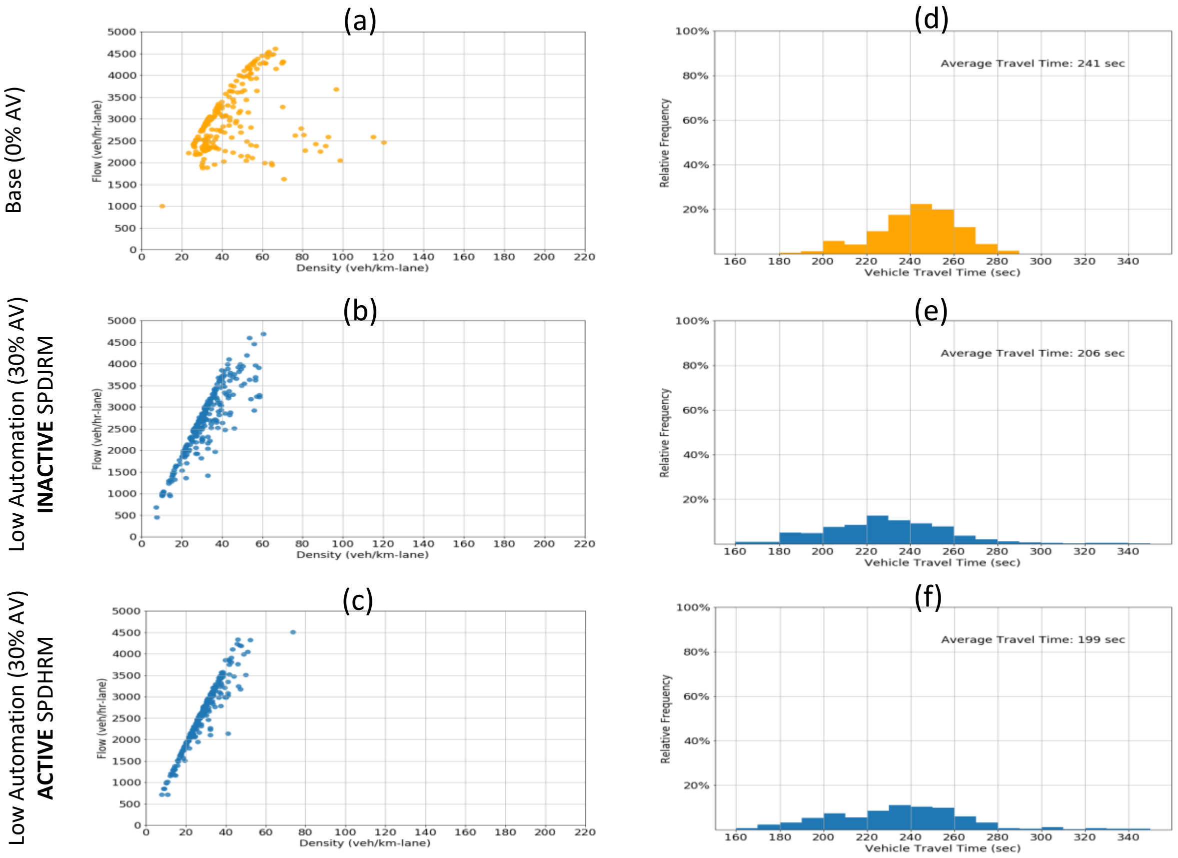
# Connectivity improves the performance of SPDHRM




Higher CV market penetration:

1. Improves congestion prediction
2. Improves speed compliance rate

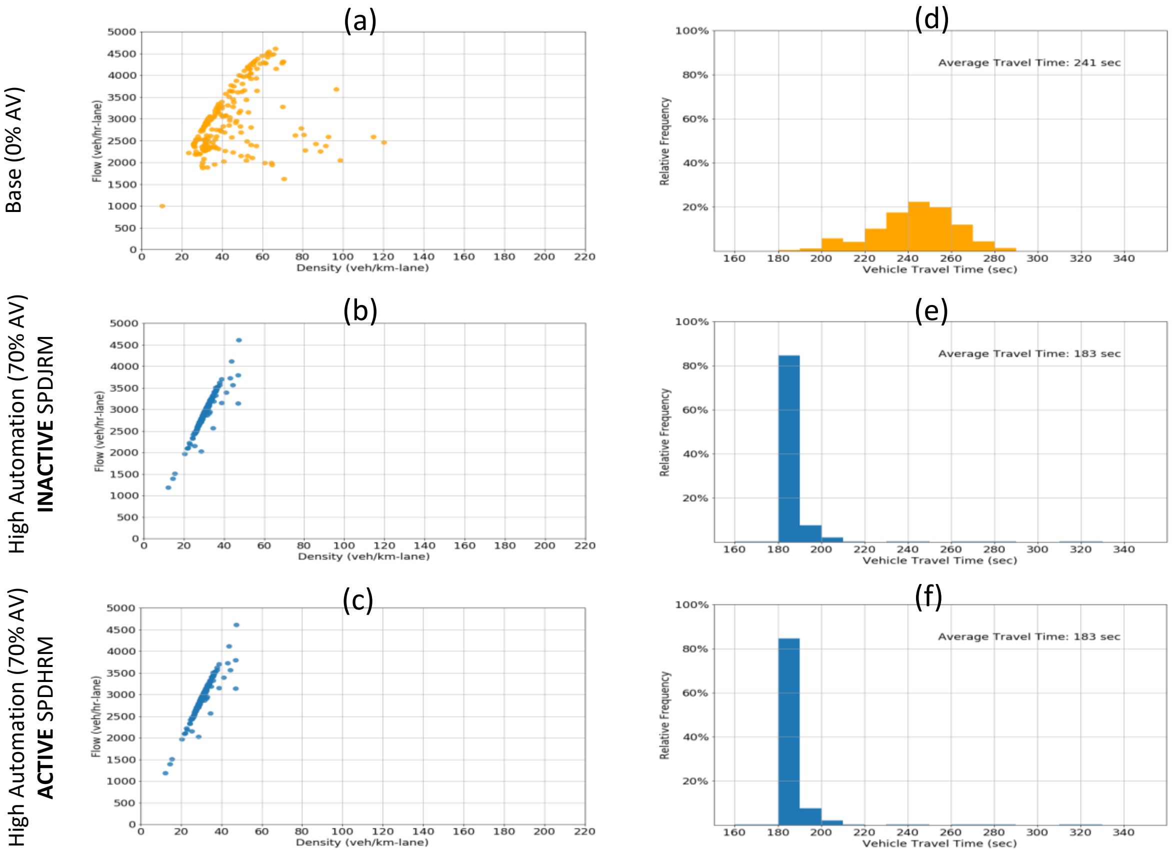
# SPDHRM improves traffic performance in low automation conditions




- 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

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# The system's design parameters need to be fine-tuned for optimal results

| Broadcasting Distance (m) | Average Travel Time (sec) | Average Speed (km/h) | StdDev Speed (km/h) |
|---|---|---|---|
| 500 | 233 | 75 | 16 |
| 1000 | 229 | 80 | 9 |
| 1500 | 237 | 76 | 13 |
| 2000 | 235 | 77 | 13 |

| Prediction Horizon (sec) | Average Travel Time (sec) | Average Speed (km/h) | StdDev Speed (km/h) |
|---|---|---|---|
| 10 | 236 | 75 | 14 |
| 20 | 229 | 80 | 9 |
| 30 | 230 | 76 | 15 |

Two ways to choose parameters:

- Scenario-analysis (field or simulations)
- Optimization

# Optimization-based Formulation for Predictive SPDHRM at the Individual Vehicle Level

$$\max \sum_{t=t_\circ}^{t_\circ+t_{oh}} \sum_{v \in V} DT_{tv}(u_v^{m5})$$

$$u_{min} \le u_v^{m5} \le u_{max}, \qquad \forall v \in V^{us}$$

$$u_v^{m5} = 5 * u_v, \qquad \forall v \in V^{us}$$

$$u_v \text{ integer}, \qquad \forall v \in V^{us}$$

| | |
|---|---|
| $t$: | time step |
| $t_\circ$: | current time step |
| $t_{oh}$: | 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) |
| $u_v^{m5}$: | 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 |

# 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

$$u \in U = \{u_{min}, (u_{min} + 5), \ldots, u_{max}\}$$
$$d \in D = \{500, 1000, 1500\}$$

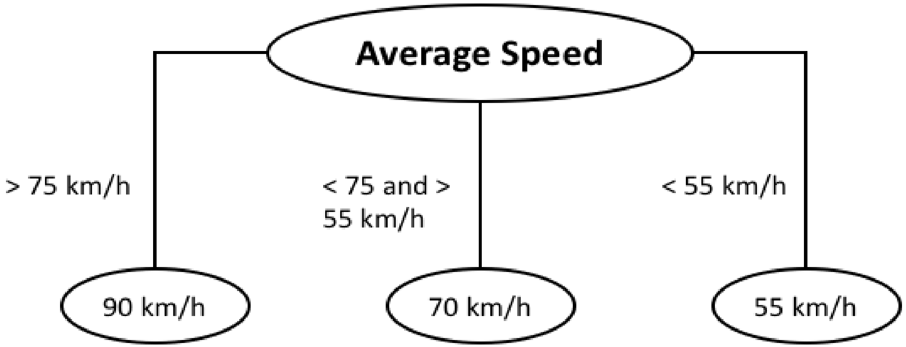
# Performance Comparison

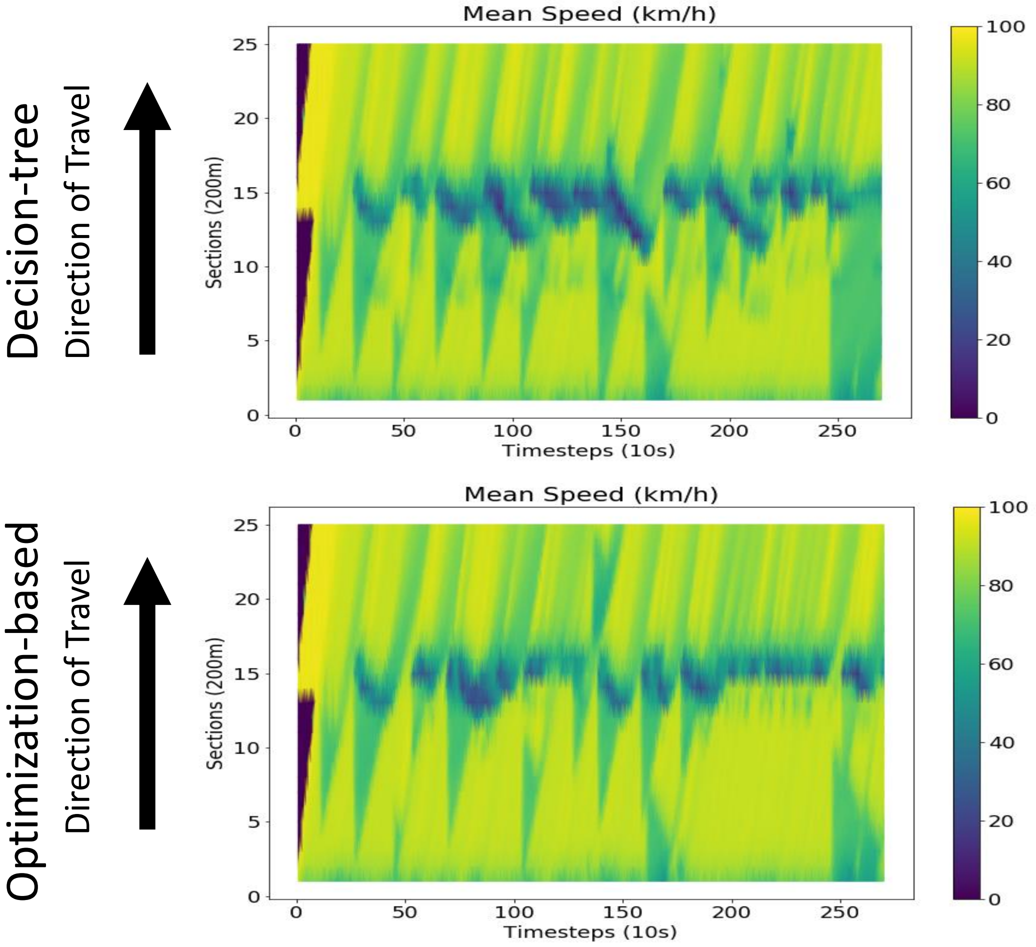
## Optimization-based vs. Decision-Tree Speed Control

$$\max \sum_{t=t_\circ}^{t_\circ+t_{oh}} \sum_{v \in V} DT_{tv}(u,d)$$

$$u \in U = \{55, 60, 65, \ldots, 100\}\ km/h$$

$$d \in D = \{500, 1000, 1500\}\ m$$

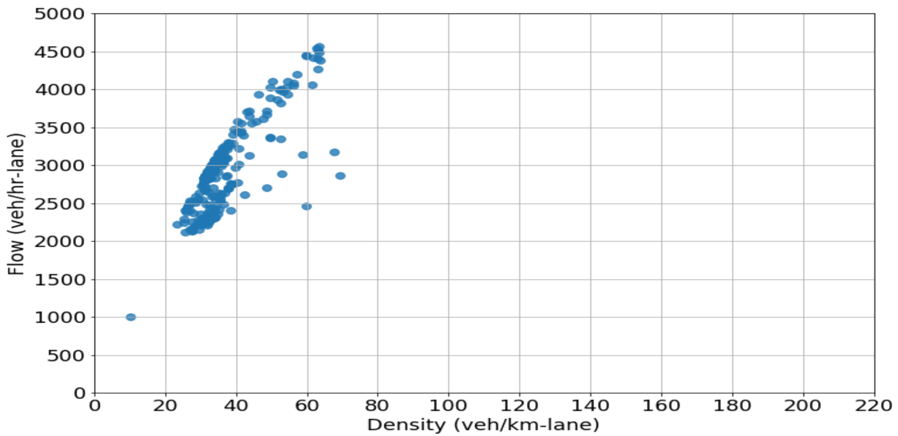




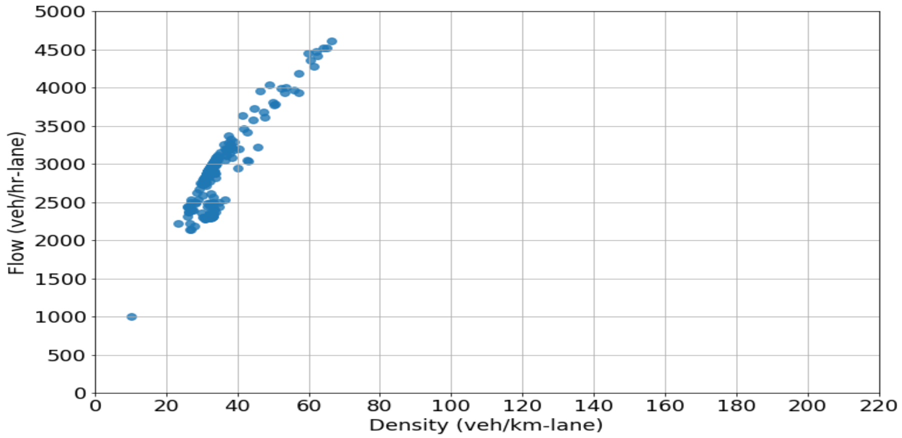

# Optimization-based speed control further reduces the severity and length of traffic shockwaves

Optimal limit selection from a wider set of speeds and optimal broadcasting distance leads to smooth transition of upstream flow

Decision-tree



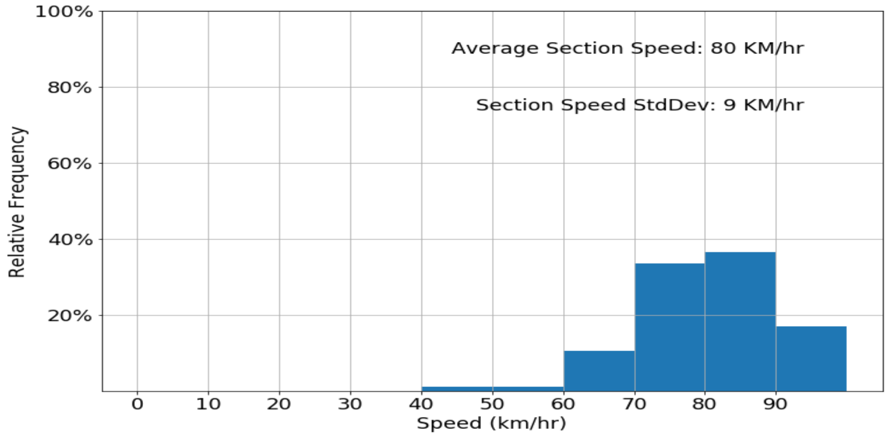

Optimization-based



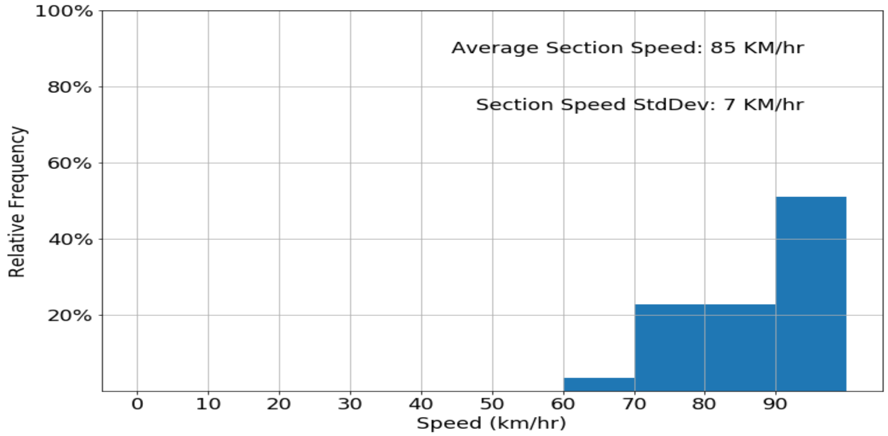

# Optimization-based speed control further improves the stability of traffic

Smooth transition in speed limits improves stability of traffic

Decision-tree




Optimization-based




# 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

| Optimization Horizon (seconds) | Average Travel Time (sec) | Average Speed (km/h) | StdDev Speed (km/h) |
|---|---|---|---|
| 10 | 232 | 75 | 16 |
| 20 | 225 | 85 | 7 |
| 30 | 221 | 85 | 7 |
| 40 | 222 | 86 | 6 |
| 50 | 220 | 81 | 9 |

- 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

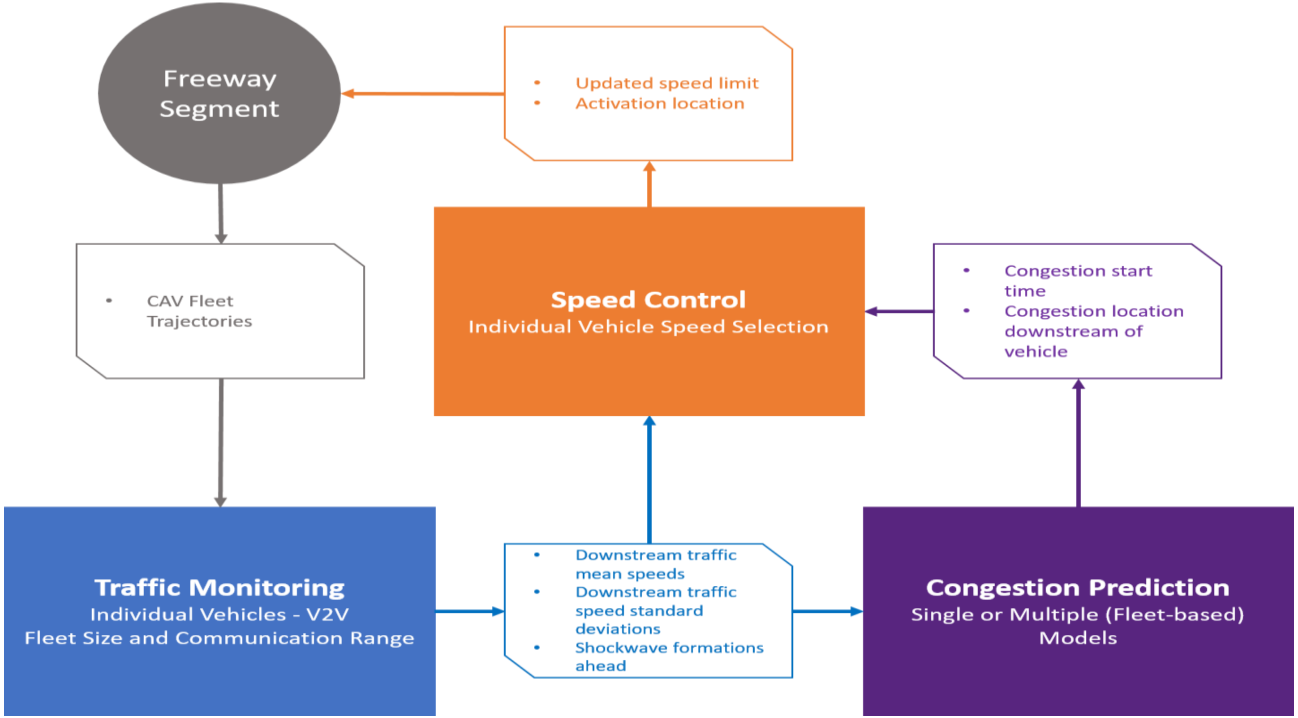
- Computationally intensive and time consuming due to running a large number of simulations
  - Parallelization
  - Optimize traffic simulator for speed
  - Reduce number of potential decision variables to test (fastest)

# Centralized SPDHRM Conclusion

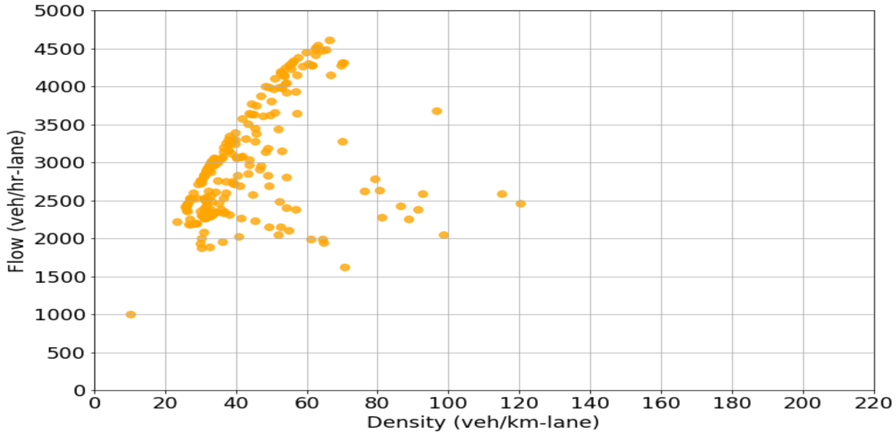
- Activating the SPDHRM system improves traffic stability, speed, and reduces travel time
- The system performance improves at higher market penetrations of CAVs
- The optimization-based control strategy further improves the performance of the system

# Control Strategy Application: Predictive Speed Harmonization in a Connected Environment with **Decentralized** Control

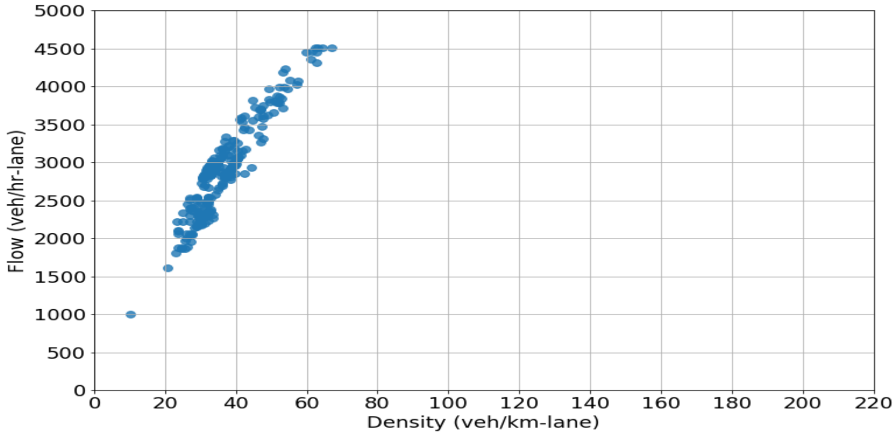
# Predictive Speed Harmonization in a Connected Environment with Decentralized Control



Base



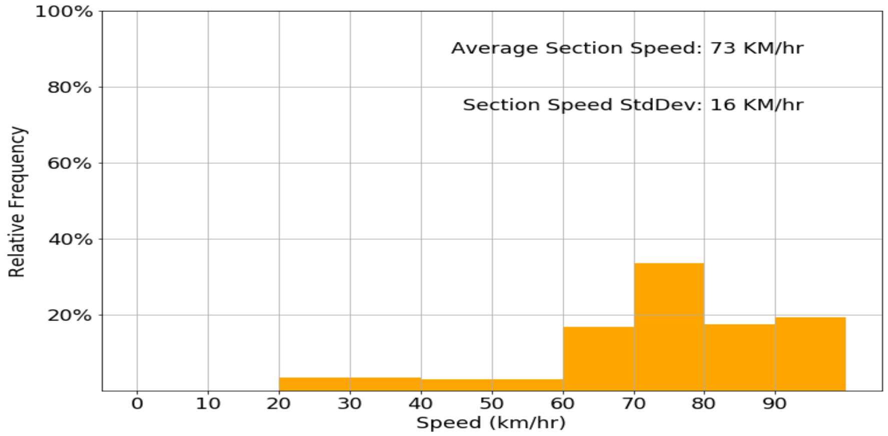

Active SPDHRM



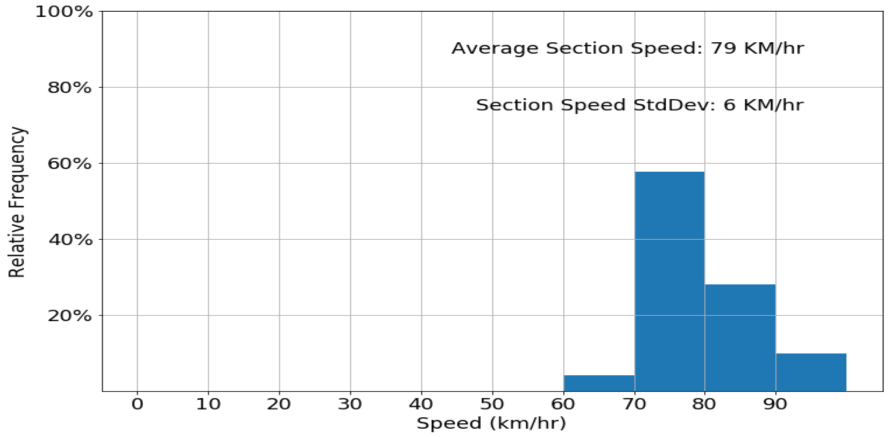

Decentralized SPDHRM improves traffic stability and performance

Northwestern

Base

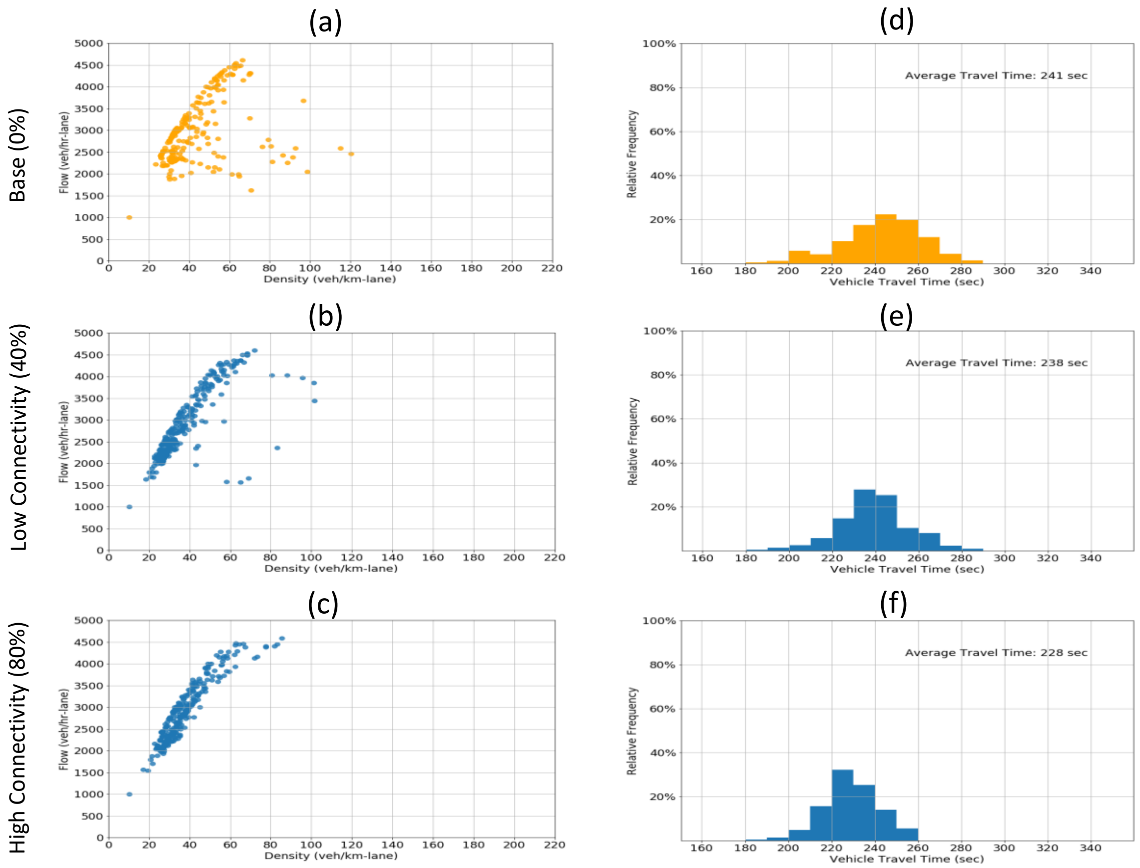



Active SPDHRM




Decentralized SPDHRM increases overall speed and reduces its variation

# Connectivity improves the performance of decentralized SPDHRM

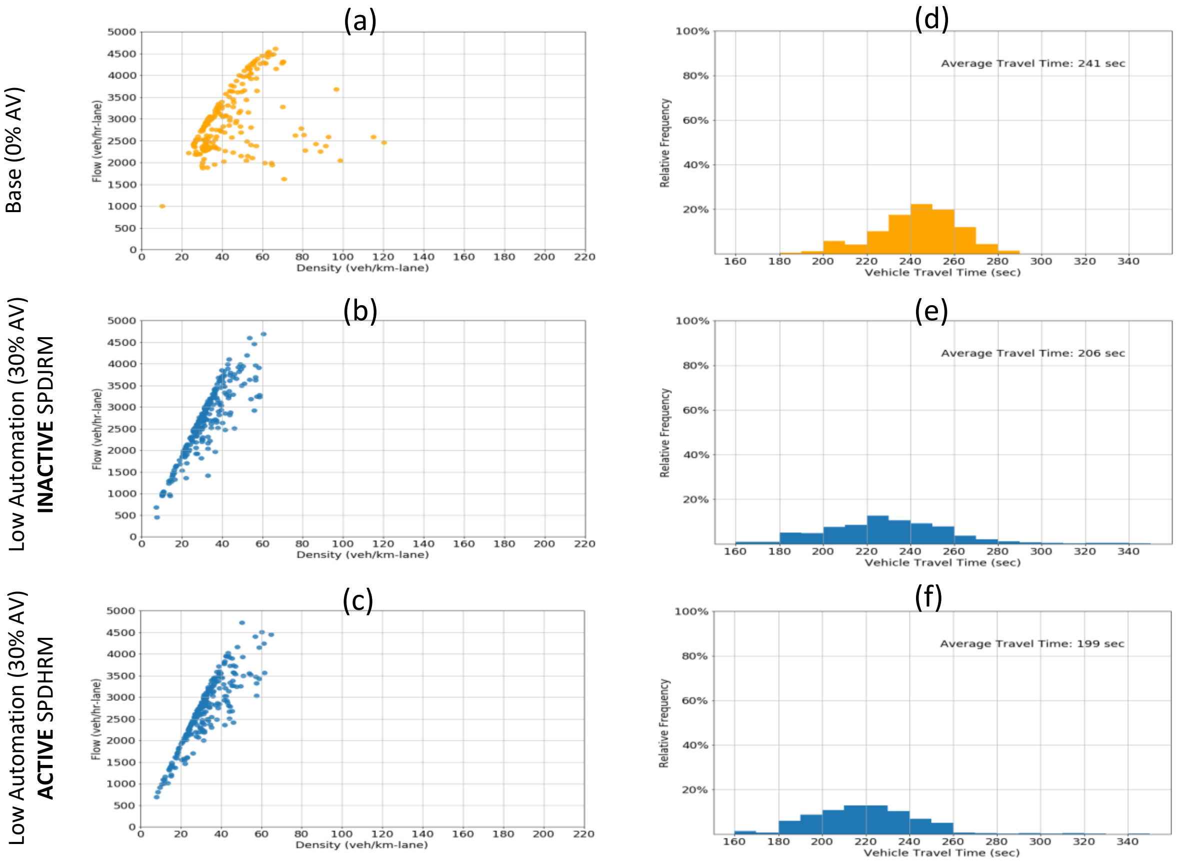



Higher CV market penetration:

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

Note: This case assumes one single fleet (same prediction model, all CV data shared)

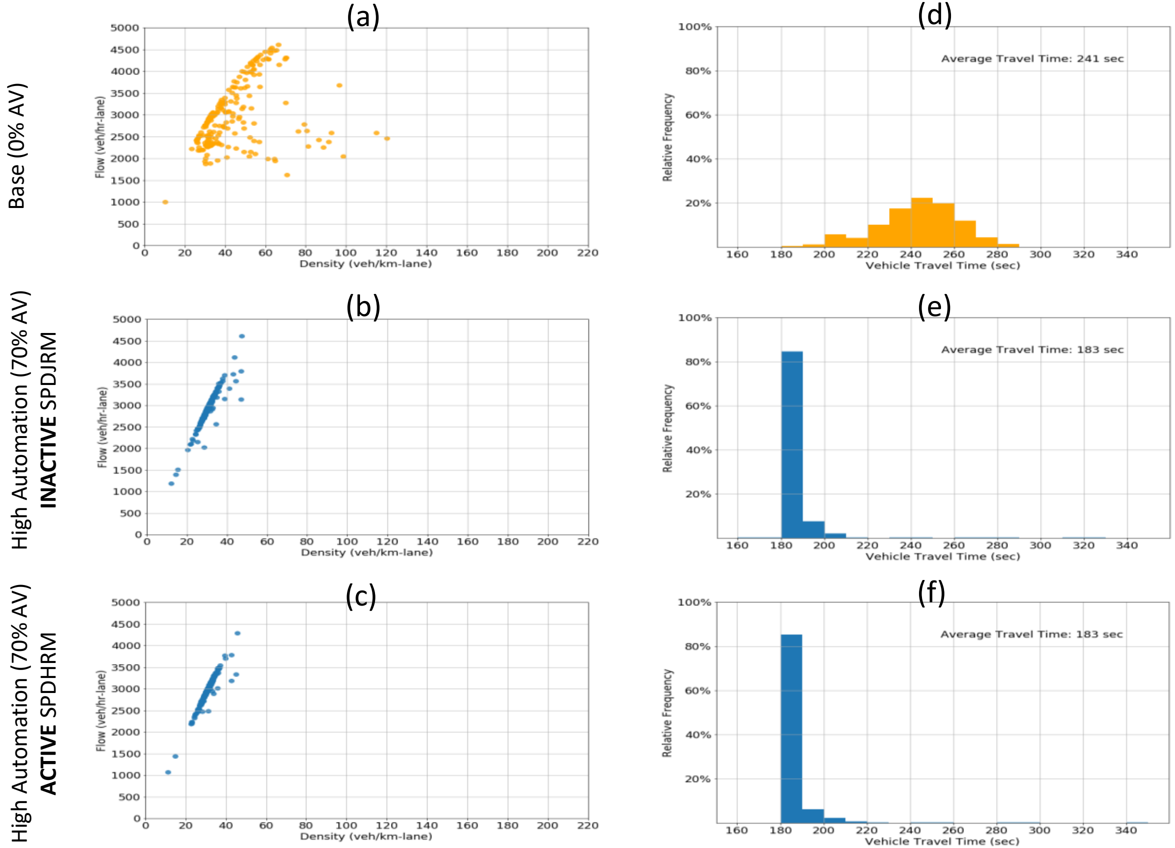
# Decentralized SPDHRM improves performance under low automation




- 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.***

Everything.

# 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.

# Thank You

## We Love Feedback

**Questions/Comments**

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