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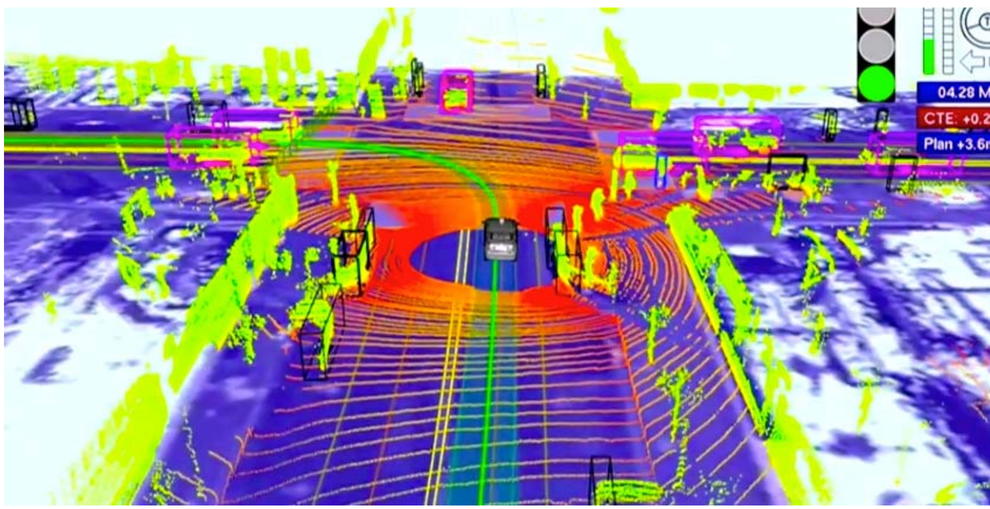
Are We Ready for Autonomous and Connected Vehicles?
Flow and Operations Considerations

Hani Mahmassani
Northwestern University

103rd Annual Transportation and Highway Engineering Conference
UIUC, February 28, 2017



OVERVIEW: KEY TAKEAWAYS

- Connected vehicle systems and autonomous vehicles likely to be major game changers in traffic and mobility. No longer a question of if, but of when, in what form, at what rate, and through what kind of evolution path.

- Agencies at a loss for how to approach the problem, and how to go about planning and designing for new operational regimes in which vehicles are connected to each other and to the infrastructure, and augmented with autonomous capabilities.

- Present modeling and simulation tools not adequate to capture either demand or supply-side implications for the transportation system.

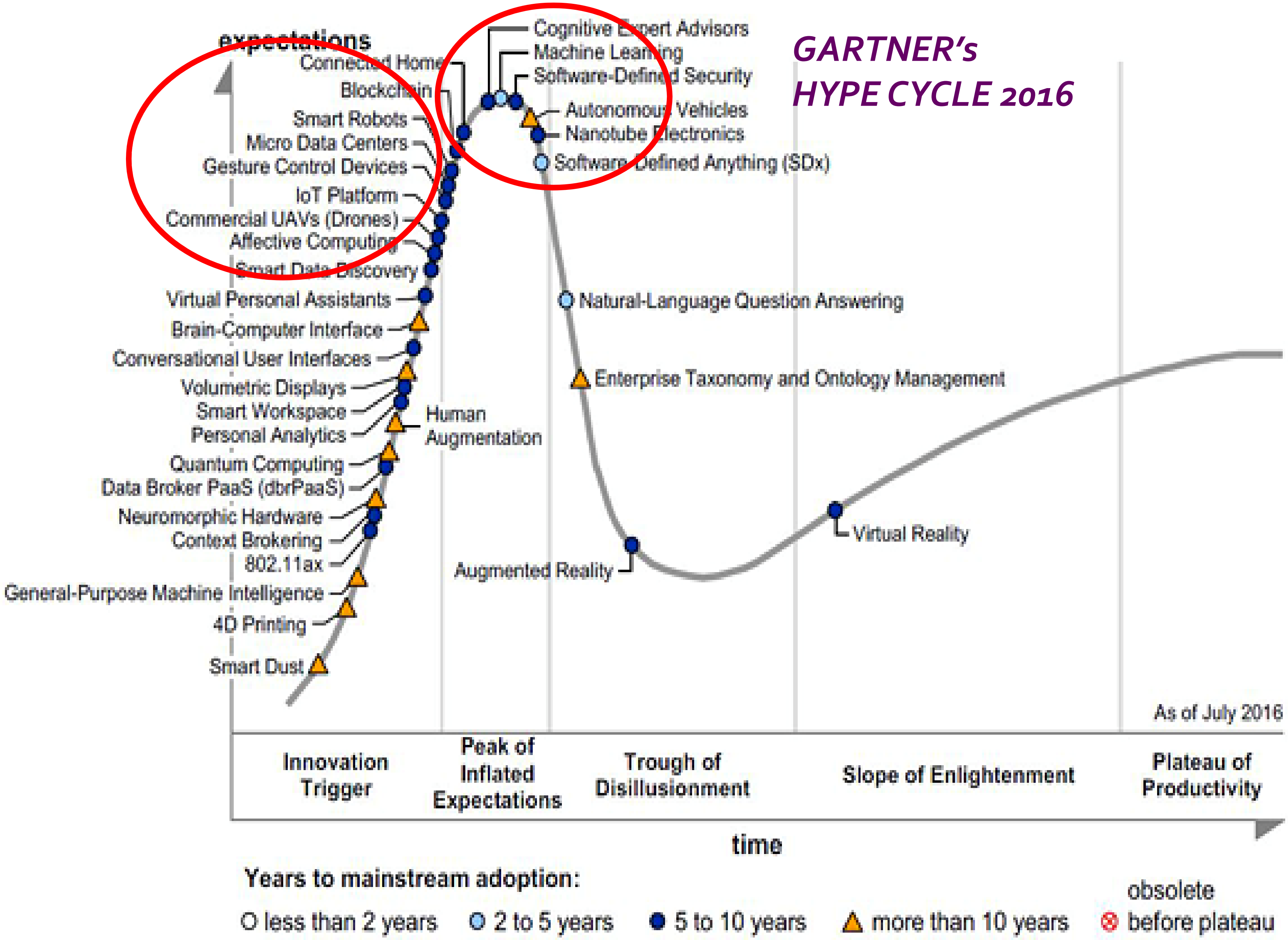
- Broader planning considerations:
    - Demand side: impact of CAV on individual and household activity patterns
    - Supply side: Emergence and growing role for shared mobility fleets, though private ownership not likely to go away.

- *At the root of these impacts are the flow and operational aspects* of connected and/or automated vehicles, especially as these become part of the traffic mix served by our transportation infrastructure.

OVERVIEW: KEY TAKEAWAYS II

- Connectivity improves performance of individual facilities as well as overall, enabling higher speeds at given density, greater travel time reliability, and more effective traffic control (e.g. speed harmonization).
- Telecommunications aspects are critical elements of CAV methodologies, and must be modeled jointly with traffic flow.
- Calibration and validation are best addressed through 3D vehicle trajectories.
- Major concern for urban streets and arterials, where gains not likely to match improvements on freeways.
- Future deployment likely to see slow penetration of connectivity in certain parts of the network, and initial automated vehicle fleets, in selected environments: Need to model CAV capabilities in mixed traffic flows, with both human drivers and robotic ones.

GARTNER's HYPE CYCLE 2016



Source: Gartner (July 2016)

Autonomous and Connected Vehicles

Big Questions:

- How to plan for a world in which vehicles are autonomous and/or connected?
- What are implications for operations on facilities and in networks?
- How do you predict adoption of these new technologies, given so many uncertainties (technology, policy, economics, new service models, etc…)

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50th Anniversary Invited Article

Autonomous Vehicles and Connected Vehicle Systems: Flow and Operations Considerations

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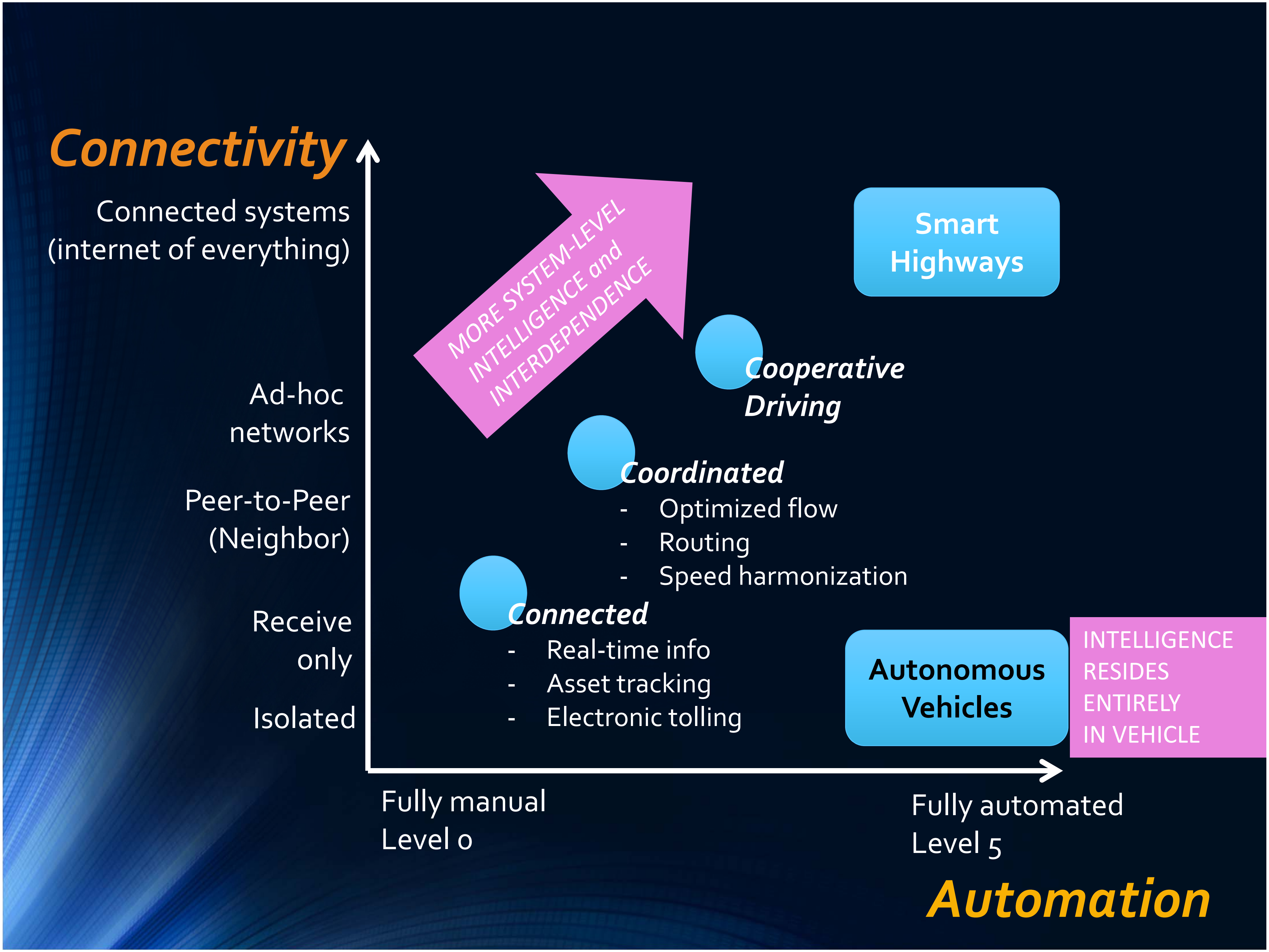
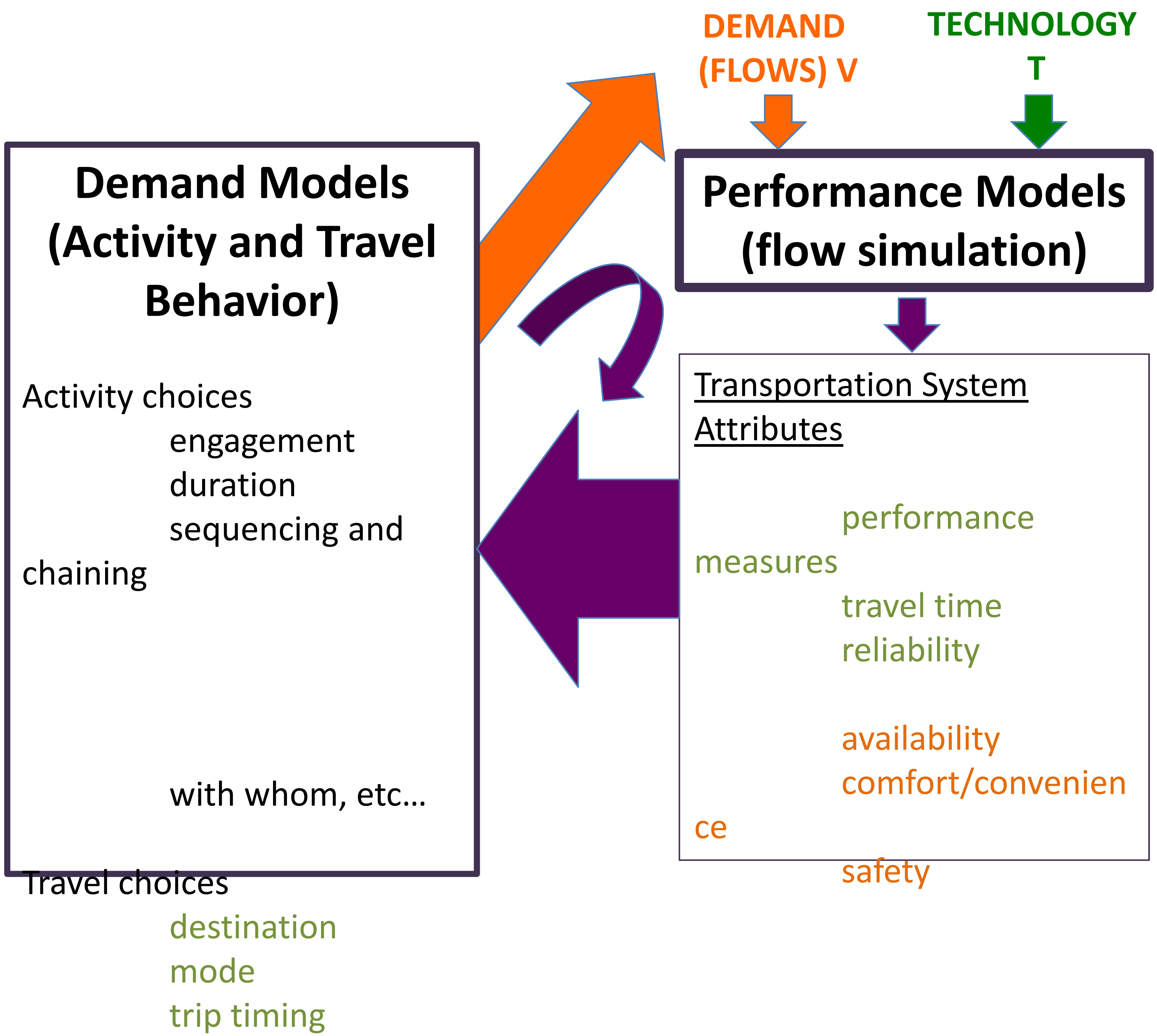

Connectivity
Connected systems (internet of everything)
Ad-hoc networks
Peer-to-Peer (Neighbor)
Receive only
Isolated
MORE SYSTEM-LEVEL INTELLIGENCE and INTERDEPENDENCE
Smart Highways
Cooperative Driving
Coordinated
- Optimized flow
- Routing
- Speed harmonization
Connected
- Real-time info
- Asset tracking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

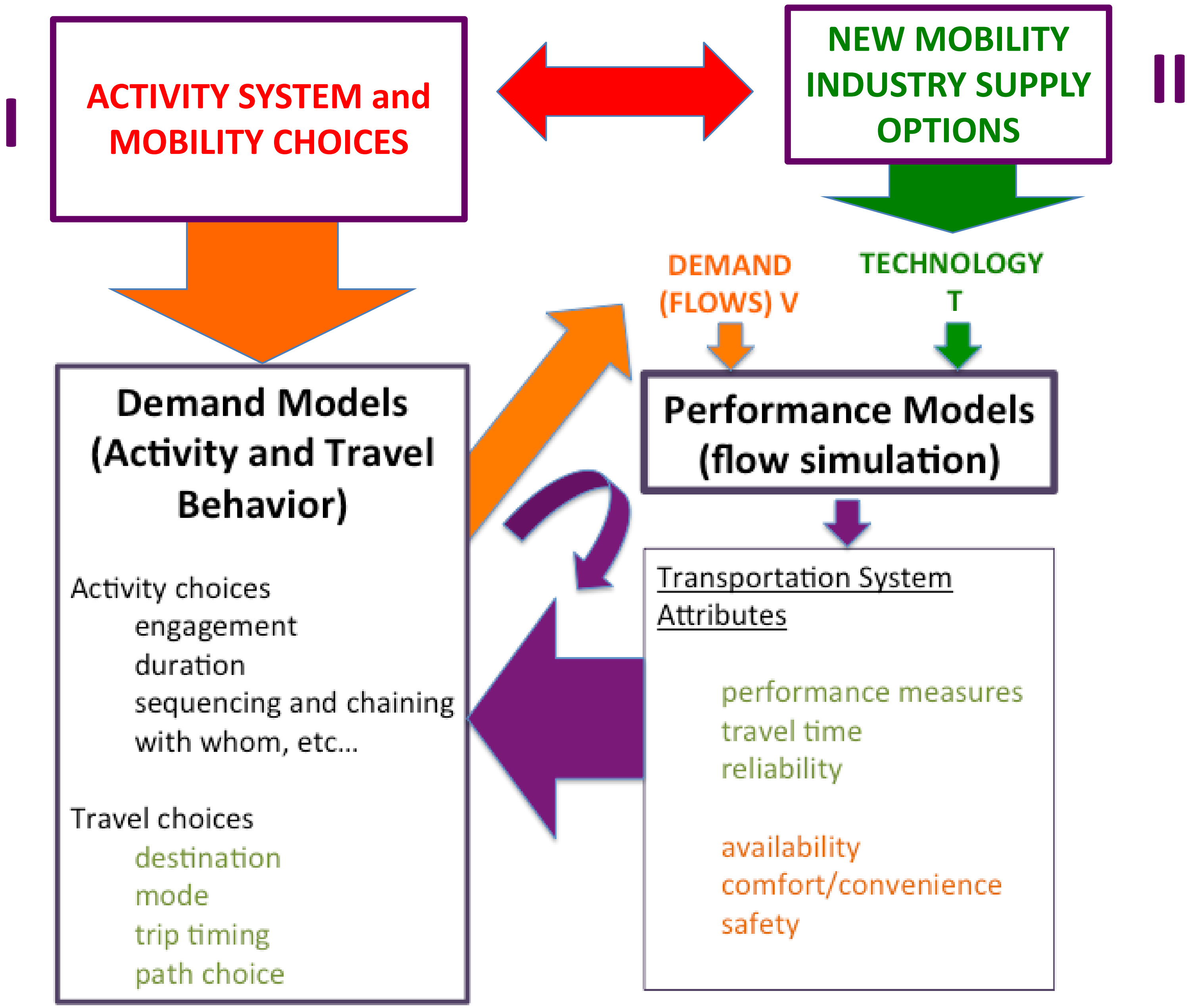
Strategic Network-Level Implications

- How adequate are existing modeling platforms to address CAV aspects?
- How will emergence of CAV impact supply of mobility services, and how will these affect existing modes (e.g. transit)?
- How will demand respond to technological features of CAV's as well as to new mobility supply options?
- How confident are we in our ability to predict these future developments and their impacts?


Demand Models (Activity and Travel Behavior)
Activity choices
engagement
duration
sequencing and chaining
with whom, etc…
Travel choices
destination
mode
trip timing
DEMAND (FLOWS) V
TECHNOLOGY T
Performance Models (flow simulation)
Transportation System Attributes
performance measures
travel time
reliability
availability
comfort/convenience
safety

An Incremental View

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


I
ACTIVITY SYSTEM and MOBILITY CHOICES
NEW MOBILITY INDUSTRY SUPPLY OPTIONS
II
DEMAND (FLOWS) V
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performance measures
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safety

Are Tools Adequate?

- Existing state-of-the-art tools could address *incremental scenario*
- Flow modeling aspects require additional calibration as technology prototypes appear; interaction between driverless and other vehicles biggest challenge, but traffic modeling community is rising to the task.
- More *uncertainty on behavior side,* though incremental scenarios could be explored under selected assumptions.
- Telecommunications aspects of V2V and V2I missing from existing traffic models (exception: Talebpour et al., 2016).

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.

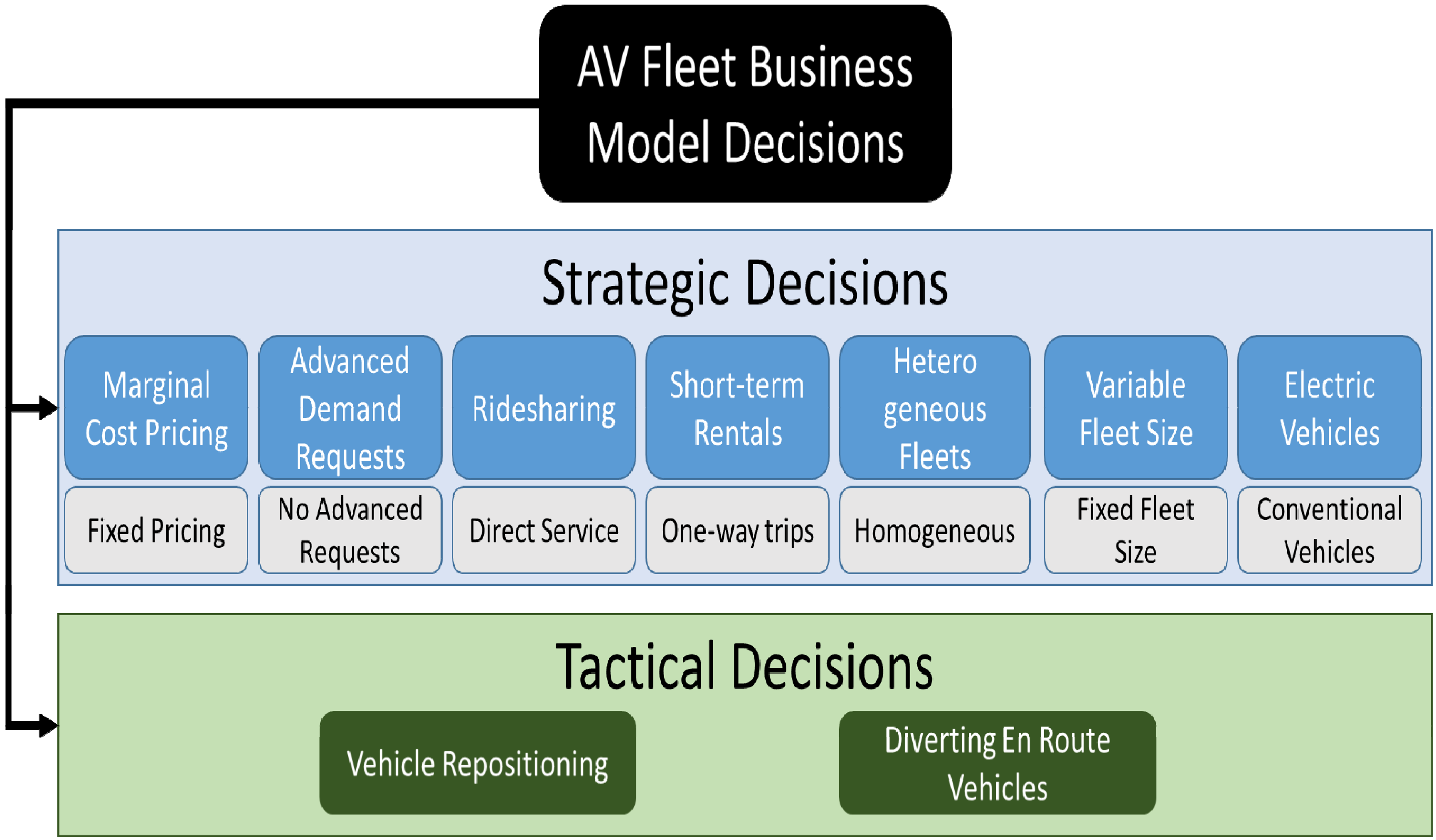
Side Note: Network Assignment

- **What is an appropriate behavioral notion for network assignment?**
  - **Does UE still make sense?**
  - **Depends on mobility ownership/sharing model: How are AV fleet routed?**
  - **Would seek to minimize traveler's time in transit when transporting someone.**
  - **What about empty vehicles (repositioned for next ride)? Potential for SO routing**
- Strong interplay between new mobility supply models and modeling network impacts.
- Sensitivity to relative market penetration not only of fraction of AV's but of ownership/sharing models.

AV Fleet Business Models

- Over 30 companies are developing autonomous vehicles
  - Ford, BMW, Tesla, Fiat-Chrysler
  - Apple and Google
  - Uber and Lyft
- Many of these companies initially plan to provide transportation services with their vehicles rather than sell individual vehicles to consumers
- We expect there to be significant variation across companies in terms of their business models

Potential AV Fleet Business Model Variants



Traffic Flow/Operational Implications: Facilities

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

- 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

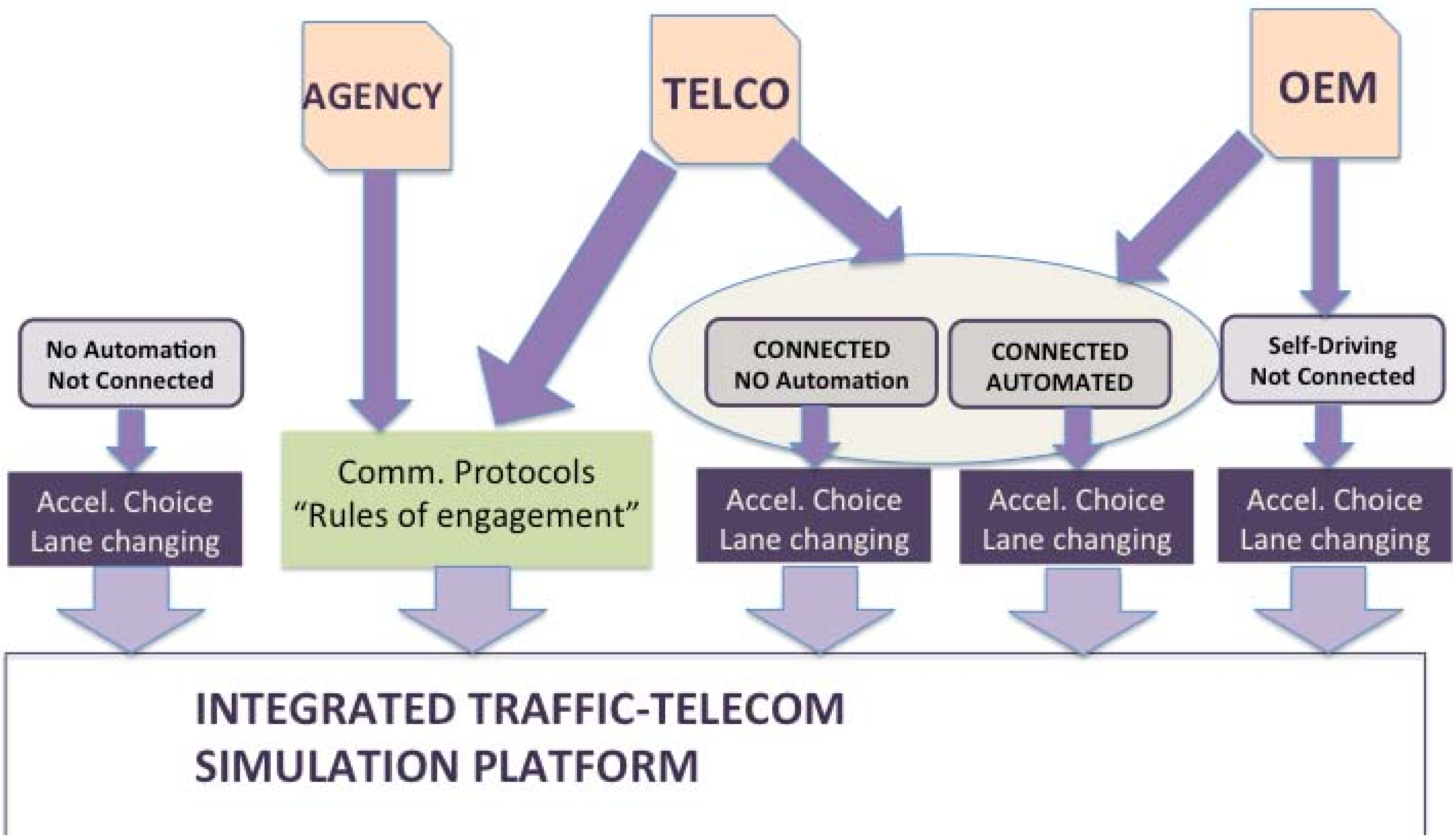
  SAFETY
  THROUGHPUT ("Capacity")
  STABILITY (➔ Safety)
  FLOW BREAKDOWN (Reliability)
  SUSTAINABILITY (Greenhouse gases, energy)

- What kinds of collective effects could we expect? Are **fundamental diagrams** still useful for this purpose?

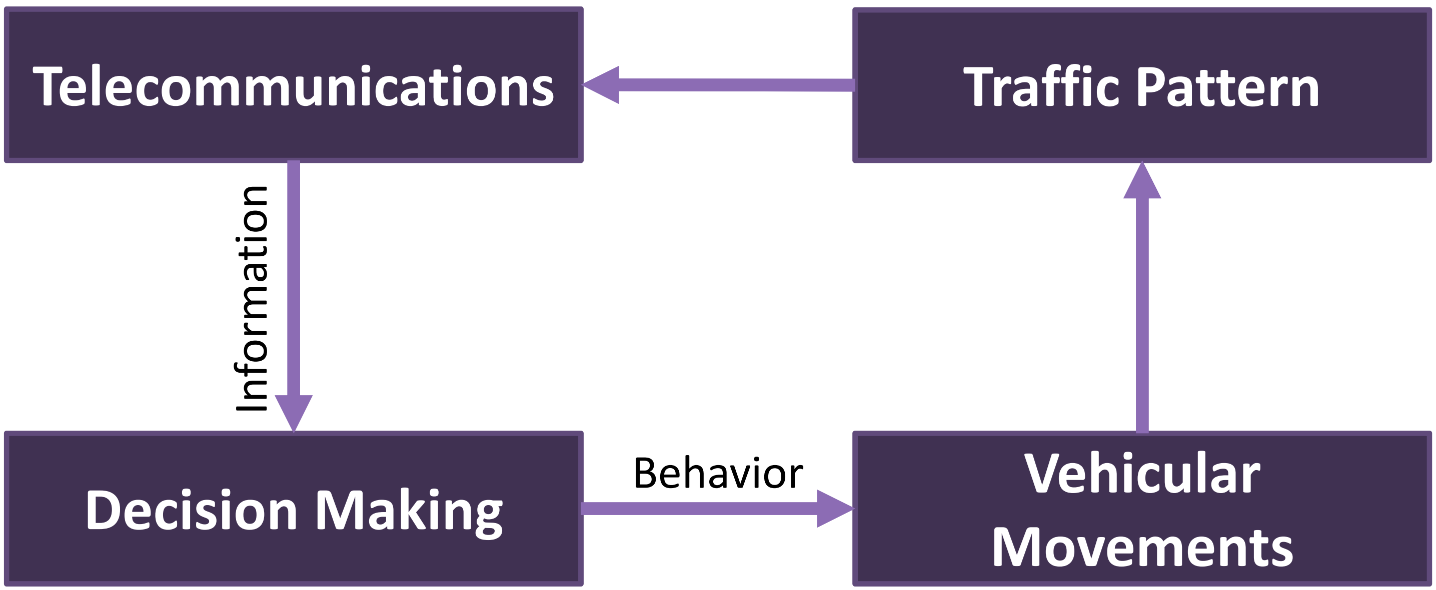
- What is the sensitivity to relative market penetration on impact on mixed traffic performance?

- What kinds of controls should agencies be contemplating?

OUR PROPOSAL



Telecommunications-Traffic Interactions



Telecommunications affect Traffic Pattern

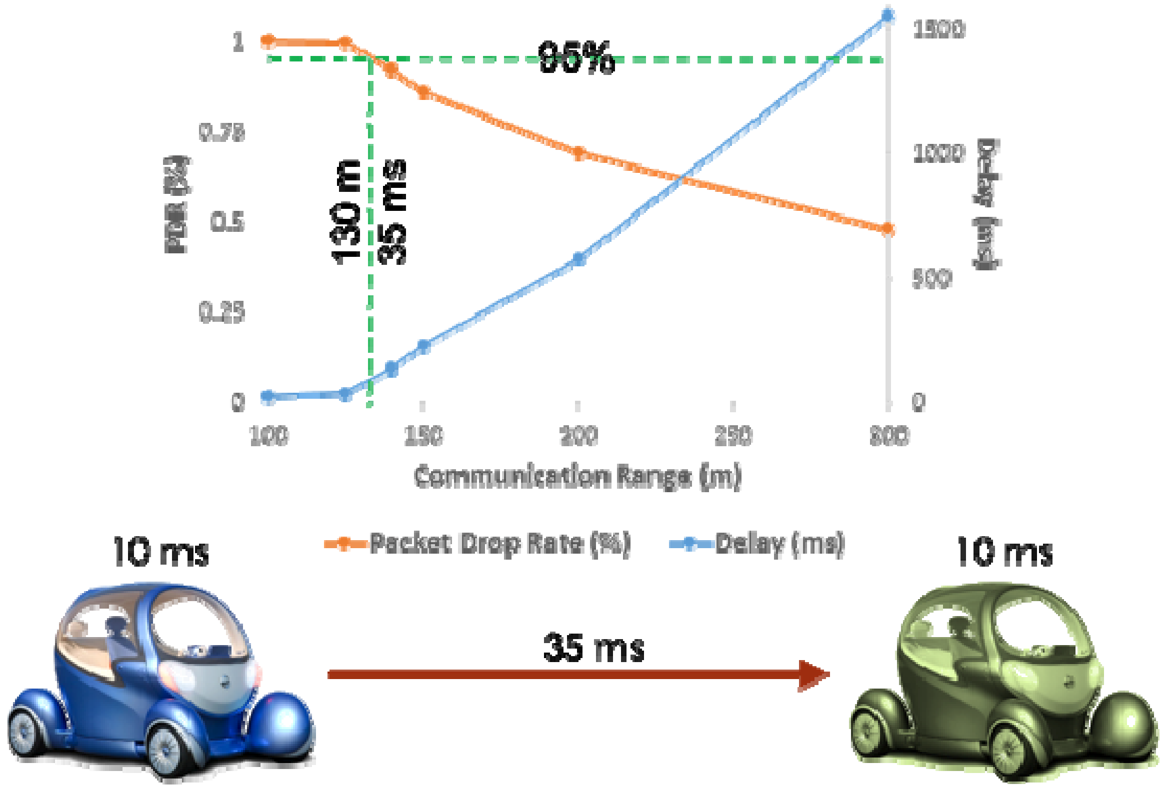
Traffic Pattern affects connectivity (Telecommunications)

V2V Communications Model

NS3 Implementation – Clustering Frequency

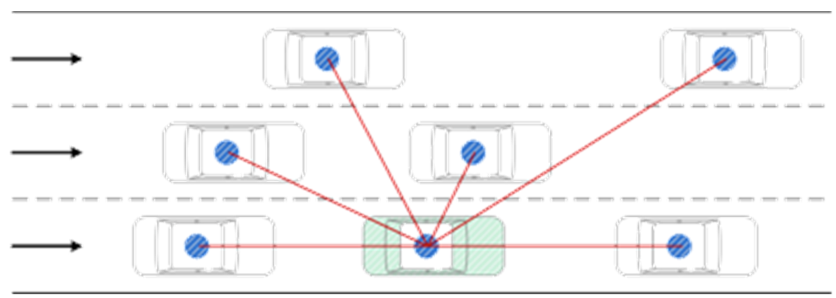
Packet size = 50 byte: Location, speed, acceleration

Packet Forwarding Overhead = 10 ms (Koizumi et al., 2012)



Clustering Algorithm

What is a cluster?



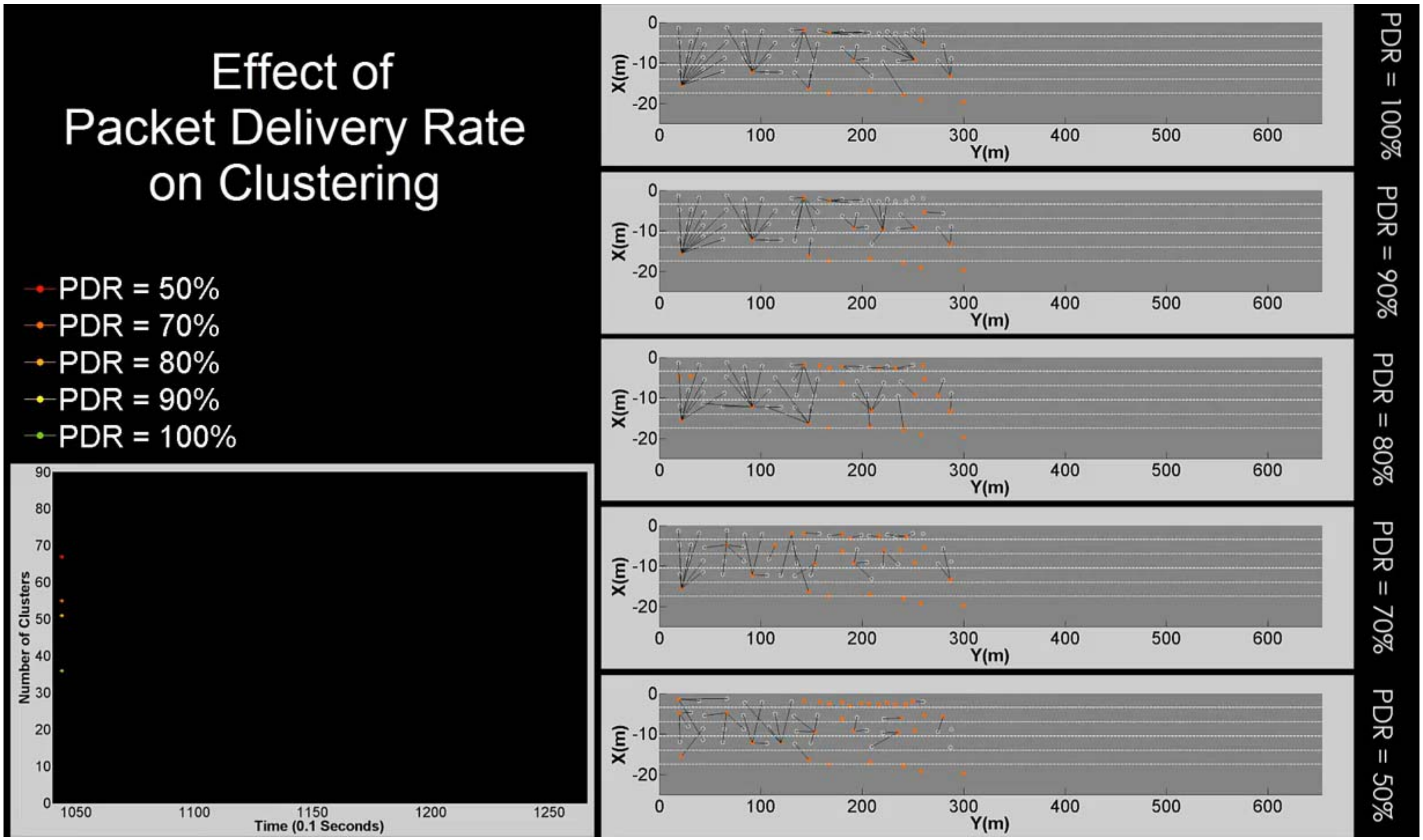
- Each cluster consists of,
  - **One** cluster head
  - **Several** cluster members
- Assumption: cluster members can only communicate with the cluster head (1-hop communication between cluster members).
- A cluster head can communicate with cluster members and other cluster heads from other clusters.

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

NS3 Implementation – Packet Delivery



Illustrating Effect of CAV on Flow Performance

Talebpour and Mahmassani, TRC 2016

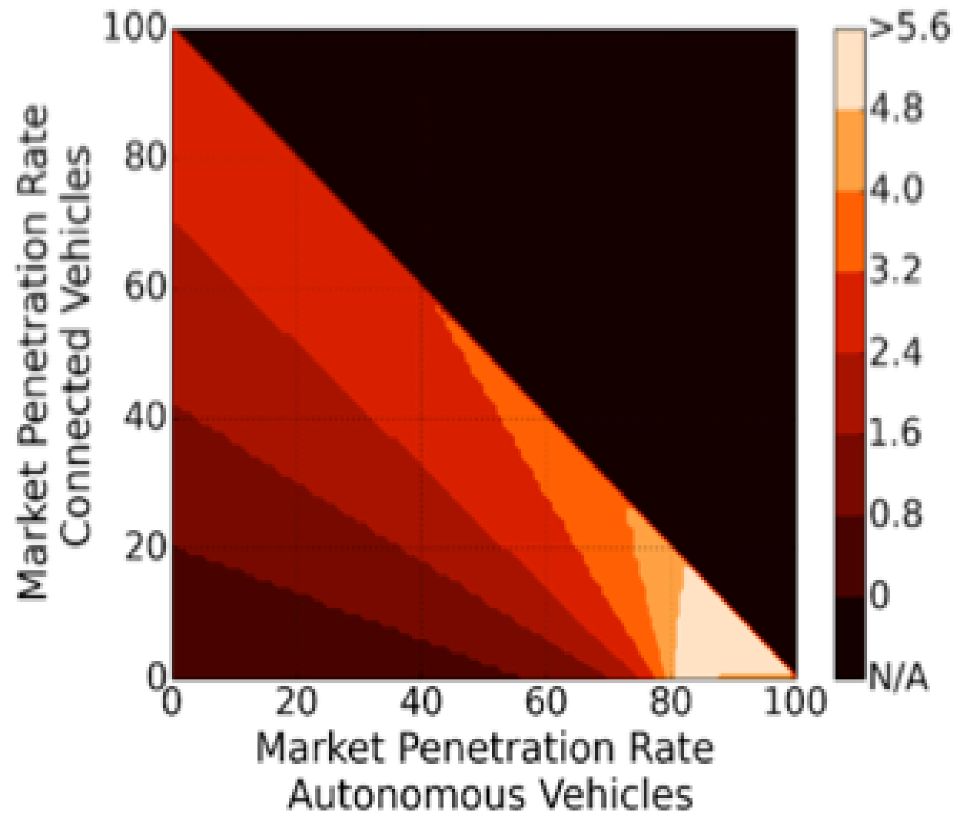
STABILITY ANALYSIS

Heterogeneous Traffic Flow

- Parameters of regular vehicles are adjusted to create a very unstable traffic flow.
- Low market penetration rates of automated vehicles do not result in significant stability improvements.
- At low market penetration rates of automated vehicles,

$$stability \sim \hat{a}.\underbrace{MPR_C}_{} + \hat{b}$$

Market penetration rate of connected vehicles



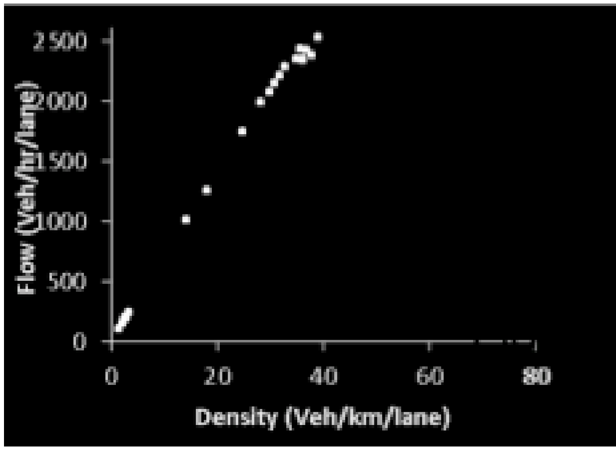
Automated, Connected, and Regular Vehicles

Illustrating Effect of CAV on Flow Performance II

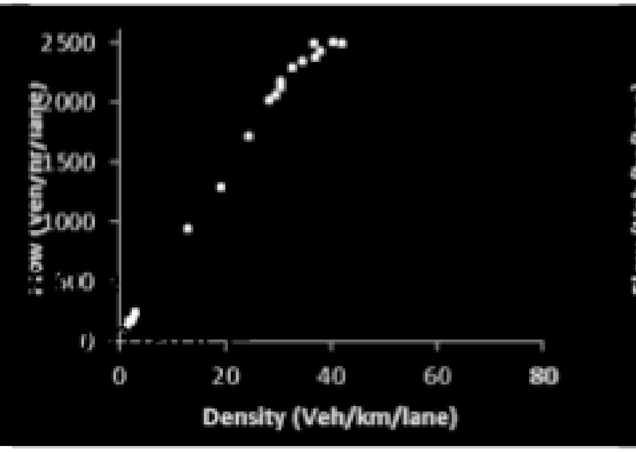
Talebpour & Mahmassani, 2016

THROUGHPUT and SPEED-DENSITY RELATION

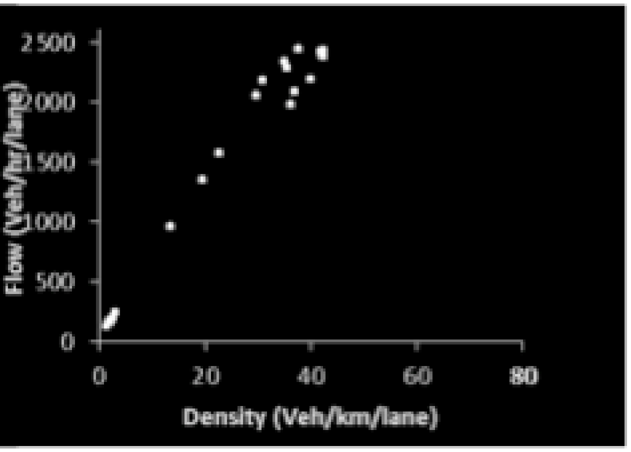
SENSITIVITY ANALYSIS – MIXED ENVIRONMENT



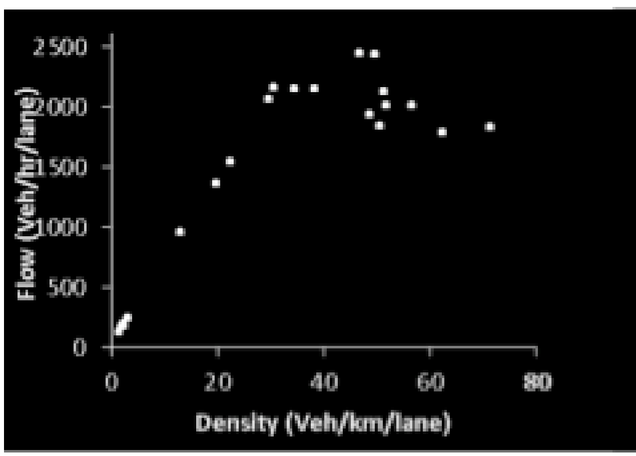
10% R– 0% C – 90% A



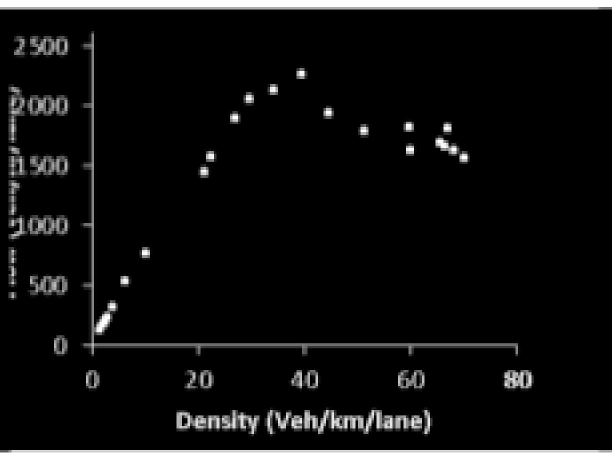
10% R– 20% C – 70% A



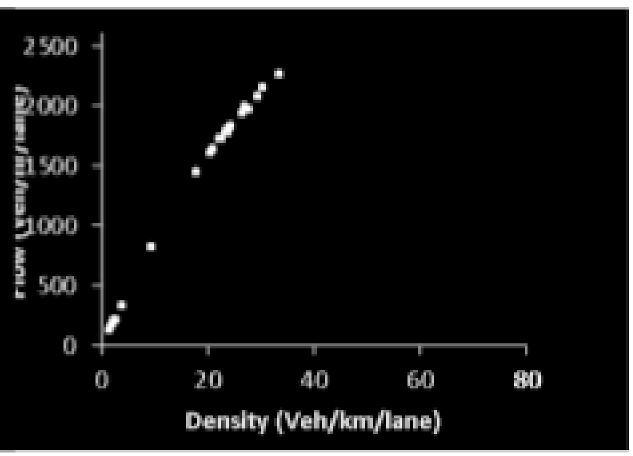
10% R– 40% C – 50% A



10% R– 50% C – 40% A



10% R– 70% C – 20% A

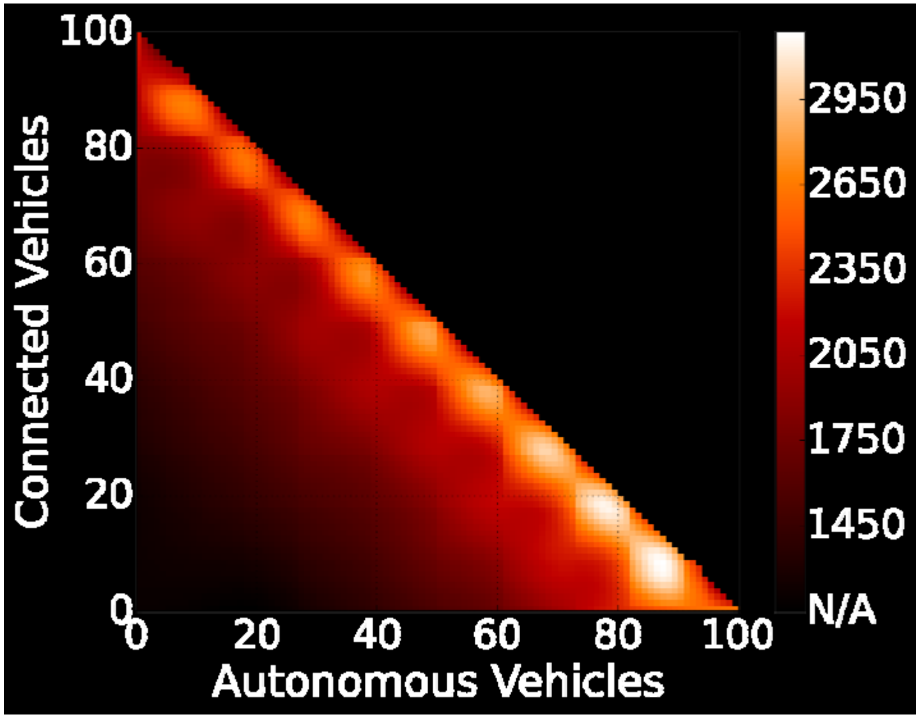


10% R– 90% C – 0% A

Illustrating Effect of CAV on Flow Performance III

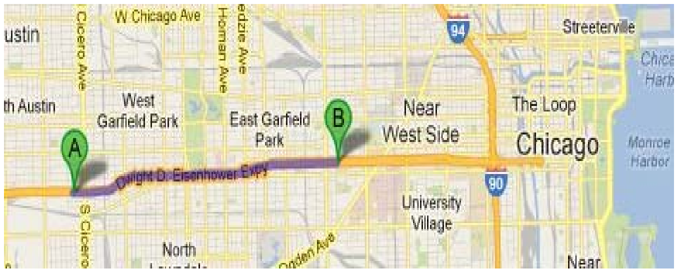
THROUGHPUT Simulation results

- 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.

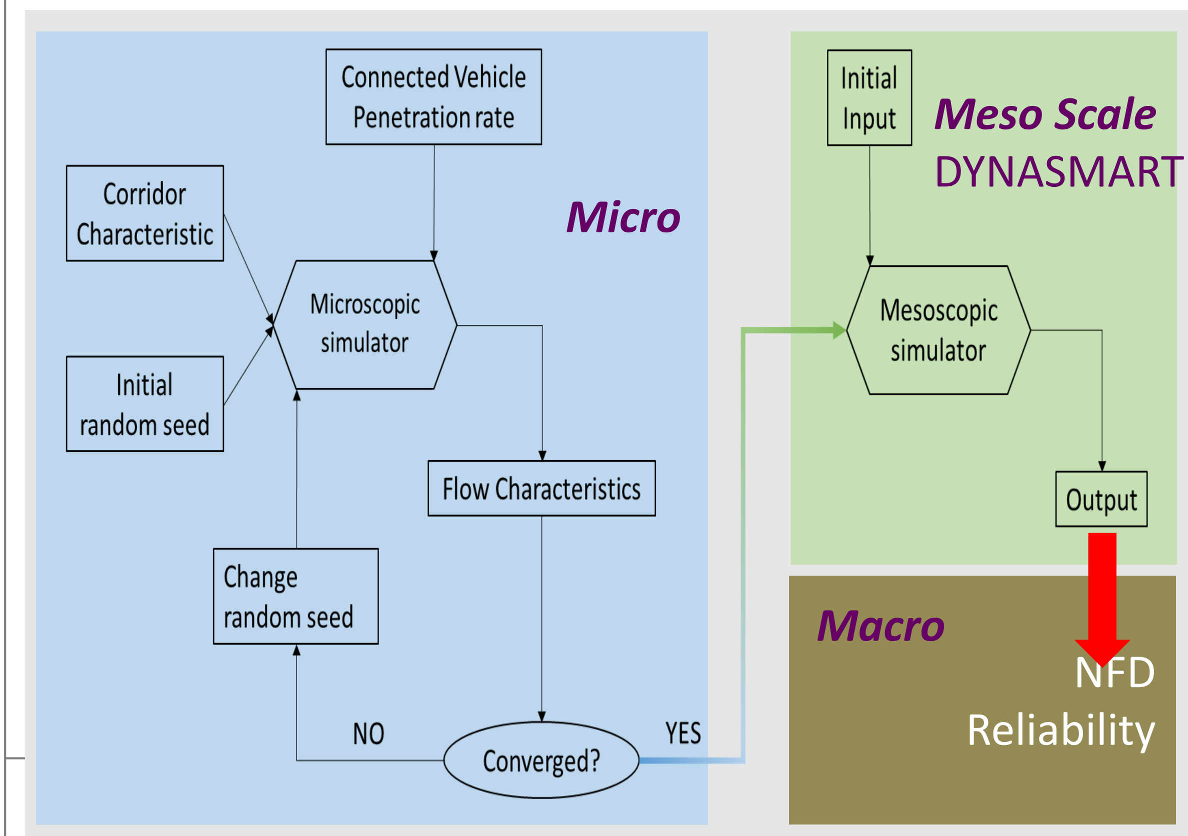


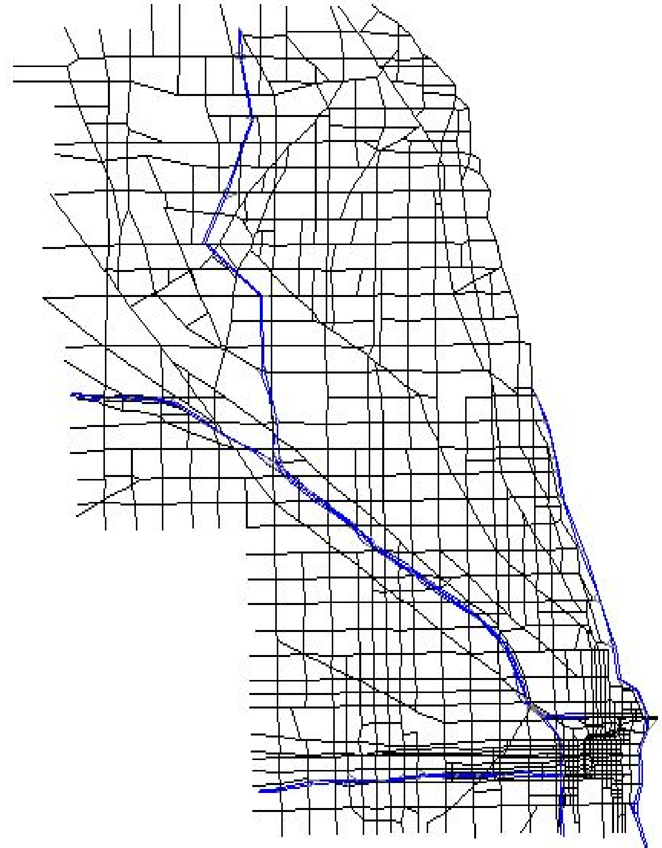
Autonomous, Connected, and Regular Vehicles

From Micro to Meso to Macro Scales



Effect of Connected Vehicle Penetration Rate on Network Performance



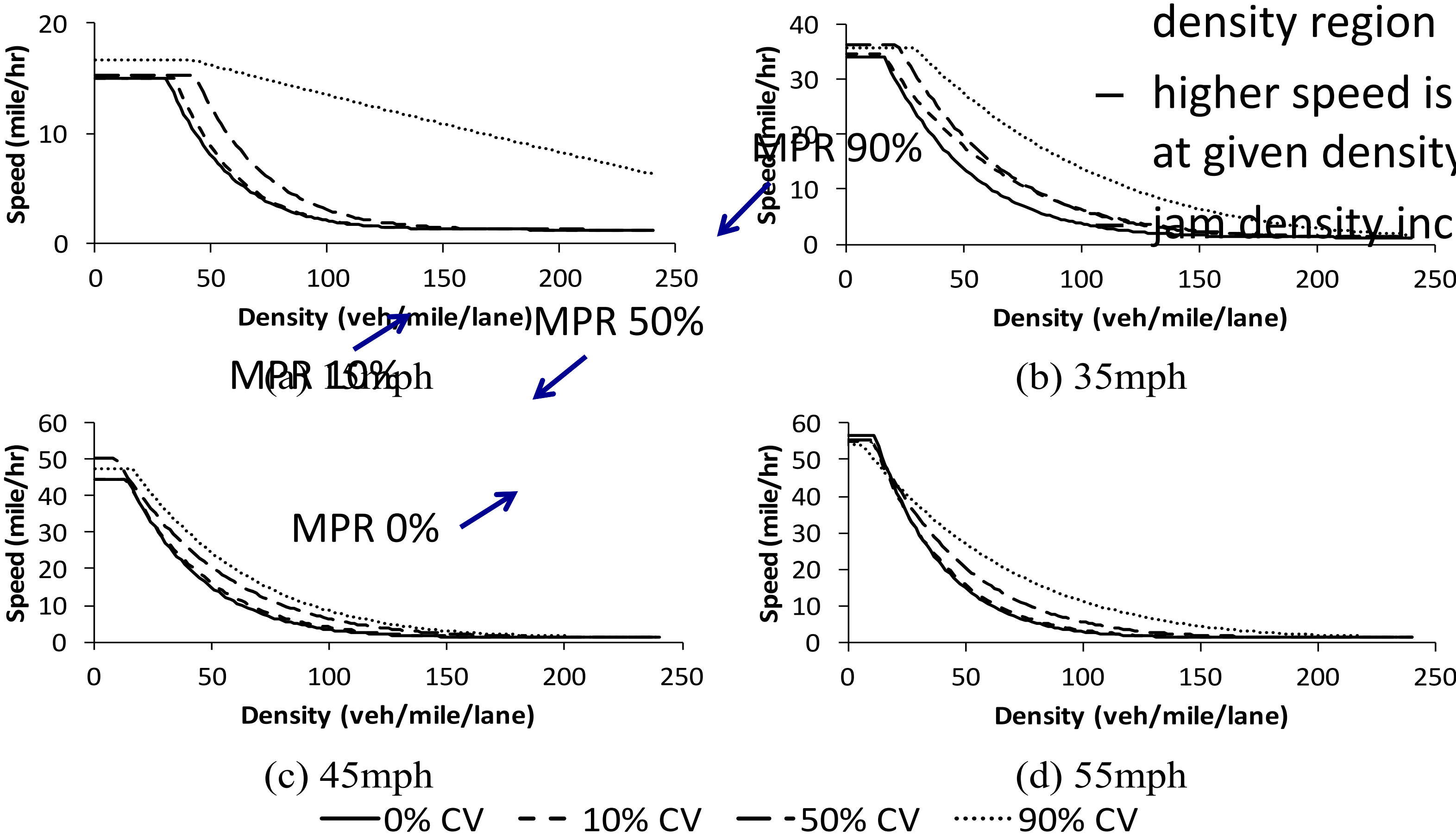


Network	Chicago
Number of nodes	1,578
Number of links	4,805
Number of vehicles	805.275
Demand duration (h)	24

Microsimulation results

Increase in MPR of CVs

- uncongested regime extends to the high density region
- higher speed is achieved at given density
- jam density increases



(a) 15mph (b) 35mph (c) 45mph (d) 55mph

Chicago Network

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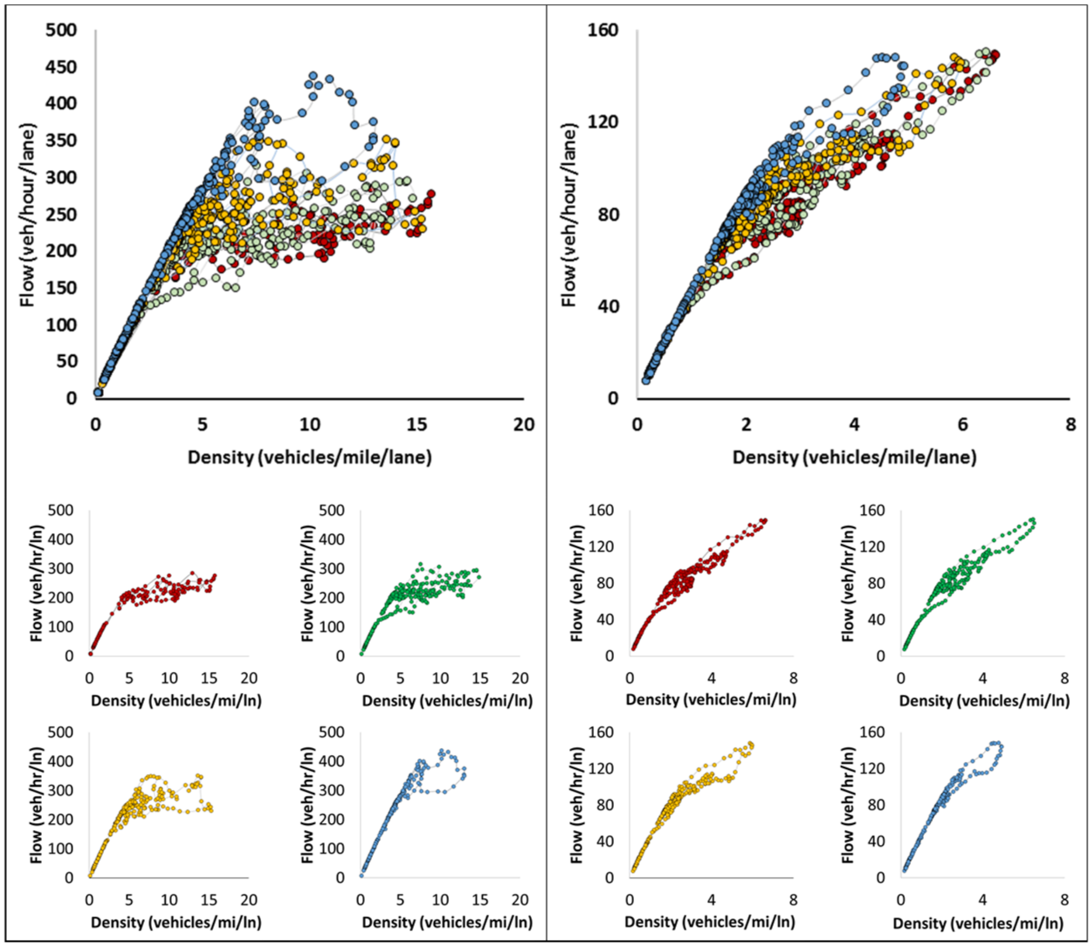
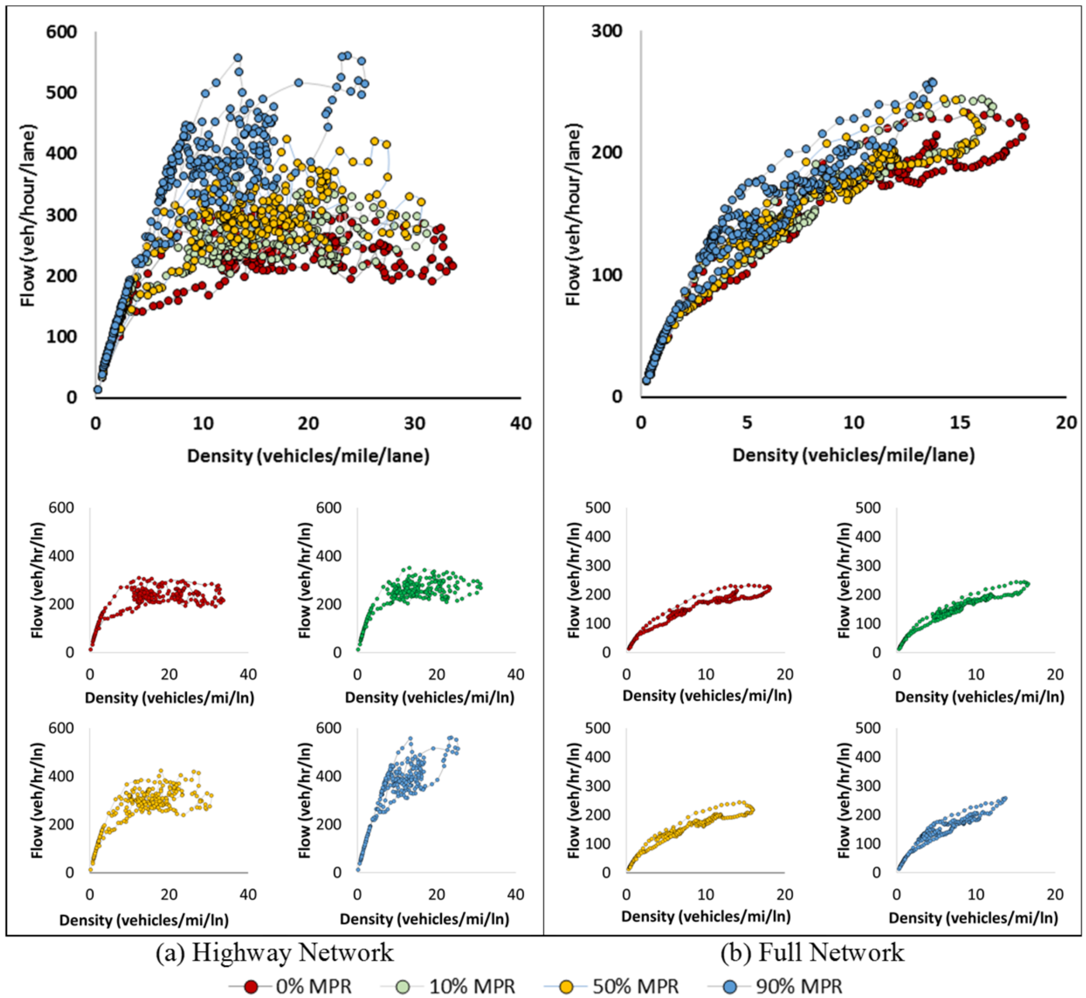
Low Demand



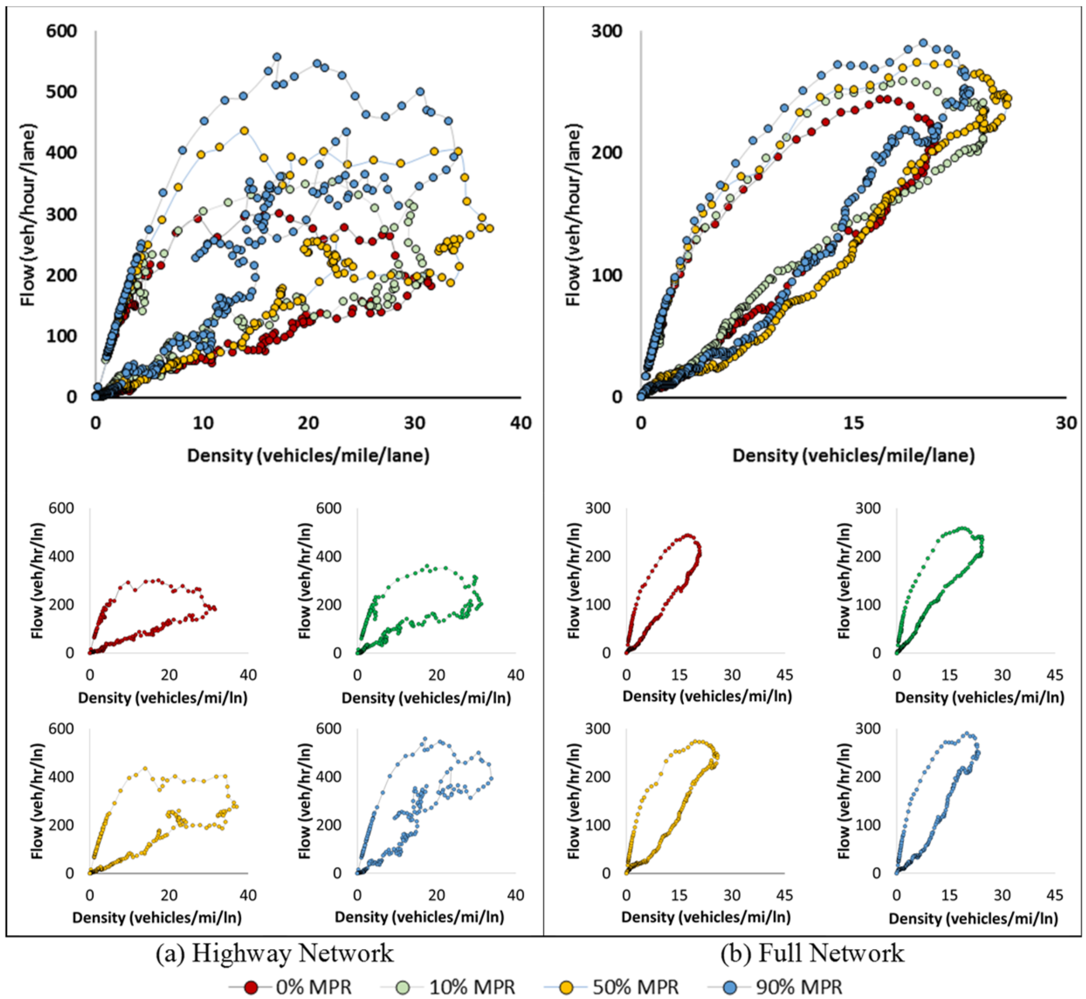
(a) Highway Network (b) Full Network

Medium Demand



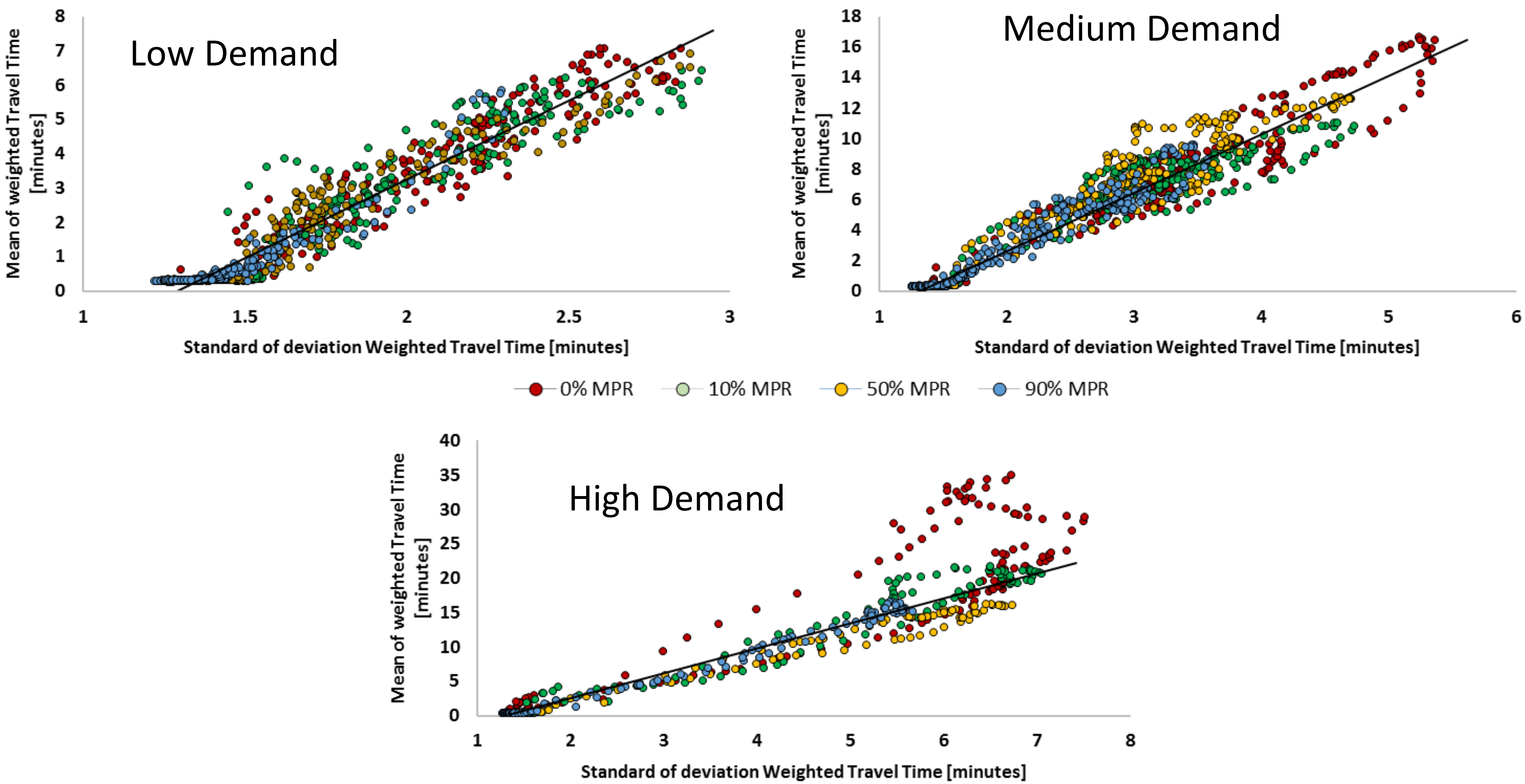
(a) Highway Network (b) Full Network

High Demand



(a) Highway Network (b) Full Network

Travel Time Reliability



Connectivity and Network Performance

- A highly connected environment has potential to help a congested network recover from flow breakdown and avoid gridlock
- Connected vehicles reduce the mean travel time while making the system more reliable
- Connectivity can improve the system's performance by increasing throughput and enhancing travel time reliability at all demand levels.

Traffic Flow/System Implications: Arterials and Urban Road Junctions

- **Will the intersection control systems be as smart as the vehicles and the communication systems would allow them to be?**
- What is the sensitivity to relative market penetration on impact on mixed traffic performance?
- **Three main opportunities:**

1. *Using data from connected vehicles to improve adaptive signal control operation.*
2. *Improving service rates through opportunistic coordinated platooning.*
3. *Eliminating signals altogether through individual trajectory coordination in a 100% connected environment, preferably with autonomous vehicles.*

- What about heterogeneous traffic– bicycles, peds, transit vehicles, delivery vehicles in addition to cars with varying degrees of autonomy and connectivity?

What About Calibration and Validation?

- **Where will the data come from:**
  - **Field tests/demonstration projects: CV's rich source of data**
  - **Leveraged through microsimulation to consider wider range of conditions**
- Trajectories are the best form of data, as they retain flexibility of application spatially and temporally; no loss of information
- **Augmented by fixed sensor data where deployed, e.g. for "ground truthing"**
- **Behavioral data may entail infringement on privacy– but not necessarily with appropriate anonymization.**
- **Important role for gaming environments and non-standard scenario explorations in studying user mobility choices and responses to CVA scenarios.**

A Vision for Transportation Infrastructure

•NUTC *Emerging Futures* Series

Series of 10 Chapters by different experts on factors affecting the future demand and supply of mobility, and the implications for the transportation infrastructure.

Topics include urban mobility, omni-channel retailing, freight and logistics, financing, green tech, etc.

The Future for Cities

3 Big Trends– shaping the future

1. **Technologies:** vehicles, IoT/smart cities & eco-friendly personal mobility tools.
2. **Societal preferences** that impact on mobility and travel.
3. **Service delivery models:** respective roles of public and private sectors.

Data. Changes. Everything.

•Implications for Infrastructure

1. Major improvement required in flow systems to accommodate requirements of mixed traffic and heterogeneous users.
2. Infrastructure deployments must integrate road/transport infrastructure with telecoms and smart (electric) grid.
3. New software platforms needed for connected vehicles and smart cities– currently major deployment bottleneck.
4. **All indications point toward more, not less travel, as connectivity creates more, not less, opportunities for personal engagement.**
5. New models of ownership/operation reflecting more flexible forms of service delivery through greater role for private sector and public-private agreements.

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WAKE UP,
ILLINOIS!

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Questions/Comments

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