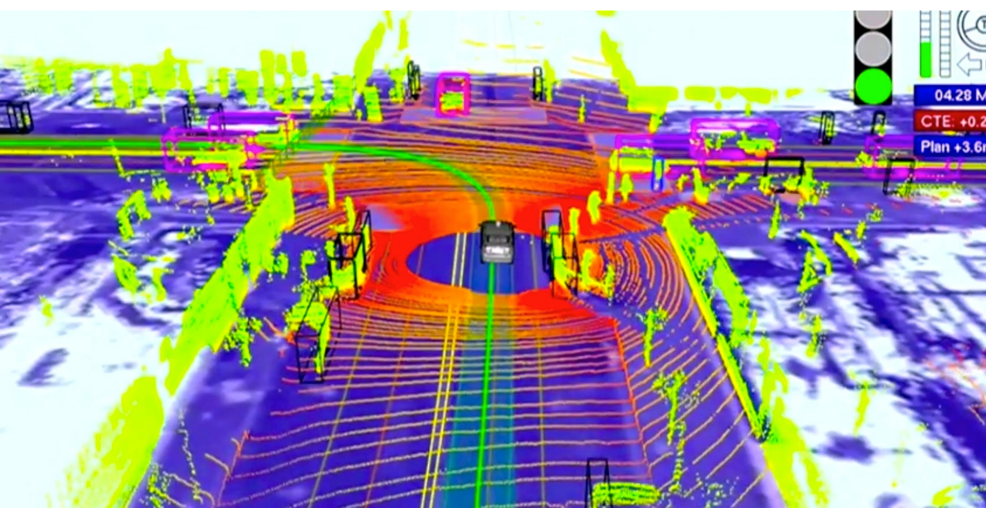
McCormick

Northwestern Engineering

Northwestern University Transportation Center

Autonomous Vehicles and Connected Systems: Market Adoption and Flow Implications

Hani Mahmassani
Northwestern University



Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- Throughput Analysis: Simulation Results
- Lane Changing in Connected Environment: Game Theory
- Takeaways, Limitations and Challenges

WHAT IS A DRIVERLESS CAR?

Federal National Highway Traffic Safety Administration (NHTSA): Four Levels of Automation

NHTSA
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

Kornhauser, 2014

Preliminary Statement of Policy Concerning Automated Vehicles

SmartDrivingCars & Trucks

Level 0 (No automation)
The human is in complete and sole control of safety-critical functions (brake, throttle, steering) at all times.

Level 1 (Function-specific automation)
The human has complete authority, but cedes limited control of certain functions to the vehicle in certain normal driving or crash imminent situations. Example: electronic stability control

Level 2 (Combined function automation)
Automation of at least two control functions designed to work in harmony (e.g., adaptive cruise control and lane centering) in certain driving situations.
Enables hands-off-wheel and foot-off-pedal operation.
Driver still responsible for monitoring and safe operation and expected to be available at all times to resume control of the vehicle. Example: adaptive cruise control in conjunction with lane centering

Level 3 (Limited self-driving)
Vehicle controls all safety functions under certain traffic and environmental conditions.
Human can cede monitoring authority to vehicle, which must alert driver if conditions require transition to driver control.
Driver expected to be available for occasional control. Example: Google car

Level 4 (Full self-driving automation)
Vehicle controls all safety functions and monitors conditions for the entire trip.
The human provides destination or navigation input but is not expected to be available for control during the trip. ***Vehicle may operate while unoccupied***. Responsibility for safe operation rests solely on the automated system

Implications of Each Level: User, Market and Society

Kornhauser, 2014

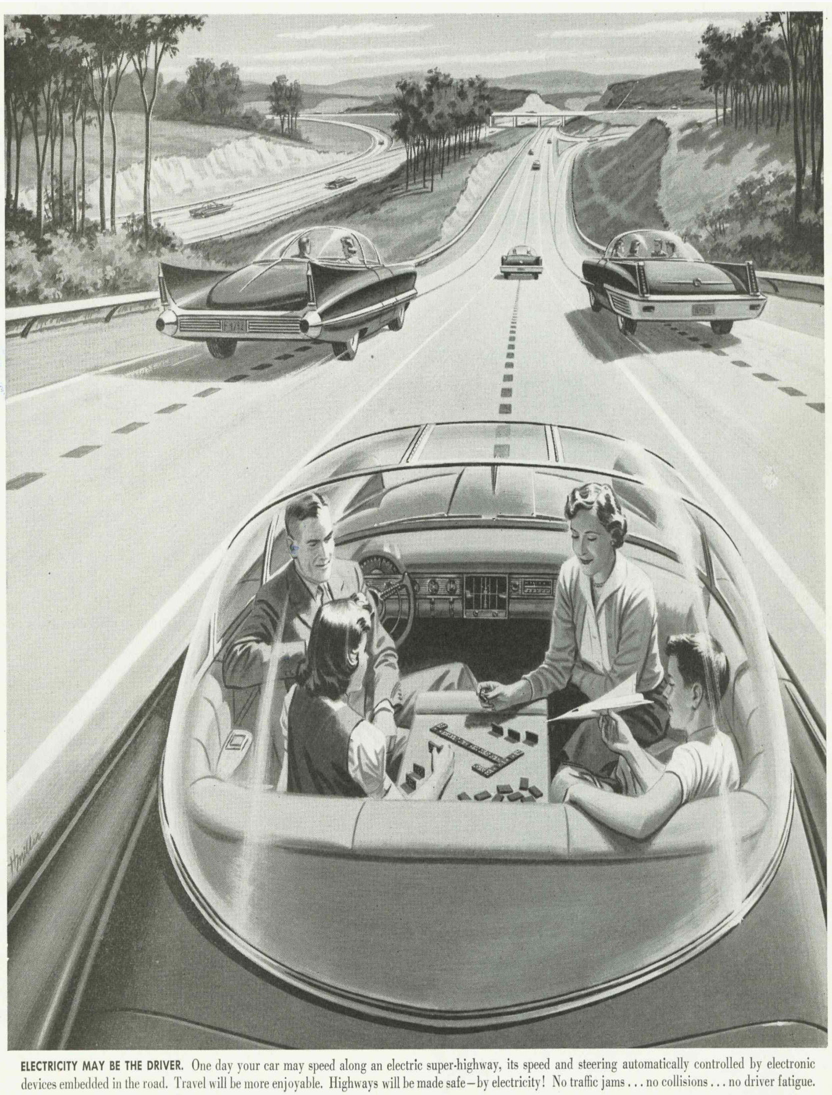
Level	"Less"	Value Proposition	Market Force	Societal Implications
0 "55 Chevy"	Zero	Zero	Zero	Zero
1 "Cruise Control"	Infinitesimal	Some Comfort	Infinitesimal	Infinitesimal
2 "CC + Emergency Braking"	Infinitesimal	Some Safety	Small; Needs help From "Flo & the Gecko" (Insurance Industry)	"20+%" fewer accidents; less severity; fewer insurance claims
3 "Texting Machine"	Some	Liberation (some of the time/places) ; much more Safety	Consumers Pull, TravelTainment Industry Push	Increased car sales, many fewer insurance claims, Increased VMT
4 "aTaxi "	Always	Chauffeured, Buy Mobility "by the Drink" rather than "by the Bottle"	Profitable Business Opportunity for Utilities/Transit Companies	Personal Car becomes "Bling" not instrument of personal mobility, VMT ?; Comm. Design ? Energy, Congestion, Environment?

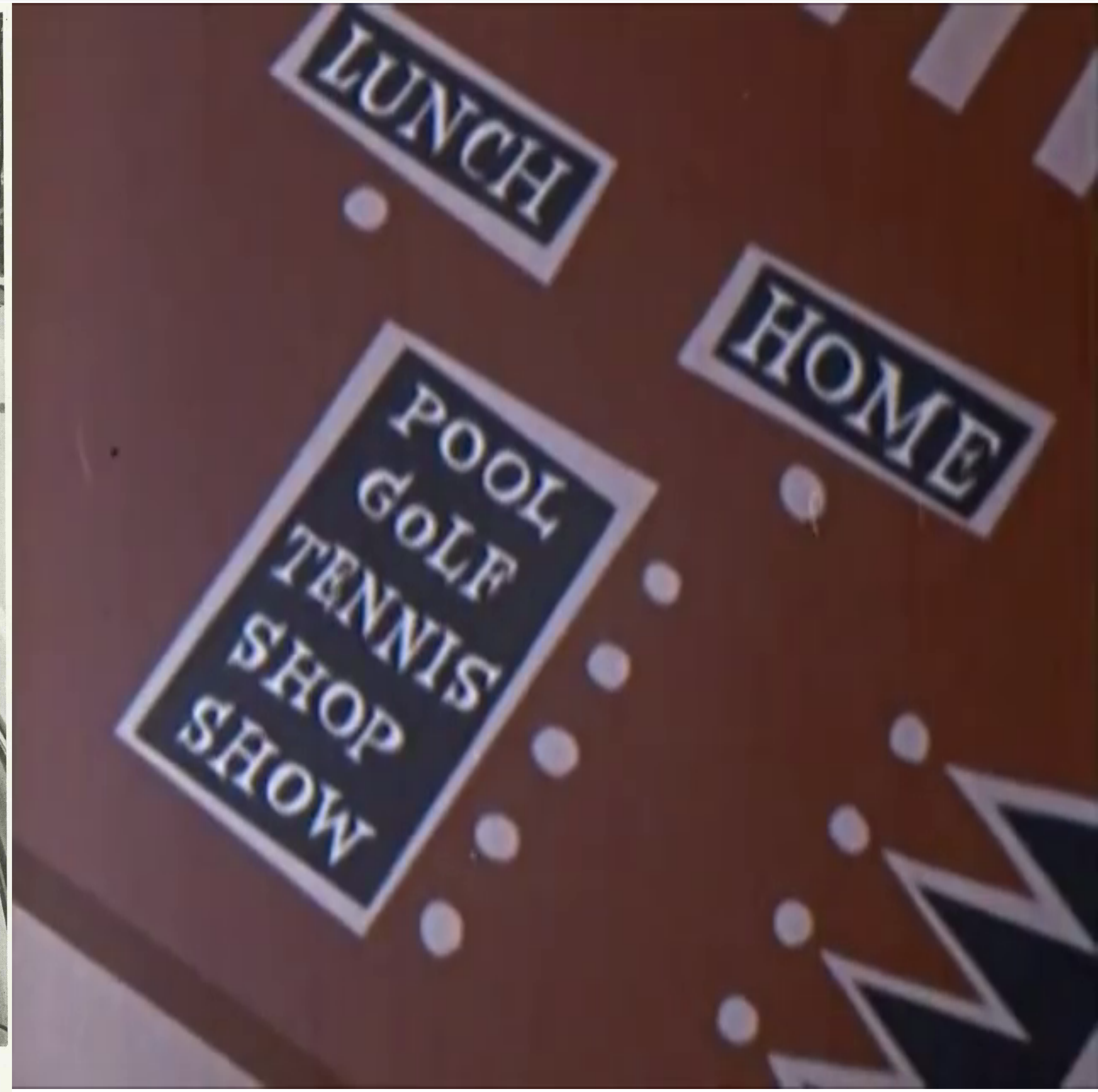
The concept is not new…

GM's Futurama exhibit at the 1939 World's Fair in NYC

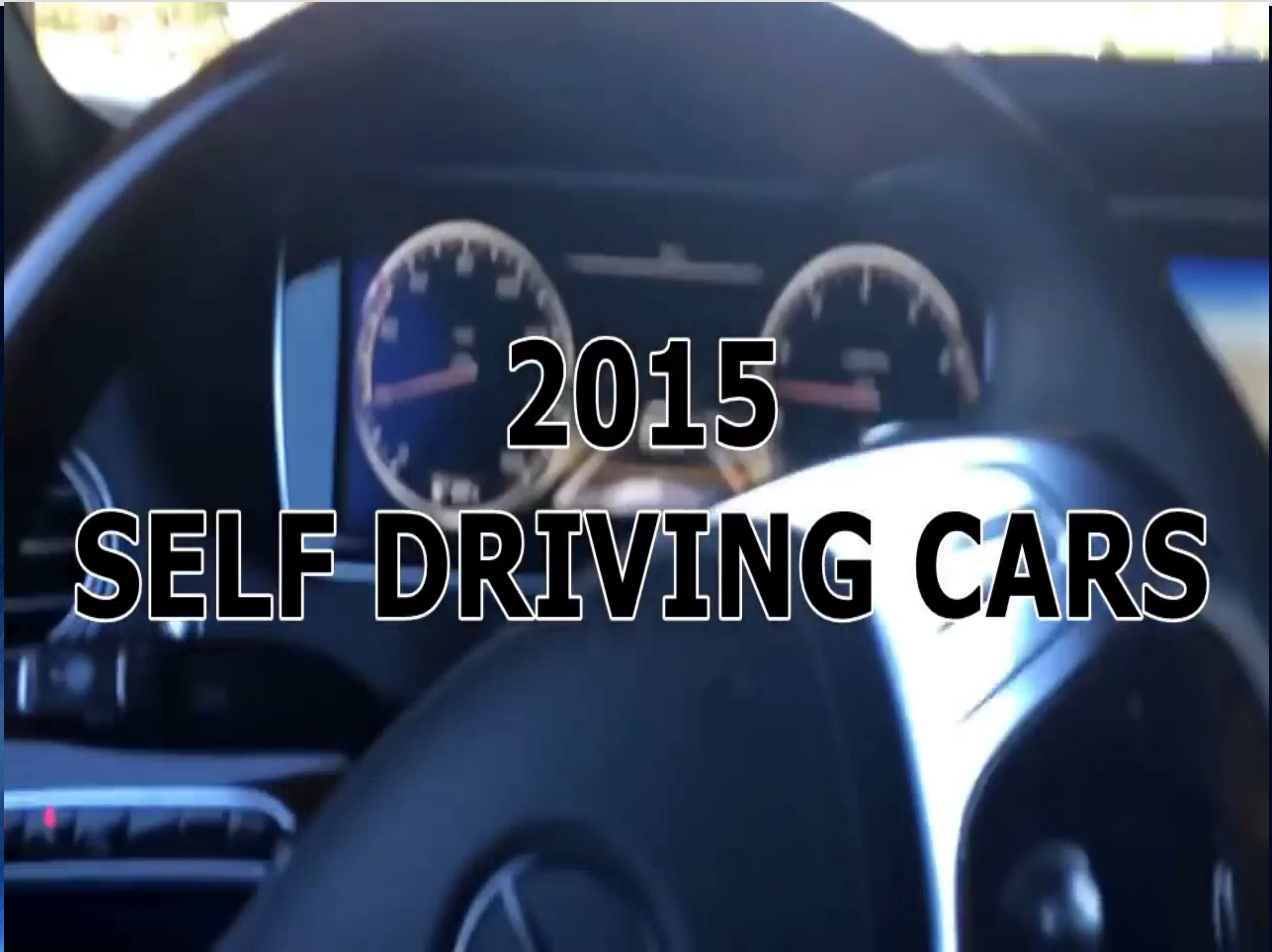
"abundant sunshine, fresh air [and] fine green parkways" upon which cars would drive themselves.

The concept is not new…





But now it is here, there and everywhere…



SAFETY FIRST: What Causes Crashes?

Table 1. Driver-, Vehicle-, and Environment-Related Critical Reasons

Critical Reason Attributed to	Estimated	
	Number	Percentage* ± 95% conf. limits
Drivers	2,046,000	94% ±2.2%
Vehicles	44,000	2% ±0.7%
Environment	52,000	2% ±1.3%
Unknown Critical Reasons	47,000	2% ±1.4%
Total	2,189,000	100%

*Percentages are based on unrounded estimated frequencies
(Data Source: NMVCCS 2005–2007)

Drivers Do!

Autonomous vehicle technologies reduce/eliminate human error

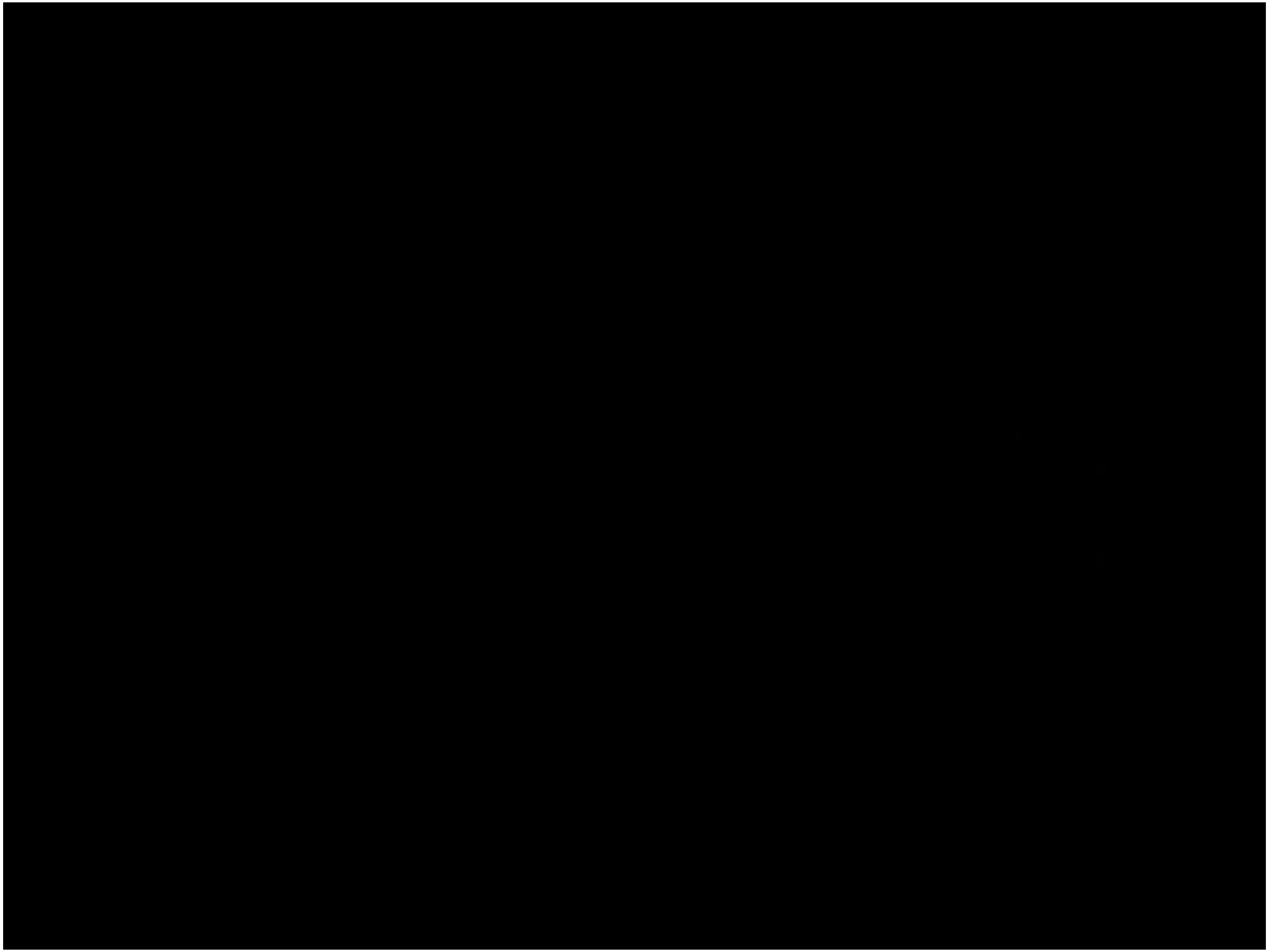
Table 2. Driver-Related Critical Reasons

Critical Reason	Estimated (Based on 94% of the NMVCCS crashes)	
	Number	Percentage* ± 95% conf. limits
Recognition Error	845,000	41% ±2.2%
Decision Error	684,000	33% ±3.7%
Performance Error	210,000	11% ±2.7%
Non-Performance Error (sleep, etc.)	145,000	7% ±1.0%
Other	162,000	8% ±1.9%
Total	2,046,000	100%

*Percentages are based on unrounded estimated frequencies
(Data Source: NMVCCS 2005–2007)

Improve Safety!

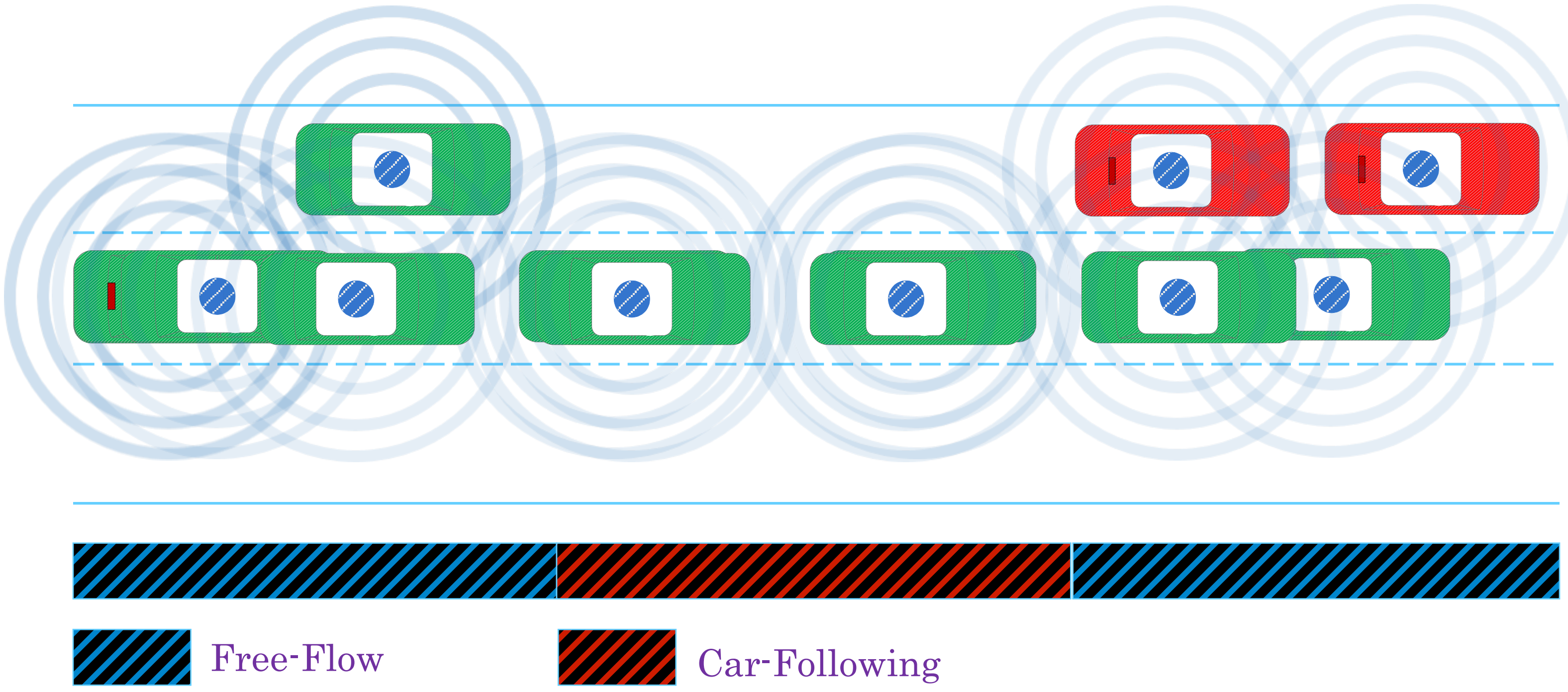
Connected Vehicles: Basic Concepts



Connected Vehicles Technology

Drivers

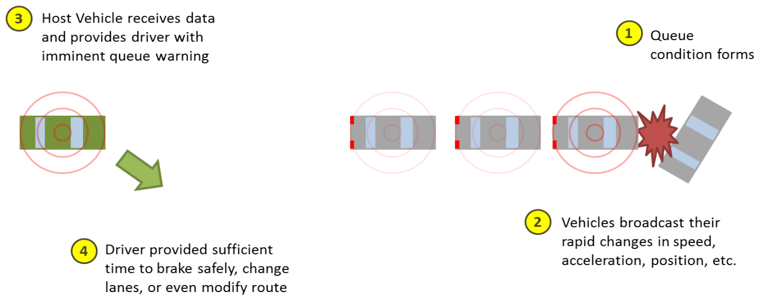
Connected Vehicles technology helps drivers with these decisions.



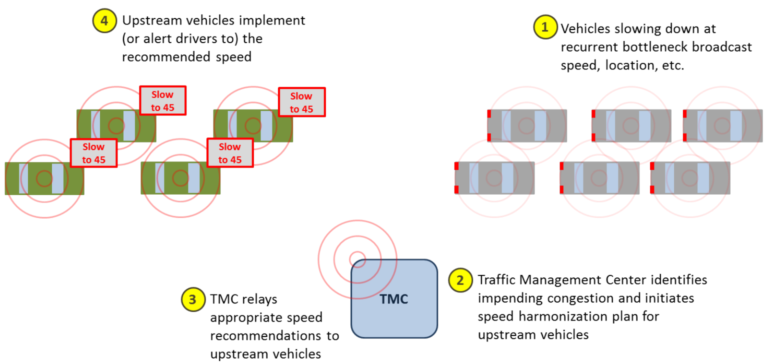
Connected Vehicles Technology

Drivers: Dynamic Mobility Applications

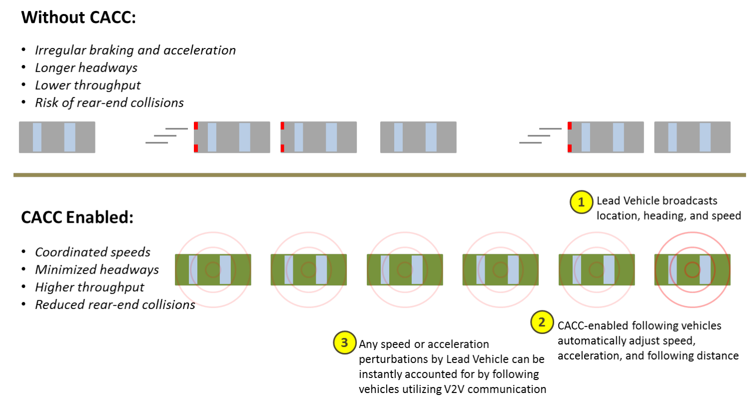
Queue Warning

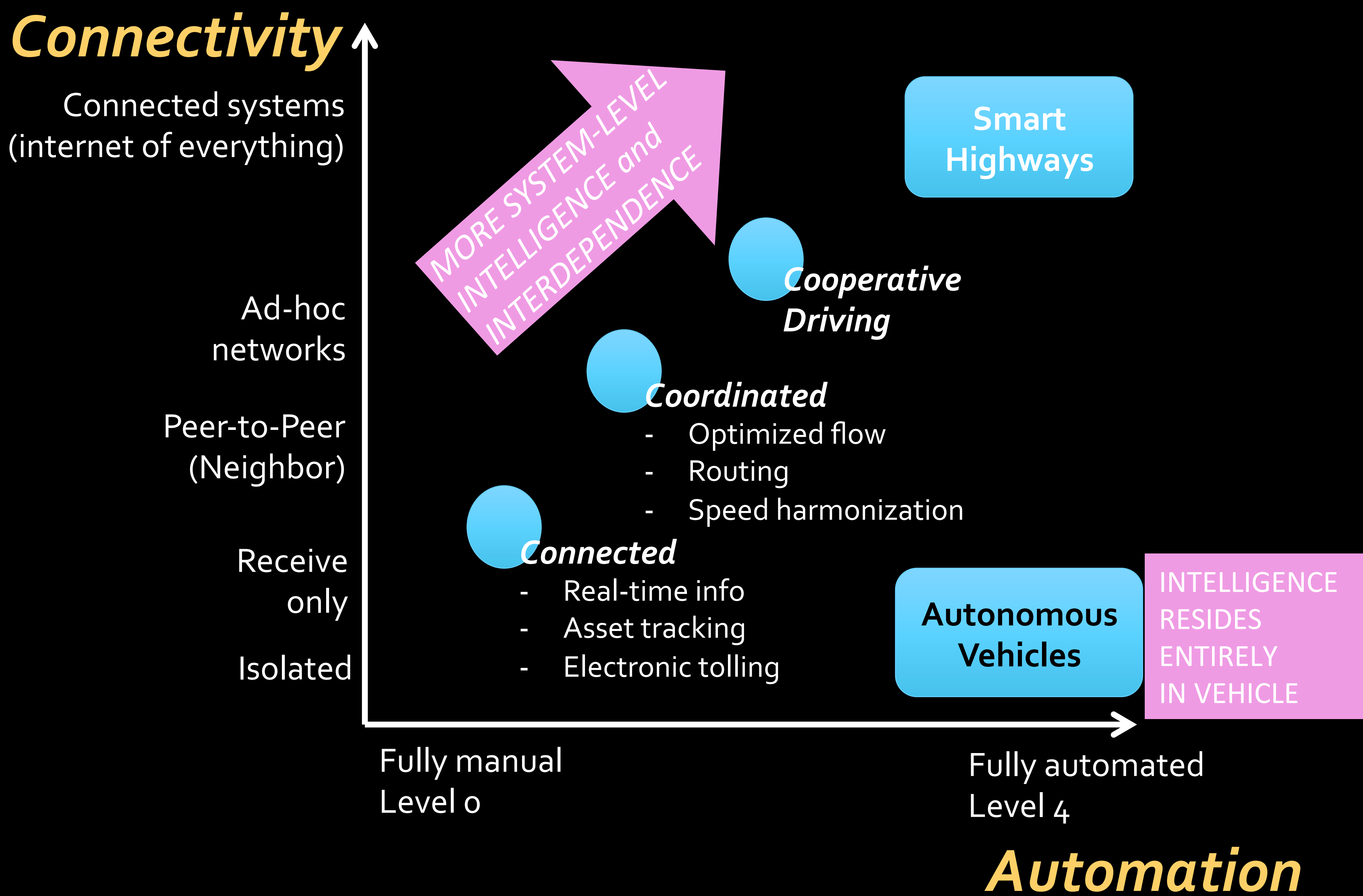


Speed Harmonization



Cooperative Adaptive Cruise Control




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 4
Automation

Coordination through connectivity and automation: Continuous-flow at-grade intersections

Two Sets of Questions:

1. Adoption Factors

- What factors affect purchase and use decisions of autonomous vehicles?
- Will people use these differently from conventional cars?
- Will new mobility service alternatives (e.g. hybrid transit) emerge in connection with these vehicles?
- How do we incorporate the implications of autonomous vehicle adoption in our planning models?
- Are current models adequate to consider these aspects?

Two Sets of Questions:

2. Traffic Flow/System Implications

- What are the implications of connectivity and/or automated functions on how we model driver behavior and traffic?
- How do we model the communications aspects (of connected systems) jointly with the traffic flow (e.g. to support operational control design)?
- What are the implications of automation vs. connectivity on traffic system performance in terms of

  SAFETY

  THROUGHPUT ("Capacity")

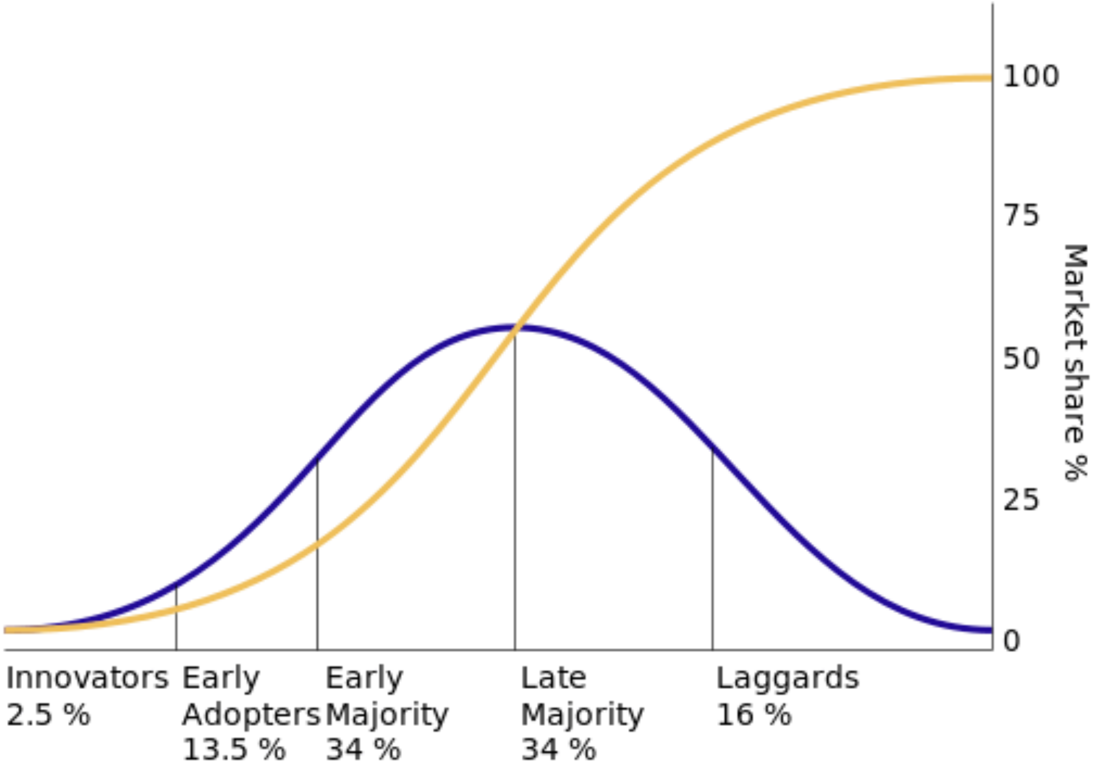
  STABILITY (→ Safety)

  FLOW BREAKDOWN (Reliability)

  SUSTAINABILITY (Greenhouse gases, energy)
- What is the sensitivity to relative market penetration on impact on mixed traffic performance?

Who will buy?

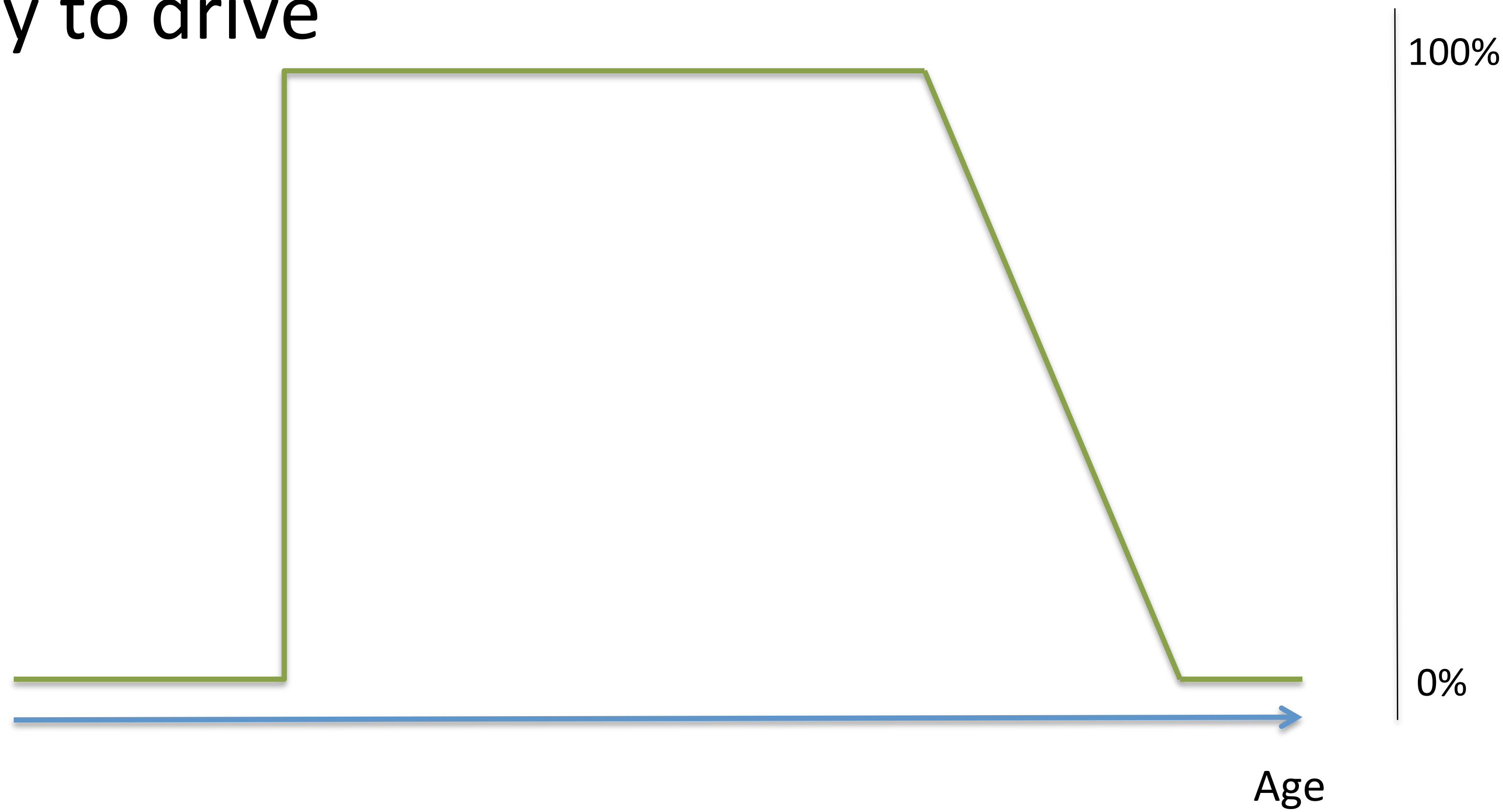
- WILL CLASSIC ROGERS' ADOPTION CURVE HOLD?



KEY ADOPTION FACTORS

- ABILITY TO DRIVE
- TRUST
- BENEFIT PERCEPTION
  - Safety
  - Mobility
  - Efficiency (time saving, constraint reduction)
- AFFORDABILITY

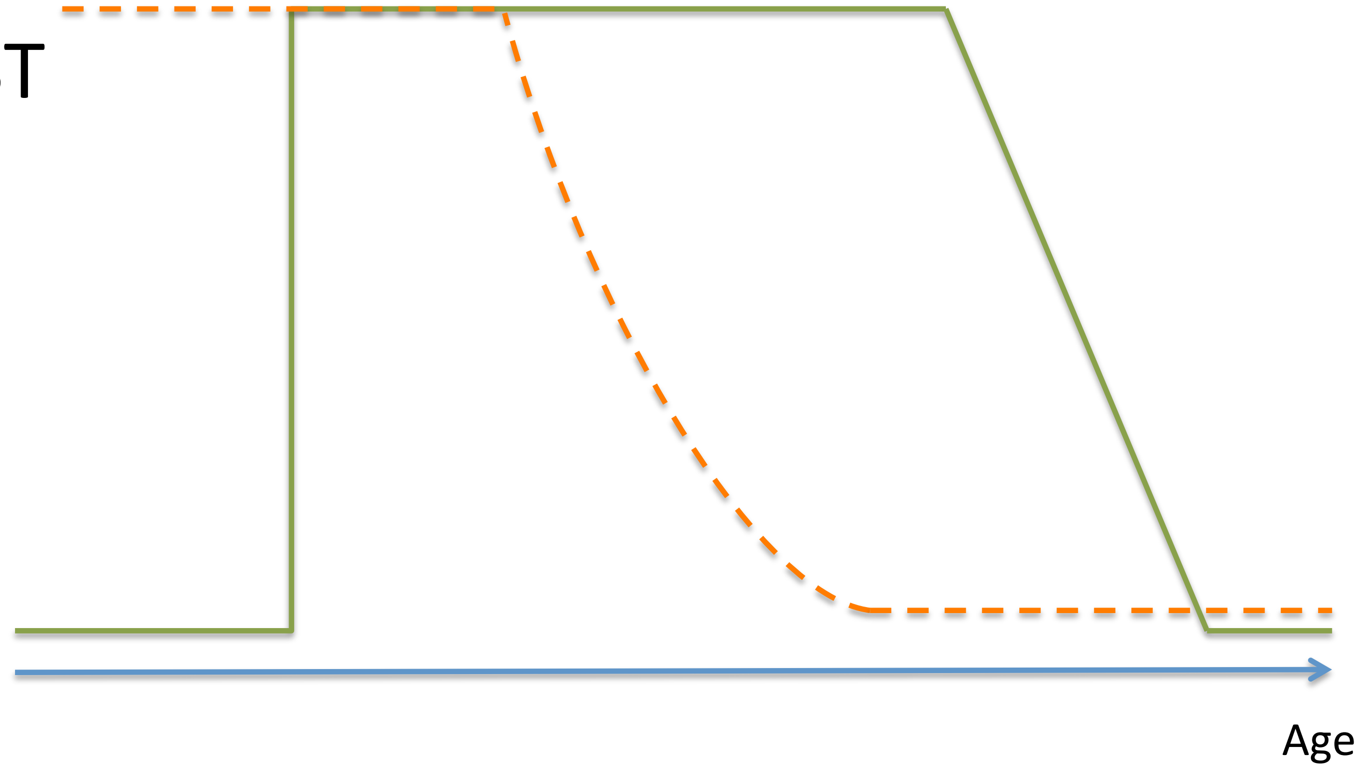
- Ability to drive

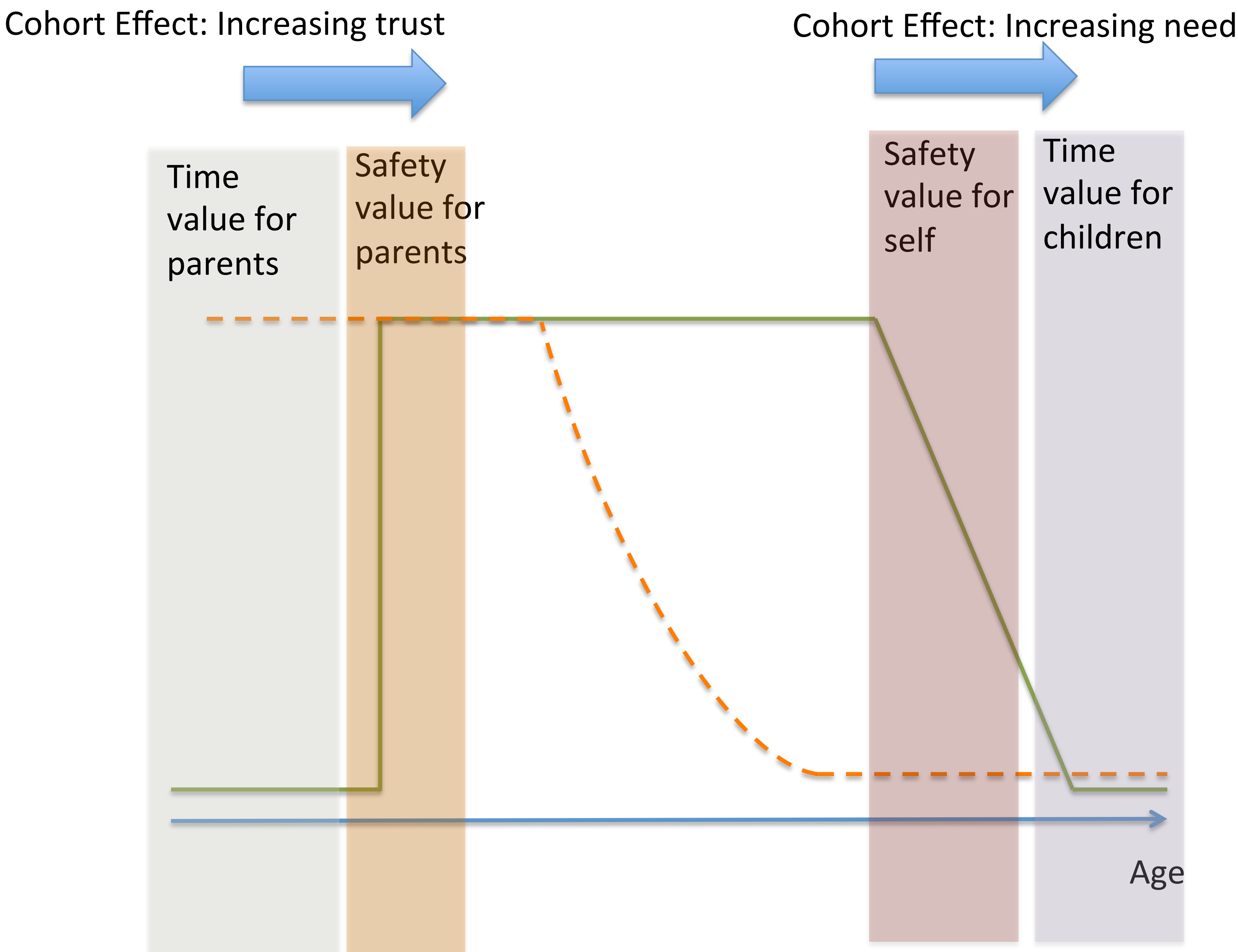


YOU and DRIVING

- THOSE WHO CANNOT DRIVE
- THOSE WHO PREFER NOT TO DRIVE
- THOSE WHO PREFER TO DRIVE
- THOSE WHO LOVE TO DRIVE

- Ability to drive
- TRUST



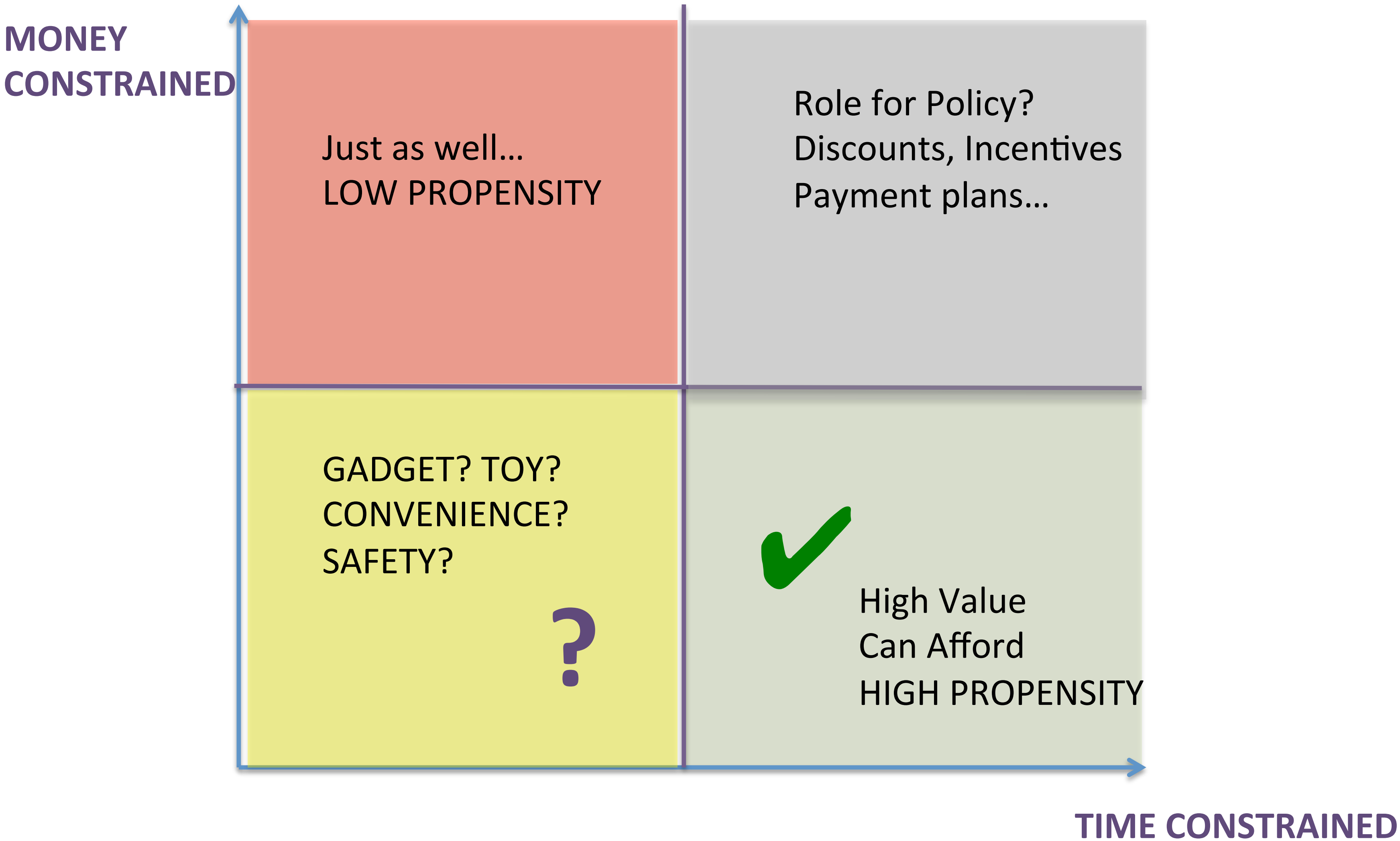


Cohort Effect: Increasing trust
Cohort Effect: Increasing need
Time value for parents
Safety value for parents
Safety value for self
Time value for children
Age

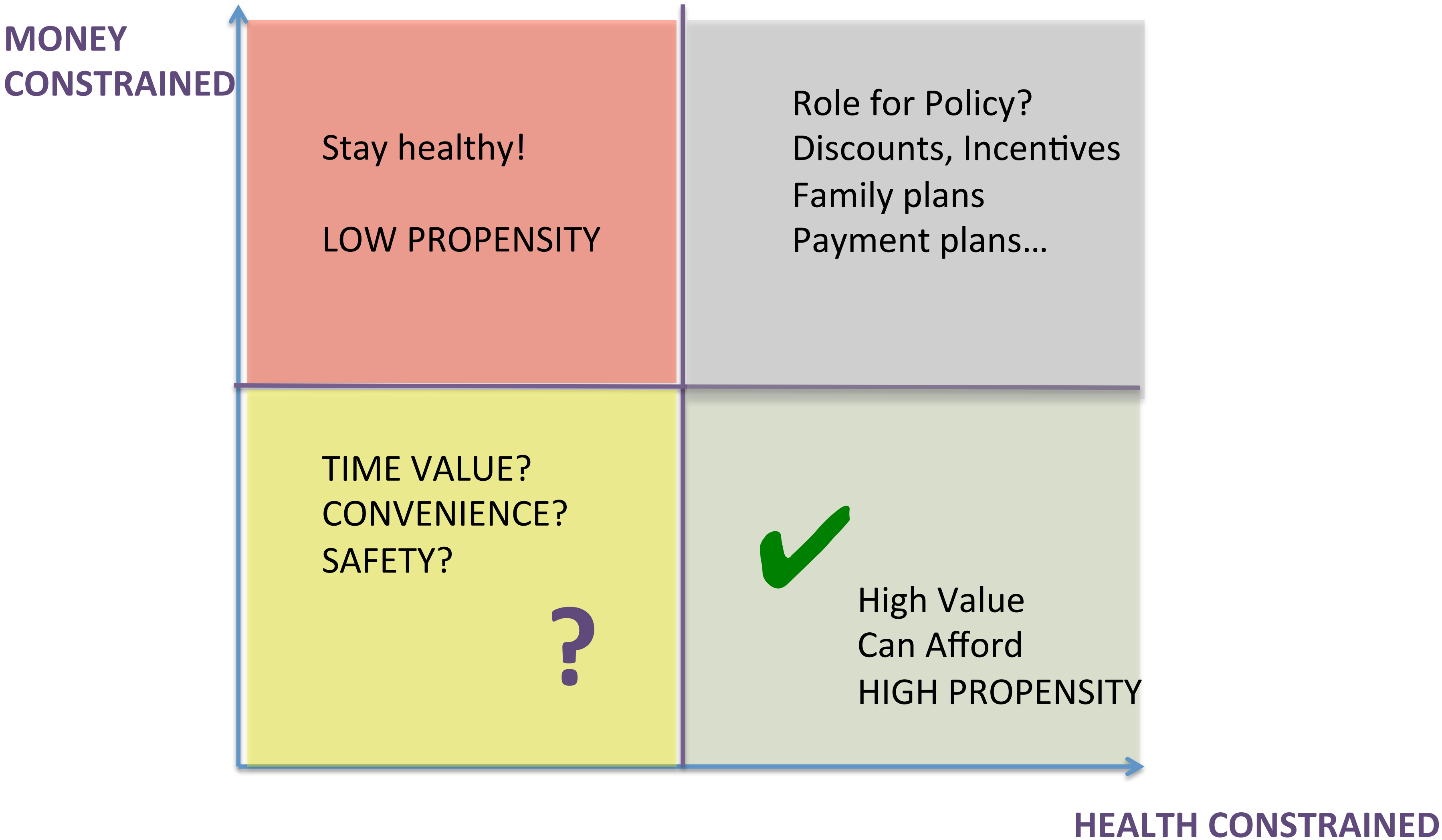
TWO KEY ASPECTS

- AUTONOMOUS CAR AS MOBILITY TOOL
  - Greater safety, efficiency, etc…
  - Enables multitasking, short vs. longer spans
- AS ROBOTIC ASSISTANT
  - Go shop, pick up kids– all mobility chores imposed by auto-centric suburban lifestyle
  - For small businesses– go deliver, pick up supplies…

ADOPTION PROPENSITY



ADOPTION PROPENSITY

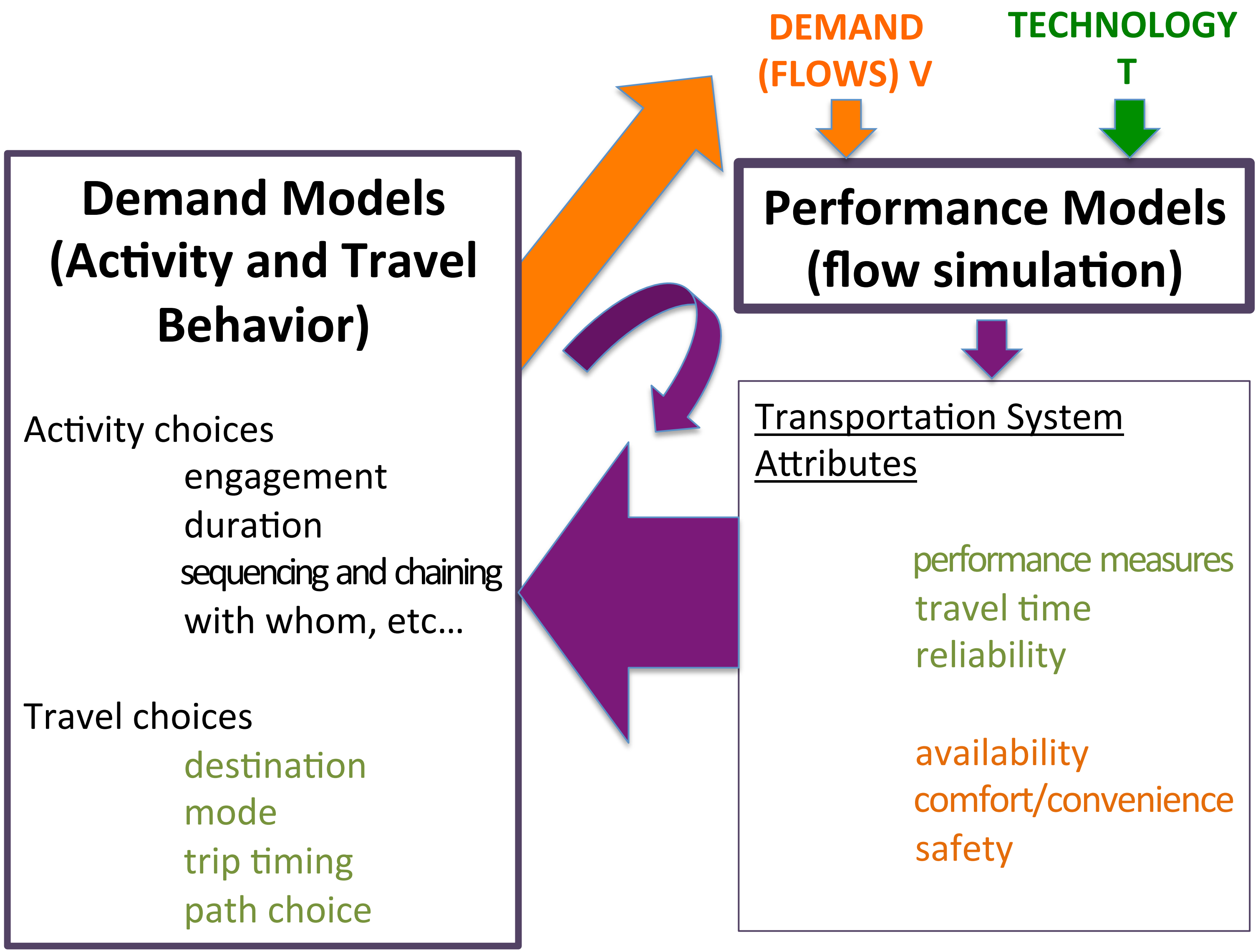


Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- **Autonomous Vehicles and Planning Models**
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- Throughput Analysis: Simulation Results
- Takeways, Limitations and Challenges

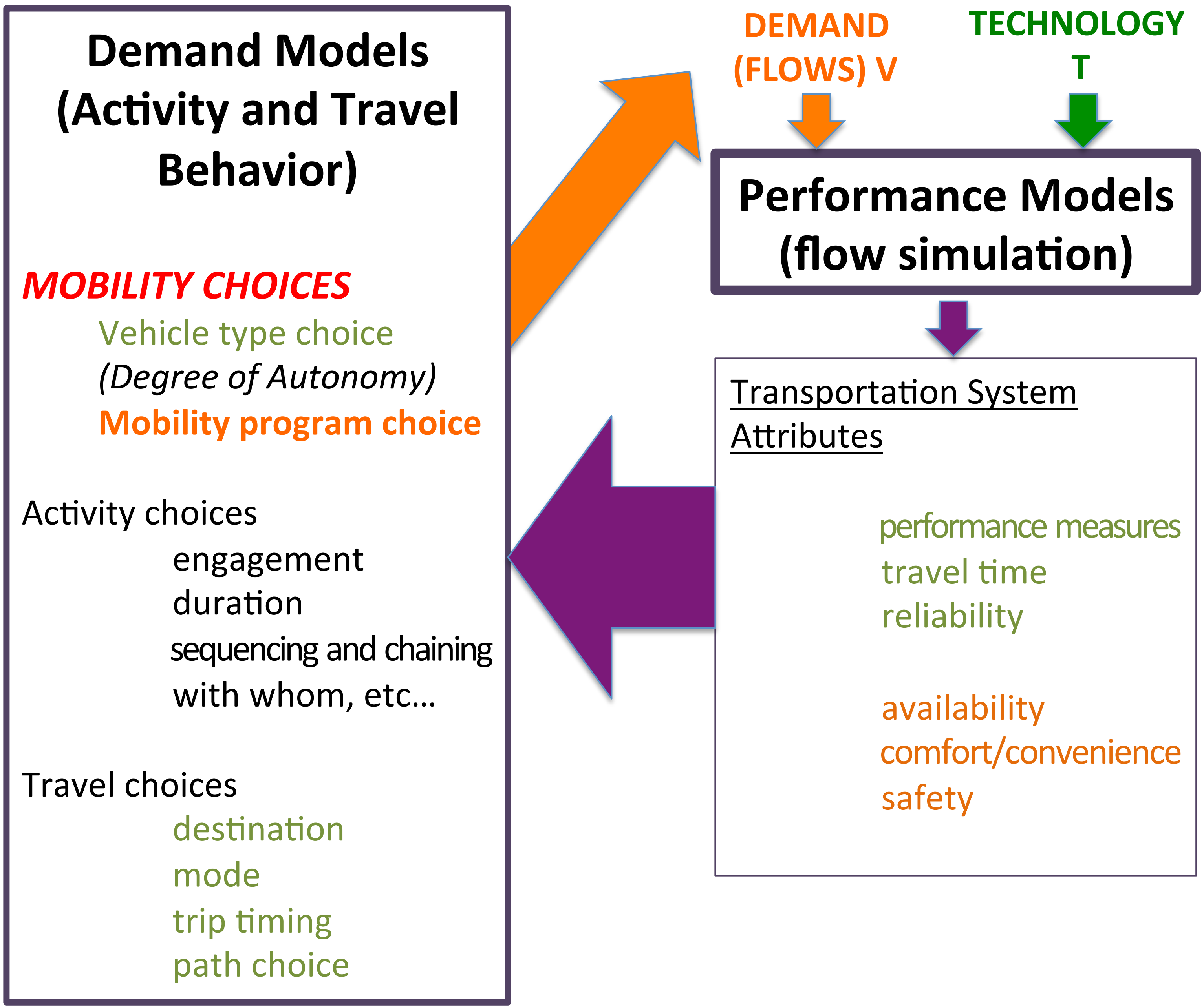
An Incremental View

- 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).


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

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.


Demand Models
(Activity and Travel
Behavior)
MOBILITY CHOICES
Vehicle type choice
(Degree of Autonomy)
Mobility program choice
Activity choices
engagement
duration
sequencing and chaining
with whom, etc…
Travel choices
destination
mode
trip timing
path choice
DEMAND
(FLOWS) V
TECHNOLOGY
T
Performance Models
(flow simulation)
Transportation System
Attributes
performance measures
travel time
reliability
availability
comfort/convenience
safety

Less Incremental I

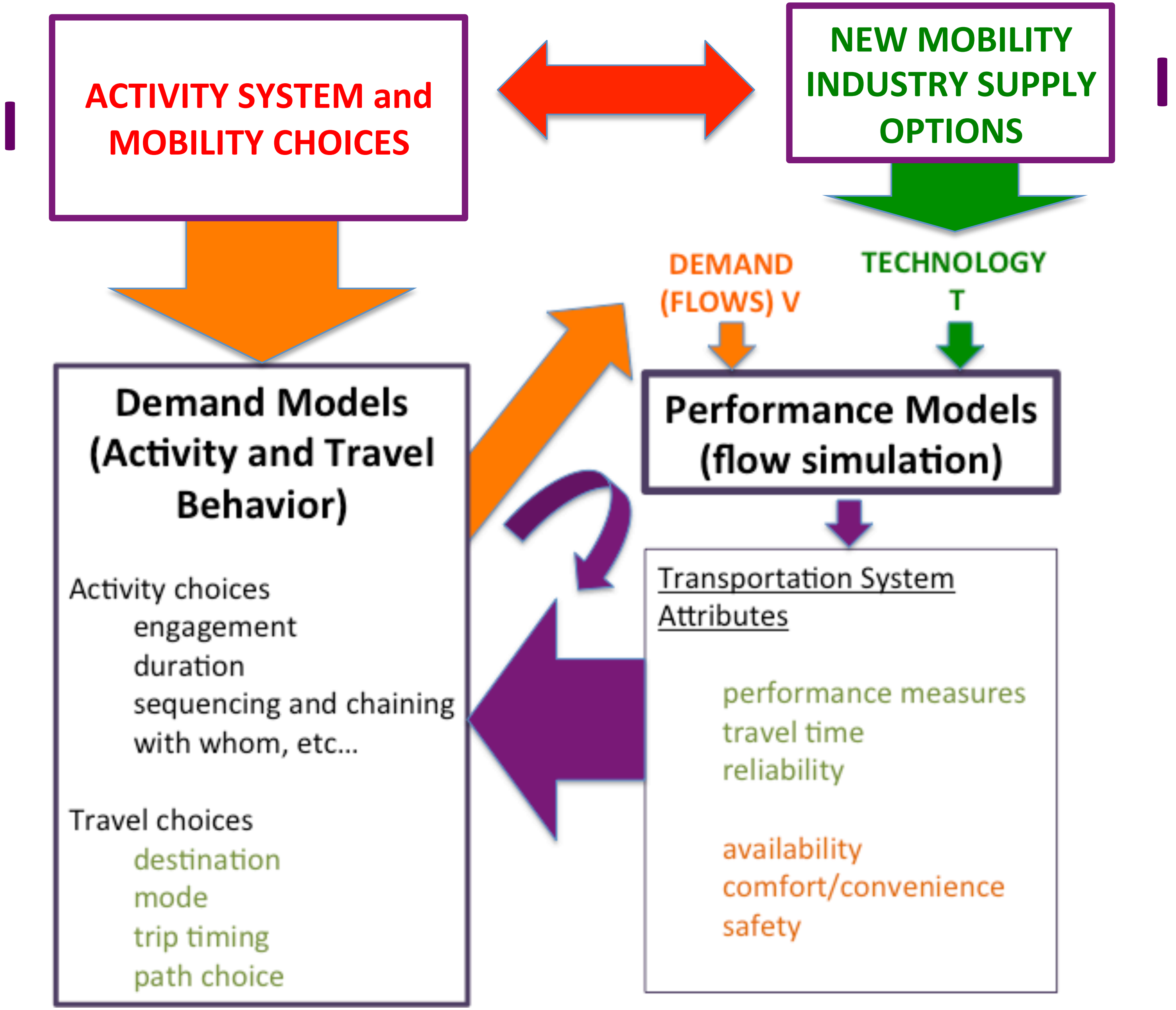
Major Activity Shifts and Mobility Use

- Driverless vehicles impact activity patterns at the individual and household levels in ways that go well beyond current ABM capabilities.
- TWO KEY ASPECTS:
  - AUTONOMOUS CAR AS MOBILITY TOOL
    - Greater safety, efficiency, etc…
    - Enables multitasking, short vs. longer spans
  - AS ROBOTIC ASSISTANT
    - Go shop, pick up kids– all mobility chores imposed by auto-centric suburban lifestyle
    - For small businesses– go deliver, pick up supplies…
- Demand-side:
  - Implications for vehicle use/sharing within household
  - "Chauffeur" features of waiting and/or showing up when needed
  - Additional trips and VMT (deadheading), remote parking…
  - Sequencing and routing
- Supply-side:
  - Vehicle availability/waiting time attribute

Less Incremental II

Major Mobility Supply Shifts

- Driverless vehicles will enables new forms of mobility supply
- New forms of car sharing with greater convenience may reduce the motivation for individual ownership
- Car-sharing marketplaces may emerge– driverless Uber, reducing cost and uncertainty of sharing model
- The realm between personal transportation and public mobility can widen considerably to include various hybrid forms
- What will become of public transit as we know it? Driverless, personalized at low density, more efficient and accessible at higher density…
- Some of these trends beginning to emerge today (e.g. Helsinki's goal of public personal urban mobility).



I
ACTIVITY SYSTEM and MOBILITY CHOICES
NEW MOBILITY INDUSTRY SUPPLY OPTIONS
II
DEMAND (FLOWS) V
TECHNOLOGY T
Demand Models (Activity and Travel Behavior)
Activity choices
engagement
duration
sequencing and chaining
with whom, etc…
Travel choices
destination
mode
trip timing
path choice
Performance Models (flow simulation)
Transportation System Attributes
performance measures
travel time
reliability
availability
comfort/convenience
safety

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.

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.

Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- **Flow Implications**
  - **Research Questions**
  - **Simulation Approach: Traffic, Wireless Communication**
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- Throughput Analysis: Simulation Results
- Takeways, Limitations and Challenges

Work in collaboration with recent PhD graduate

Alireza Talebpour

Currently Assistant Professor at Texas A&M University

Acceleration Framework

No Automation
Not Connected

No Automation
Connected

Self-Driving
Not Connected

Acceleration Framework

No Automation Not Connected | **No Automation Connected** | **Self-Driving Not Connected**

• 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

Acceleration Framework

No Automation Not Connected | **No Automation Connected** | **Self-Driving Not Connected**

Active V2V Communications	Inactive V2V Communications
Active V2I Communications	Inactive V2I Communications

• Acceleration Behavior:	Deterministic
• Perception of Surrounding Traffic Condition:	Accurate
• Reaction Time:	Low
• Safe Spacing:	Low
• High-Risk maneuvers:	Very Unlikely

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

Acceleration Framework

No Automation Not Connected

No Automation Connected

Self-Driving Not Connected

Active V2V Communications	**Inactive V2V Communications**
Active V2I Communications	Inactive V2I Communications

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

Acceleration Framework

No Automation Not Connected | **No Automation Connected** | **Self-Driving Not Connected**

Active V2V Communications	Inactive V2V Communications
Active V2I Communications	Inactive V2I Communications

- 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 Automation Not Connected | **No Automation Connected** | **Self-Driving Not Connected**

Active V2V Communications	Inactive V2V Communications
Active V2I Communications	**Inactive V2I Communications**

- No communication between vehicle and TMC
- Depending on the availability of V2V Communications:
  - Active V2V Communications: IDM
  - Inactive V2V Communications: Talebpour , Hamdar, and Mahmassani

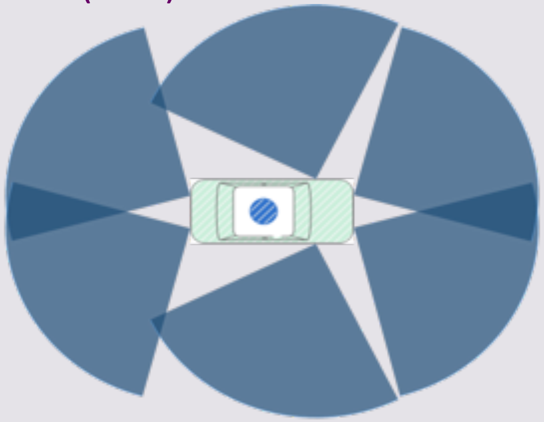
Acceleration Framework

No Automation Not Connected

No Automation Connected

Self-Driving Not Connected

- 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).



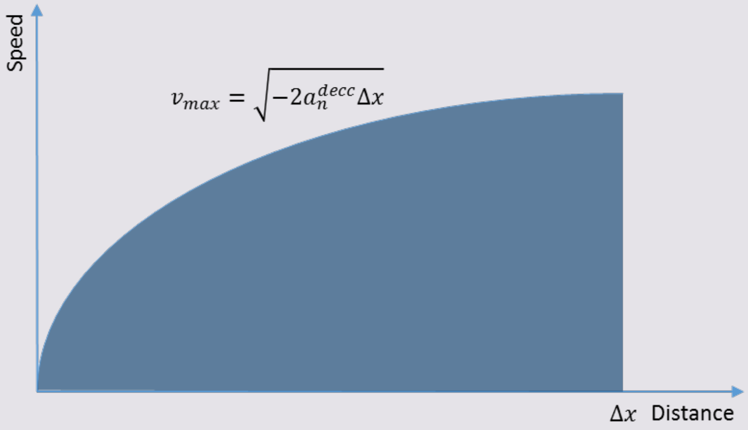
Acceleration Framework

No Automation Not Connected

No Automation Connected

Self-Driving Not Connected

- Speed should be low enough so that the vehicle can react to any event outside of the sensor range ($v_{\max}$) (Reece and Shafer, 1993 and Arem, Driel, Visser, 2006).



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

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

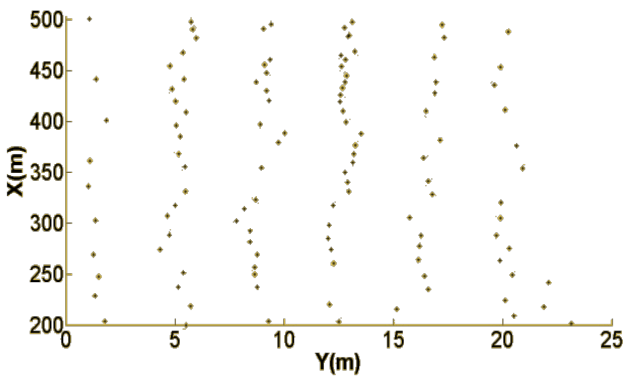
Connected Vehicles Technology
Communication

- It is essential to consider the V2V/V2I communications when modeling a connected environment.
- Connectivity through the vehicular ad hoc network (VANET) is a key element.
- Several studies focused on connectivity in a VANET,
    - Jin et al. (2011)
    - Ajeer et al. (2011)
    - Durrani et al. (2010)

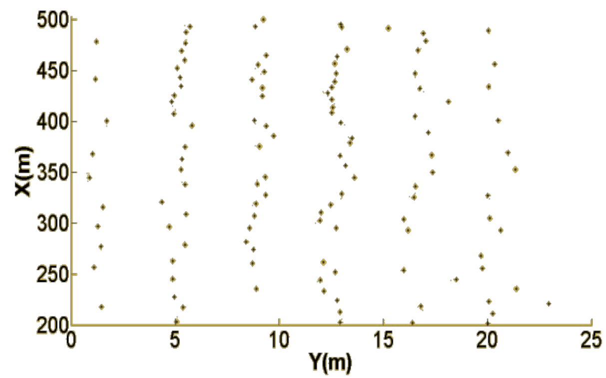
Connected Vehicles Technology
Communication

- Most of these studies,
    - Assume homogenous Poisson distribution for vehicles along a road segment.
    - Consider road segments as one-dimensional objects.
    - Assume normal distribution for speed.
- It is essential to study the connectivity of VANET by considering
    - Non-homogenous distribution for vehicles along a road segment.
    - Road segments as two-dimensional objects.
- Existence of a communication link between two nodes depends on,
    - Wireless technology
    - Transmission power and rate
    - Distance and geographical location
    - Signal propagation and interference

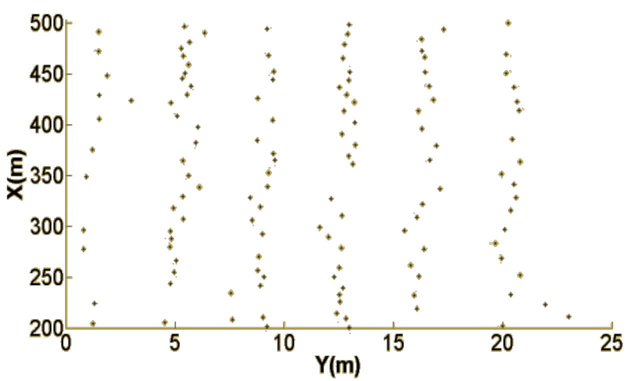
Communication Network
Dynamic Nature of Vehicular Movements



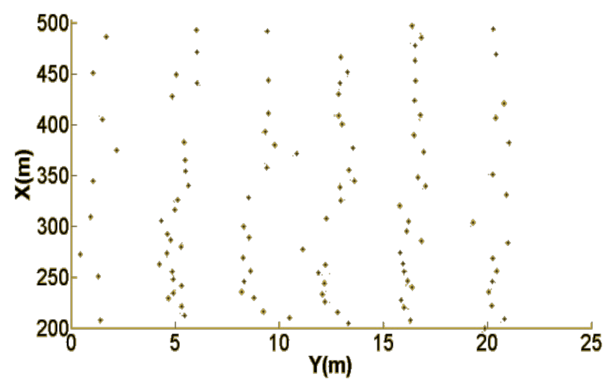
t = 0 Sec



t = 100 Sec



t = 500 Sec



t = 1000 Sec

Based on NGSIM Data

Communication Network
Percolation

- There are many instances in which

  a fluid spreads through a medium,

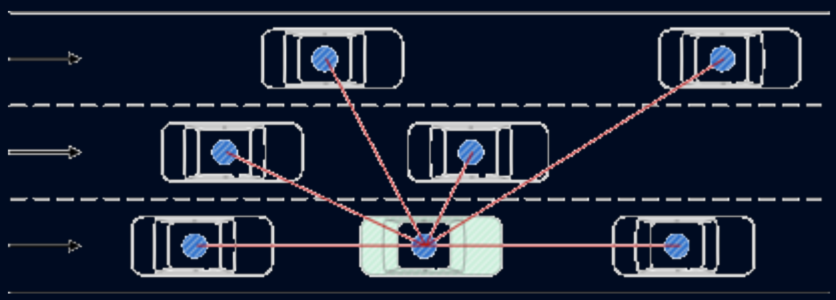
  a disease spreads among people,

  information spreads in social networks, and

  a liquid penetrates into a porous material.

- Broadbent and Hammersley (1957) introduced the “percolation theory” to model these instances.
- There are two models, Discrete Percolation and Continuum Percolation
- *Design question: how to form clusters of communicating vehicles, with a “leader” communicating with the infrastructure (V2I) and other groups, and transmitting information within the group?*

Clustering Algorithm
What is a cluster?



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

Having stable clusters is the key to reducing signal interference.

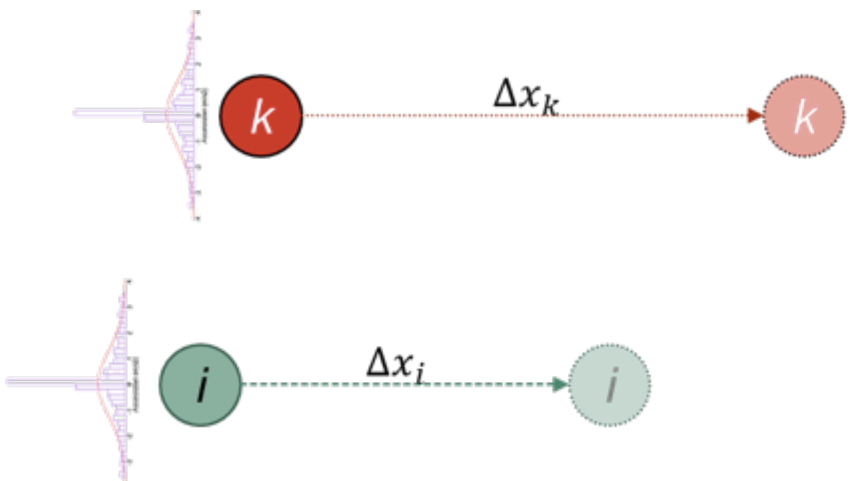
This study incorporated driving history and driver heterogeneity, in addition to the usual distance and speed measures into VANET clustering algorithms.

V2V Communications Model
Clustering

A clustering algorithm based on Affinity Propagation (Hassanabadi et al., 2014 and Frey and Dueck, 2007) is used for clustering.

Model Parameters:

- $s(i,k)$: similarity between i and k indicates how well k can be i's exemplar.



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

V2V Communications Model
NS3 Implementation

Network Simulator 3 (NS3) is a discrete-event communication network simulator.

Dedicated Short-Range Communication (DSRC) Protocol is the standard protocol for V2V communications. DSRC in 5.9GHz spectrum.

DSRC interface uses 7 non-overlapping channels (Xu et al., 2012):

- A control channel with 1000m range.
- Six service channels with 30-400m range.

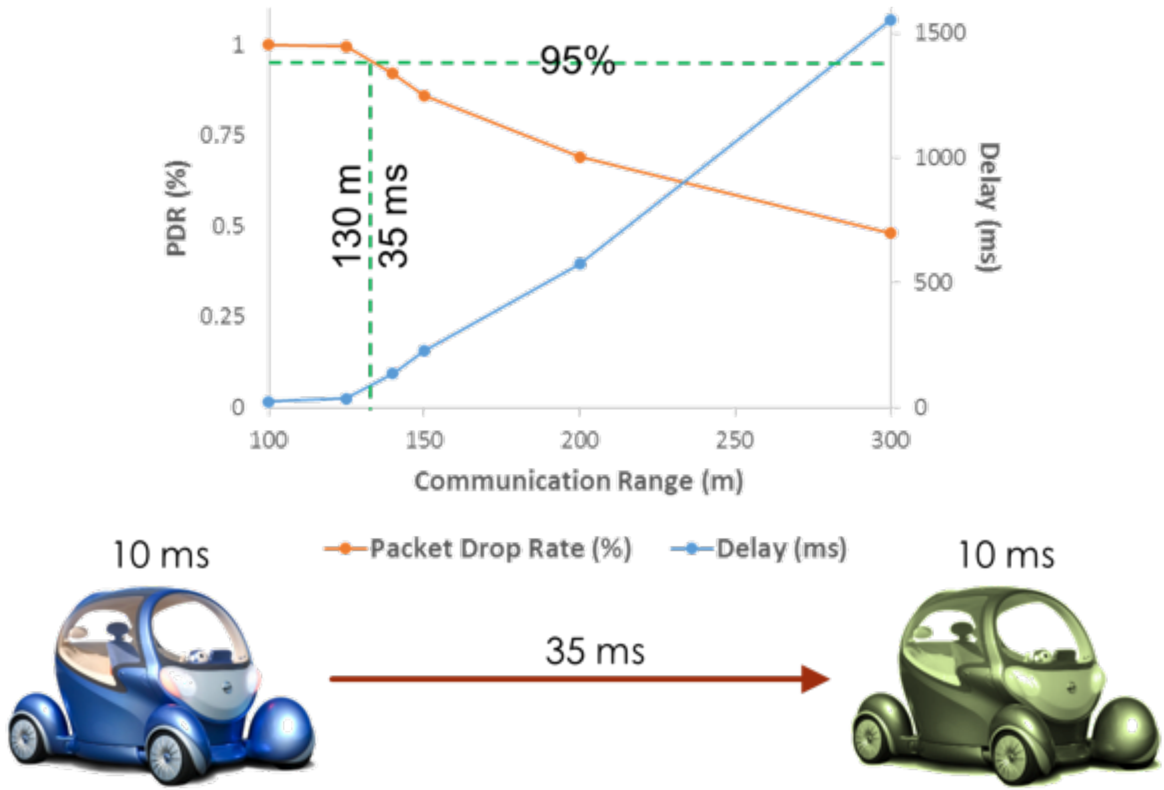
DSRC uses

- 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

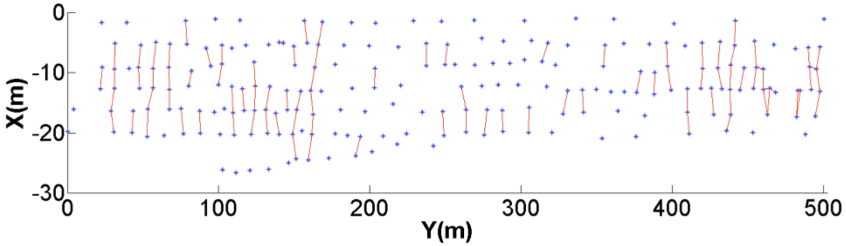
Packet size = 50 byte: Location, speed, acceleration

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

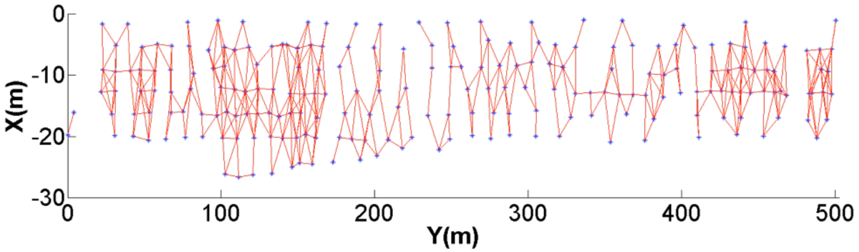


Communication Network

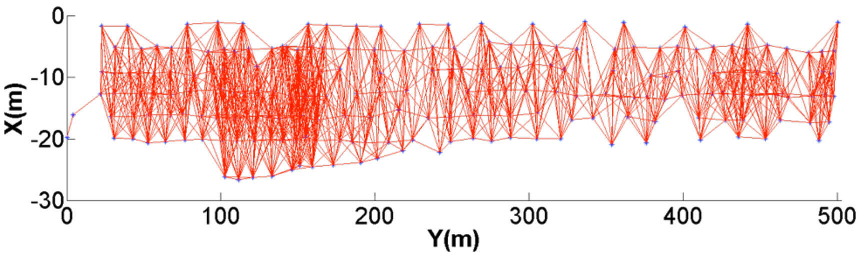
Connectivity: Constant Transmission Power



Effective Transmission range = 5m
Biggest Cluster Size = 8



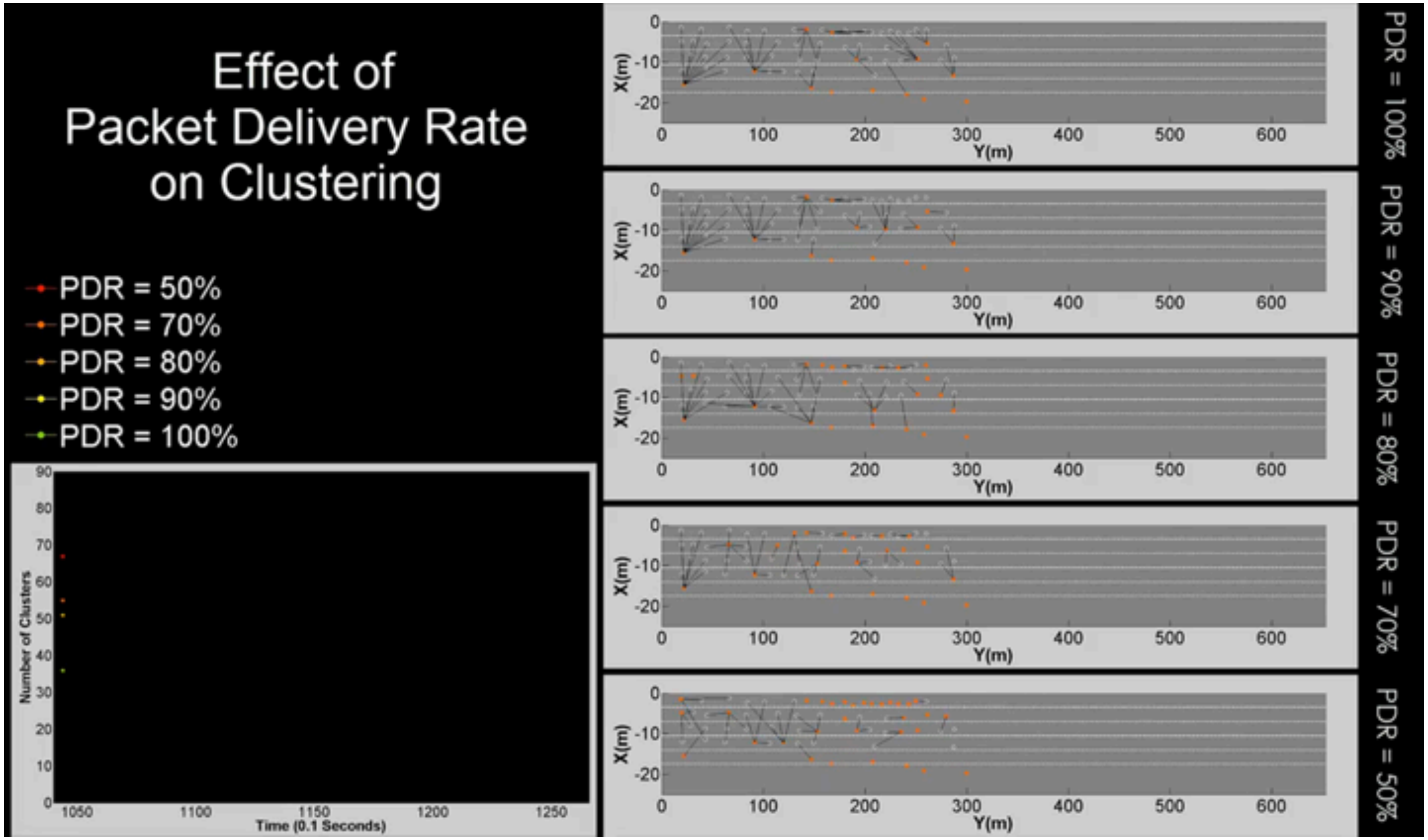
Effective Transmission range = 10m
Biggest Cluster Size = 93



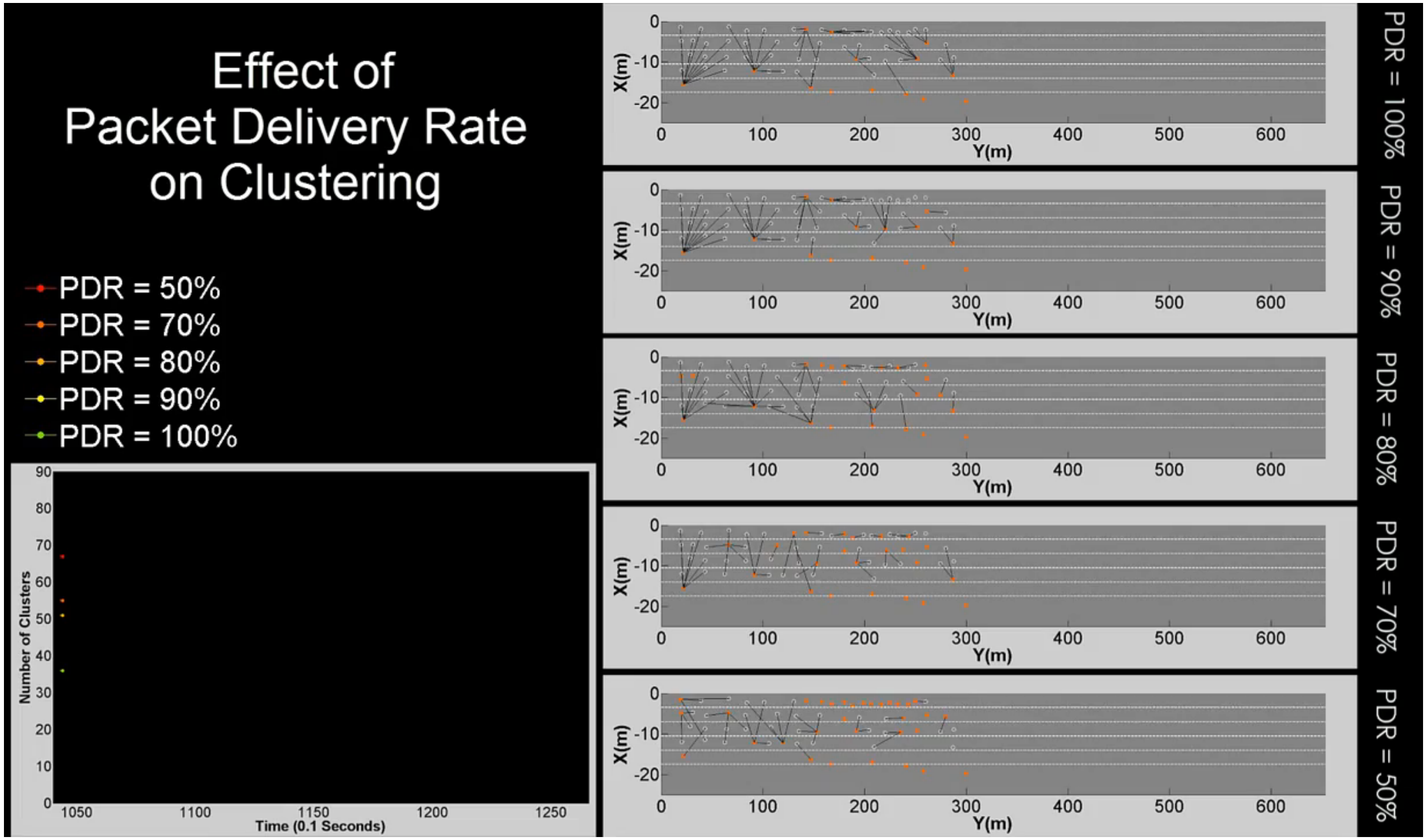
Effective Transmission range = 20m
Biggest Cluster Size = 216

DSRC in 5.9GHz spectrum.

V2V Communications Model
NS3 Implementation – Packet Delivery



V2V Communications Model
NS3 Implementation – Packet Delivery

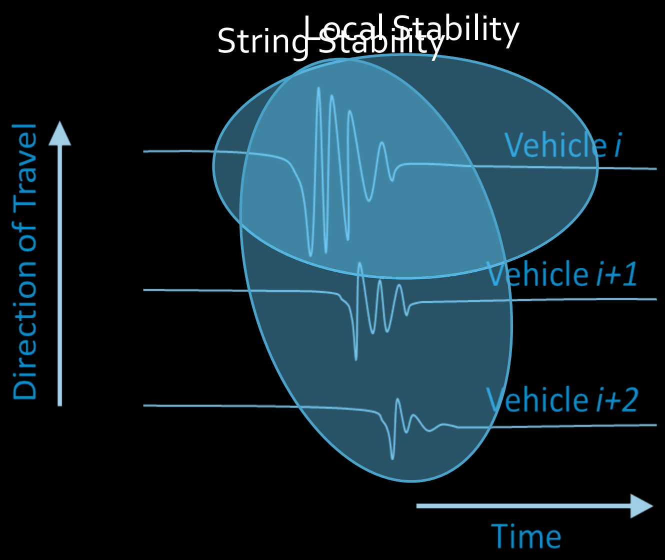


Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- **Stability Analysis:**
  - **Analytical Approach**
  - **Simulation Results Trajectory Processor for particle-based simulators**
- Throughput Analysis: Simulation Results
- Takeways, Limitations and Challenges

Stability Analysis

- Local Stability vs. String Stability



Wilson, R. E., and J. A. Ward. (2010)
Car-following models: fifty years of linear stability analysis – a mathematical perspective.
Transportation Planning and Technology

Stability Analysis

A car-following model can be formulated as:

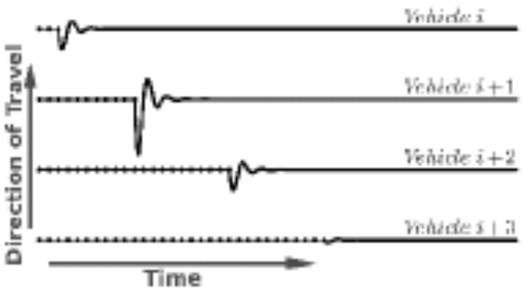
$$\dot{x}_n = v_n$$
$$\dot{v}_n = f\left(s_n, \Delta v_n, v_n\right)$$

Empirical observations suggest that there exists an equilibrium speed-spacing relationship:

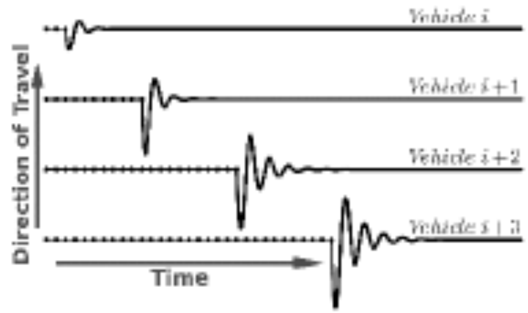
$$f(s^*, 0, V(s^*)) = 0, \ \forall s^* > 0$$

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

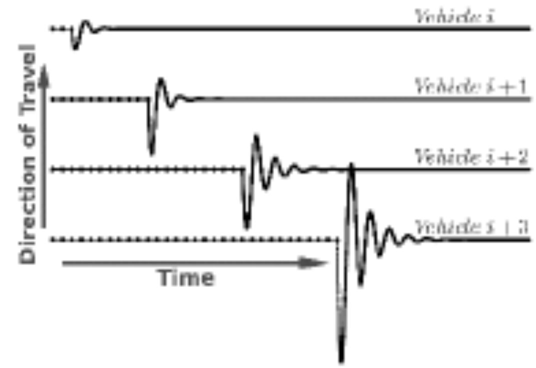
Stability Analysis



String Stable Regime



Unstable Oscillatory Regime



Unstable Collision Regime

Stability Analysis

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

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

where

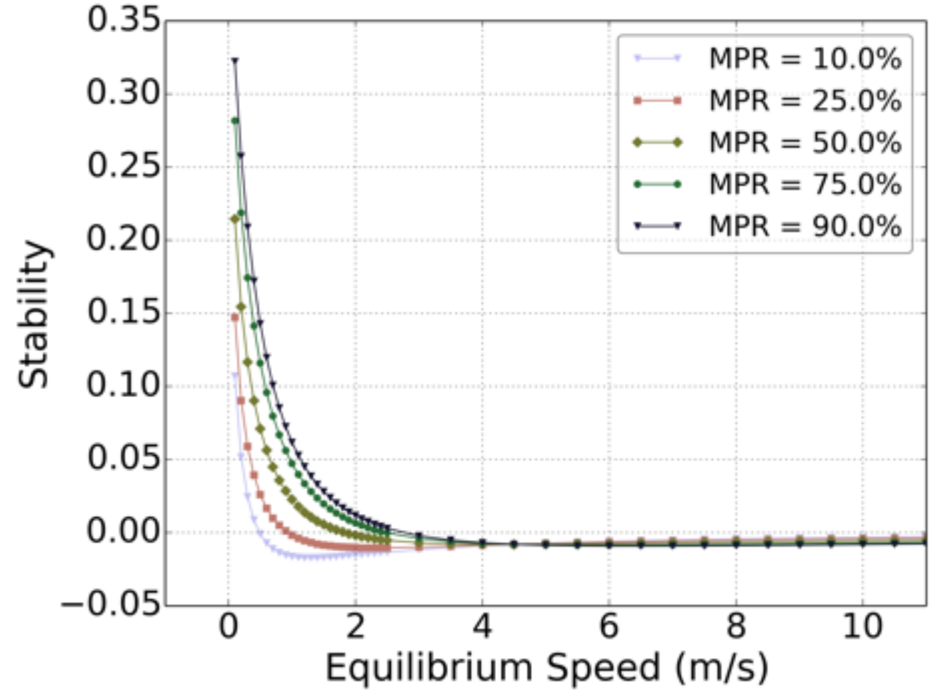
$$f_s^n = \left. \frac{\partial f\left(s_n, \Delta v_n, v_n\right)}{\partial s_n} \right|_{(s^*, 0, V(s^*))}$$

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

Stability Analysis
Heterogeneous Traffic Flow

- Parameters of regular vehicles are adjusted to create a very unstable traffic flow.

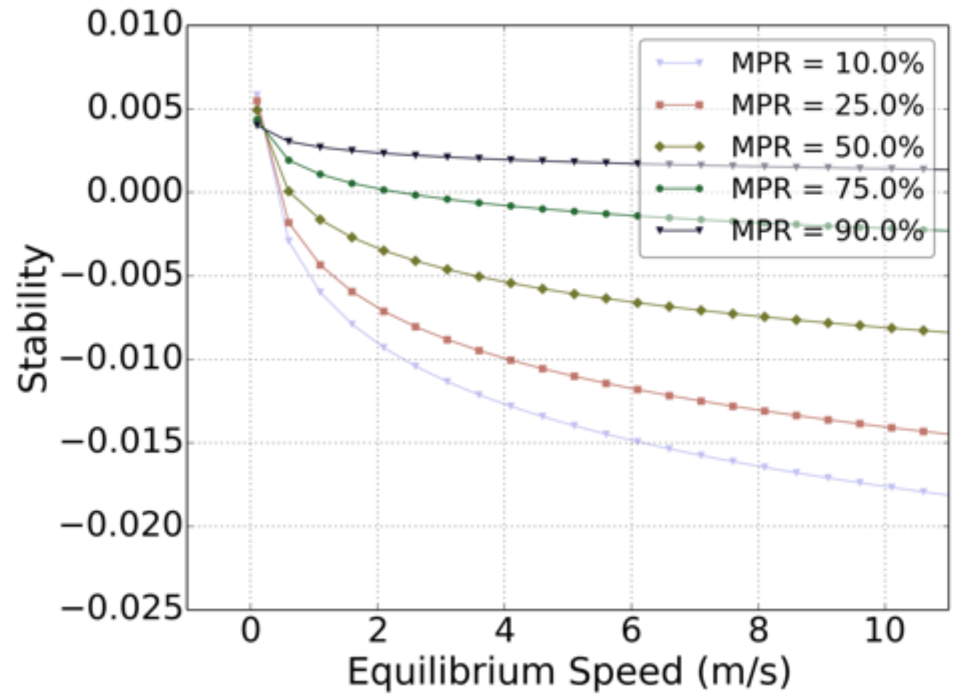
- As the number of connected vehicles increases, stability of the heterogeneous traffic flow increases.



Connected and Regular Vehicles

Stability Analysis
Heterogeneous Traffic Flow

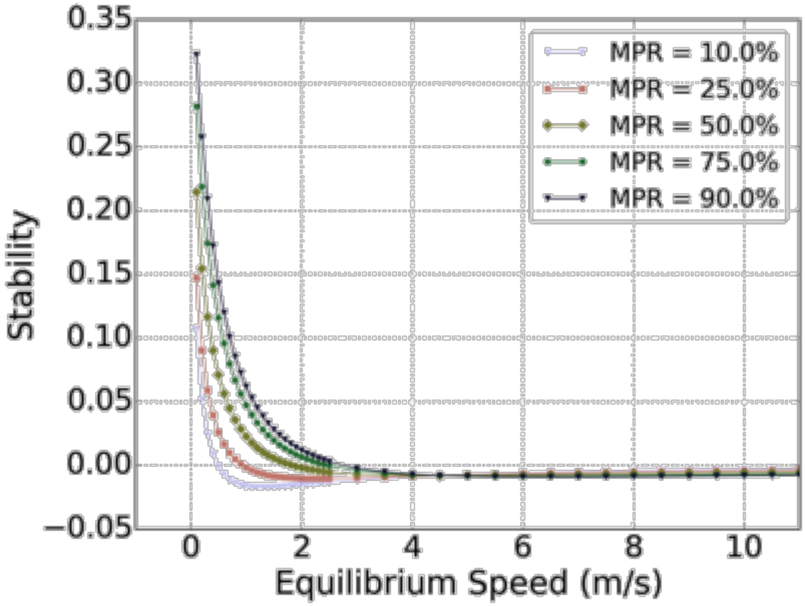
- Parameters of regular vehicles are adjusted to create a very unstable traffic flow.
- As the number of automated vehicles increases, stability of the heterogeneous traffic flow increases.



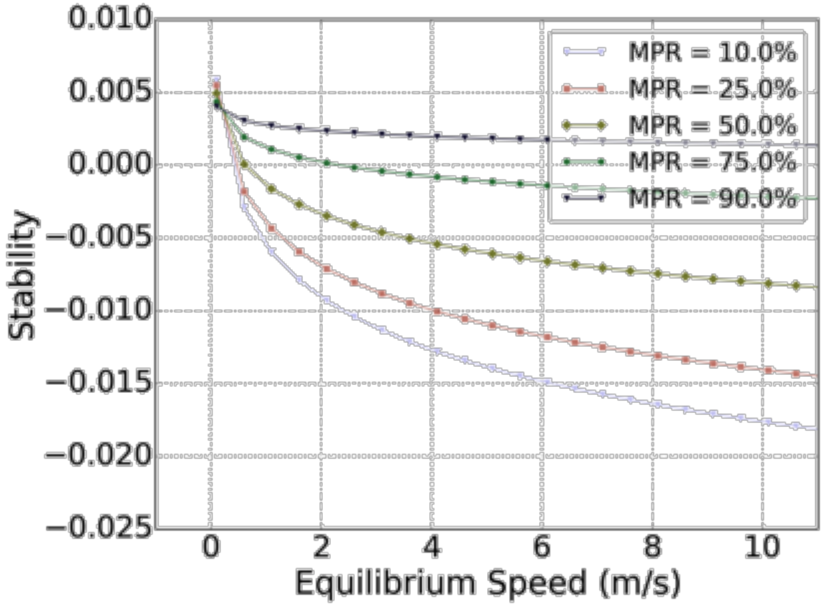
Automated and Regular Vehicles

Stability Analysis
Heterogeneous Traffic Flow

Connected and Regular Vehicles



Automated and Regular Vehicles



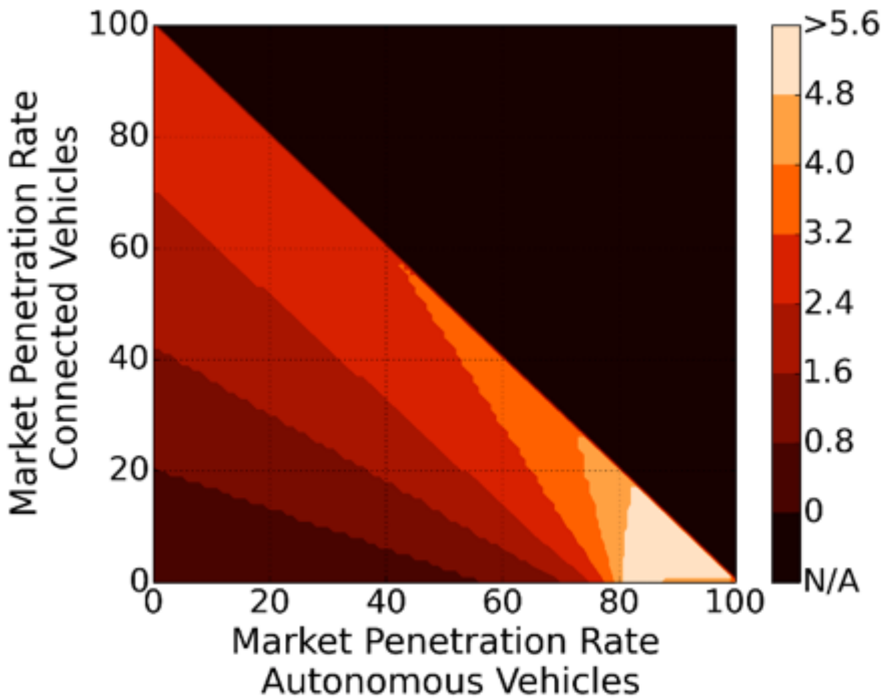
At high market penetration rates, The effect of autonomous vehicles on stability is more pronounced than the effect of connected vehicles.

Stability Analysis
Heterogeneous Traffic Flow

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

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

Market penetration rate of connected vehicles



Automated, Connected, and Regular Vehicles

Stability Analysis

Simulation Segment – Ring Road

- 200 vehicles with 40 meters initial spacing.
- To create perturbation:

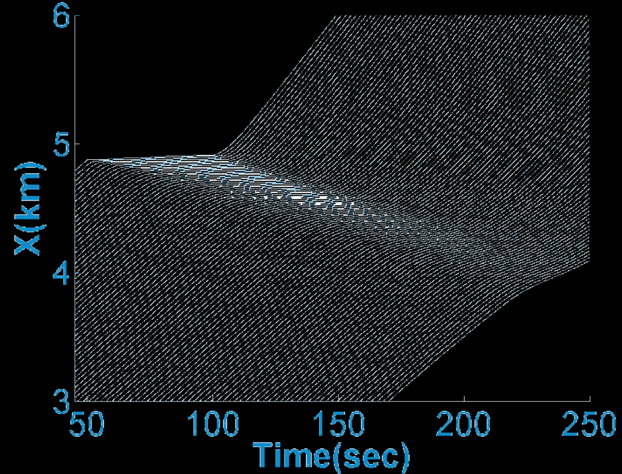
One vehicle is slowed down to $v = 1$ *m/s*

with maximum deceleration (-8 m/s^2).

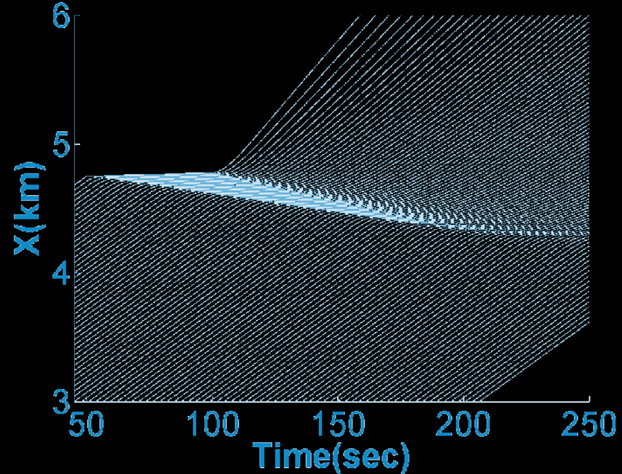
Speed is kept at *1 m/s* for *50 s*.

Stability Analysis

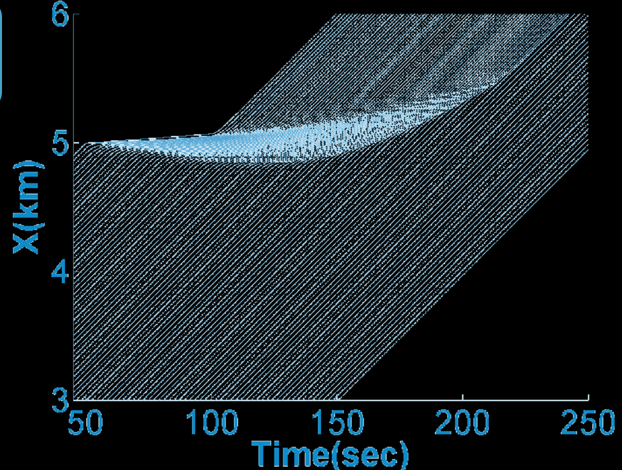
Ring Road Analysis



No Automation
Not Connected



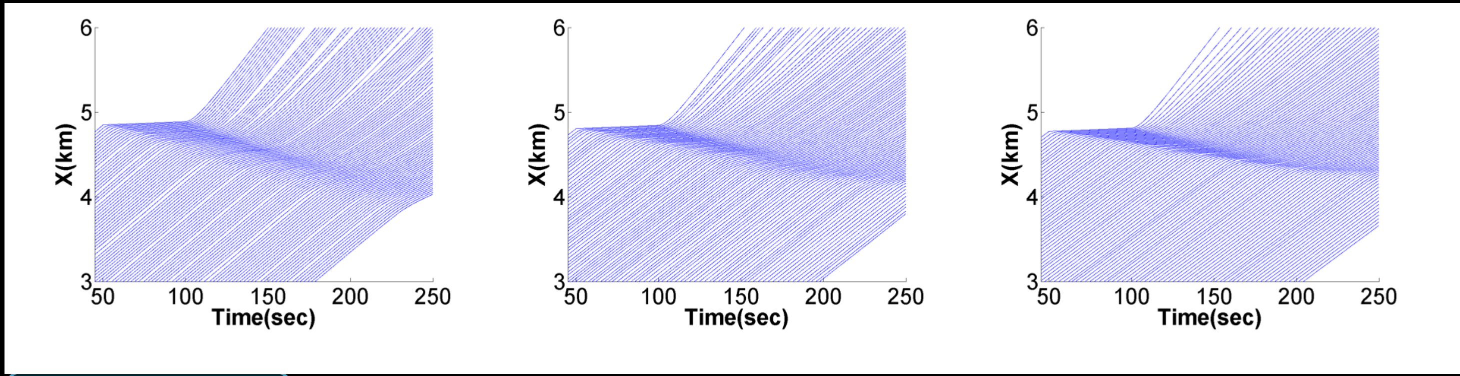
No Automation
Connected



Self-Driving
Not Connected

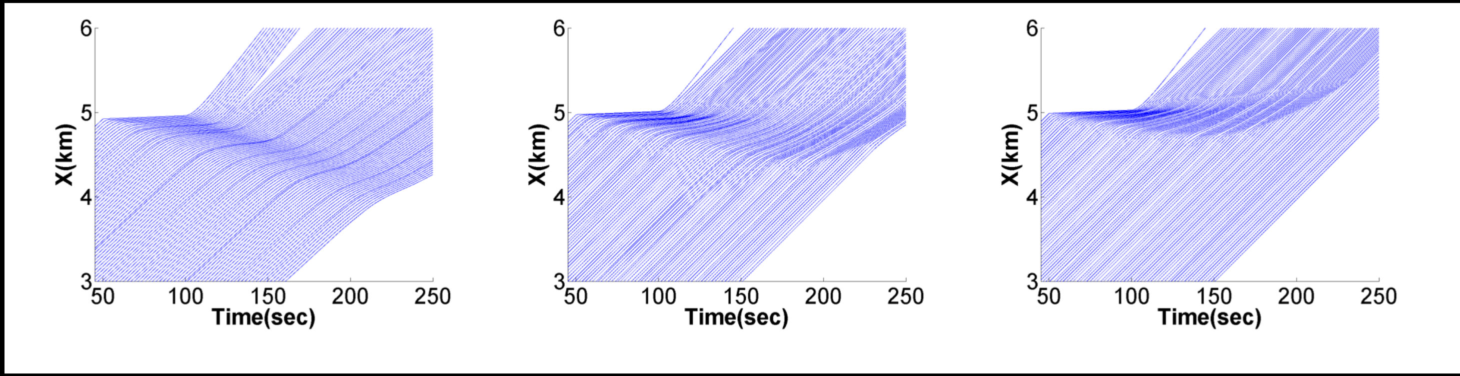
Stability Analysis

Ring Road Analysis



No Automation Connected

Market Penetration Rates of Connected Vehicles:
10% 50% 90%



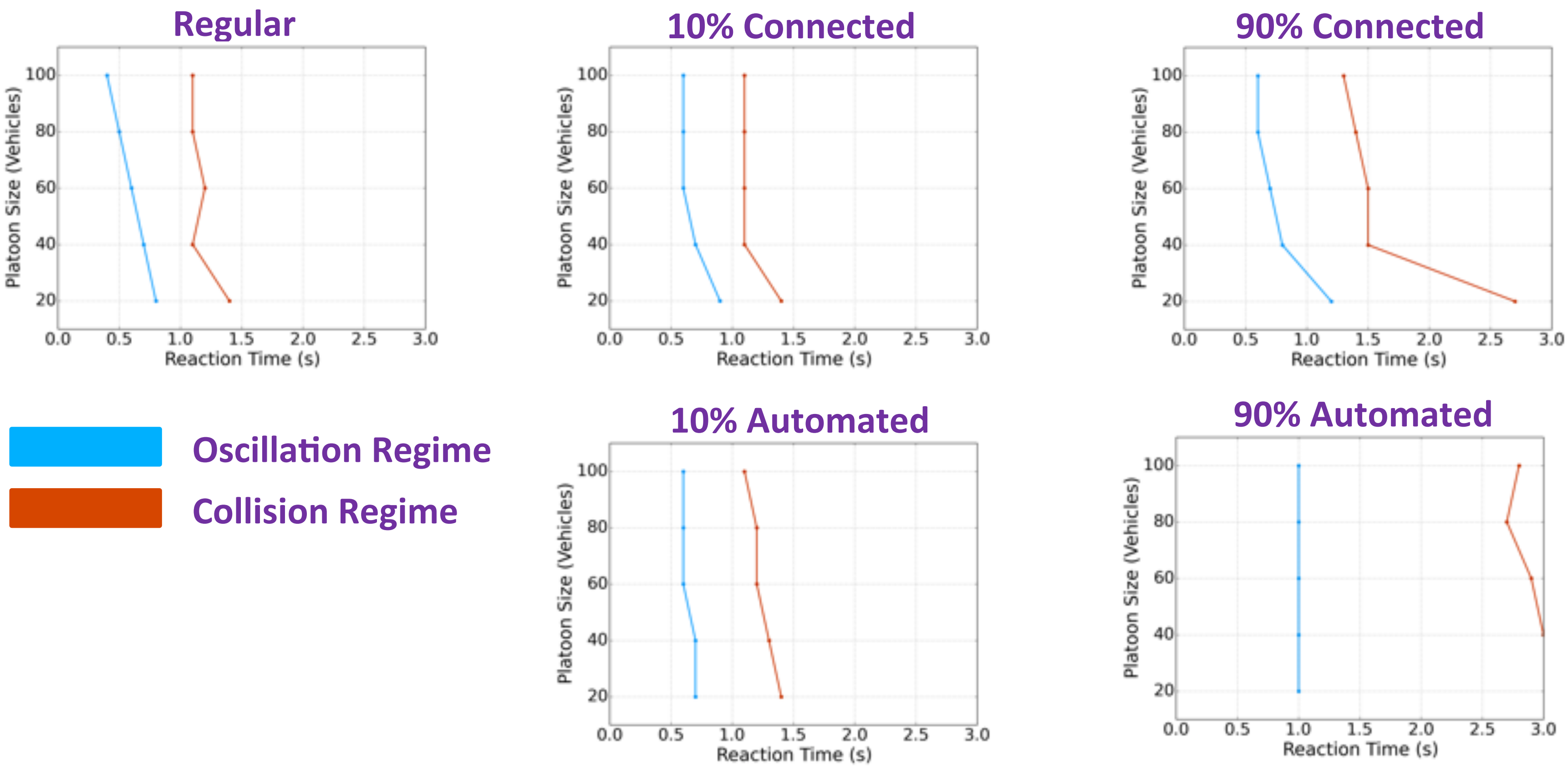
Self-Driving Not Connected

Market Penetration Rates of Autonomous Vehicles:
10% 50% 90%

Stability Analysis
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.



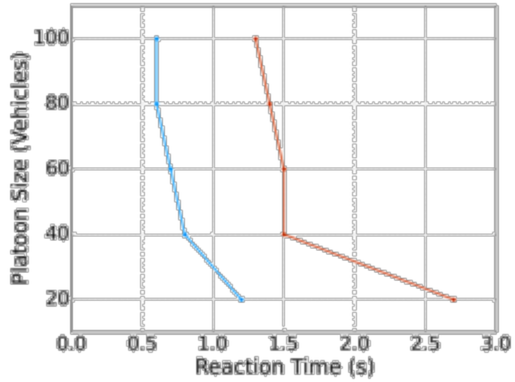
Stability Analysis
Simulation Results

Oscillation and collision thresholds increase as platoon size decreases.

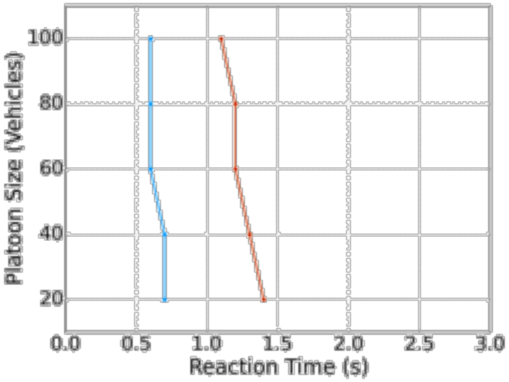
Oscillation and collision thresholds increase as market penetration rate increases.

At high market penetration rates, Autonomous vehicles have more positive effect on both oscillation and collision thresholds compared to connected vehicles.

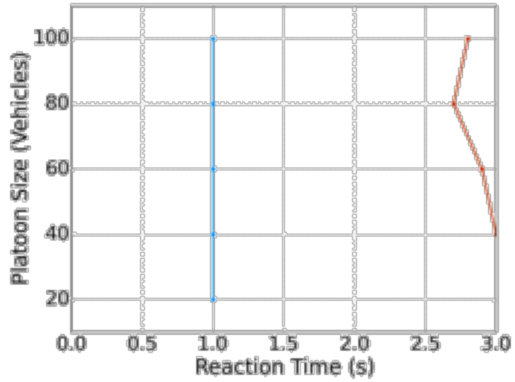
90% Connected



10% Automated



90% Automated



Stability Analysis
Summary

The presented acceleration framework is string stable.

Analytical investigations show that string stability can be improved by the addition of connected and automated vehicles.

- Improvements are observed at low market penetration rates of connected vehicles (unlike automated vehicles).

- At high market penetration rates, automated vehicles have more positive impact on stability compare to connected vehicles.

Simulation results revealed that

- Oscillation and collision thresholds increase as platoon size decreases.
- Oscillation and collision thresholds increase as market penetration rate increases.
- Automated vehicles have more positive impact on stability compare to connected vehicles.

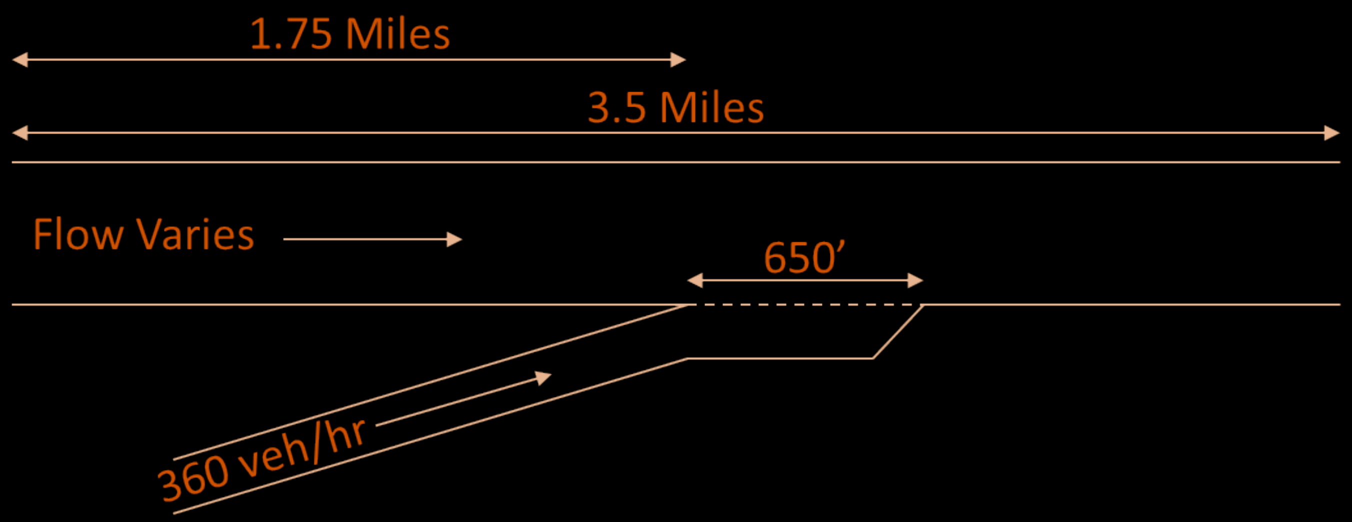
Outline

- Motivation: Autonomous Vehicles, Connected Systems
- Adoption Factors: A Speculative Conceptualization
- Autonomous Vehicles and Planning Models
- Flow Implications
  - Research Questions
  - Simulation Approach: Traffic, Wireless Communication
- Stability Analysis:
  - Analytical Approach
  - Simulation Results Trajectory Processor for particle-based simulators
- **Throughput Analysis: Simulation Results**
- Takeways, Limitations and Challenges

THROUGHPUT AND FLOW-DENSITY

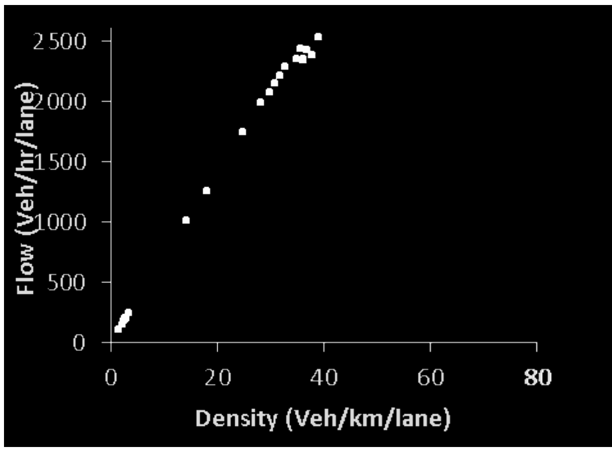
SIMULATION SEGMENT

The average breakdown flow in a series of simulations is considered as the bottleneck capacity.

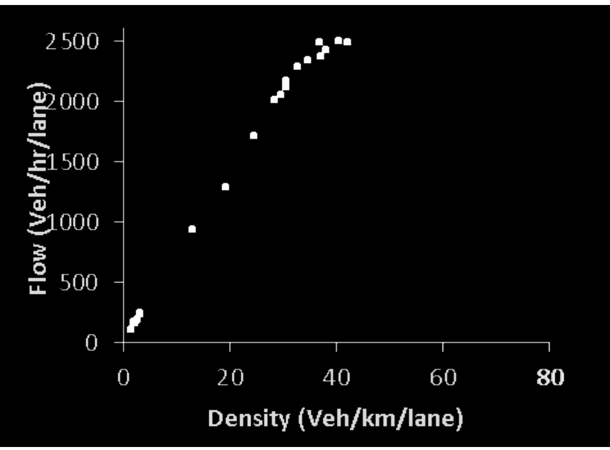


THROUGHPUT and SPEED-DENSITY RELATION

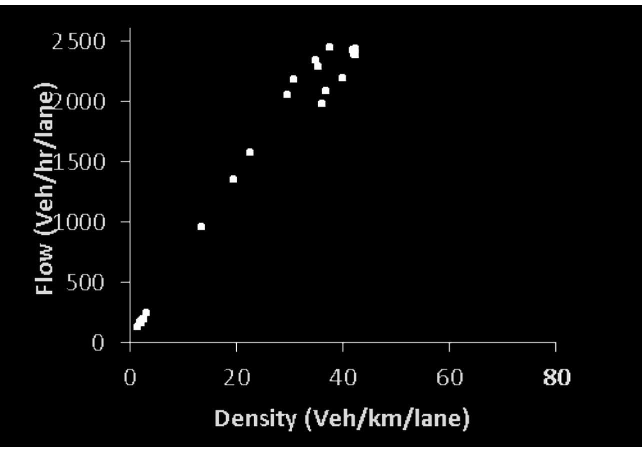
SENSITIVITY ANALYSIS – MIXED ENVIRONMENT



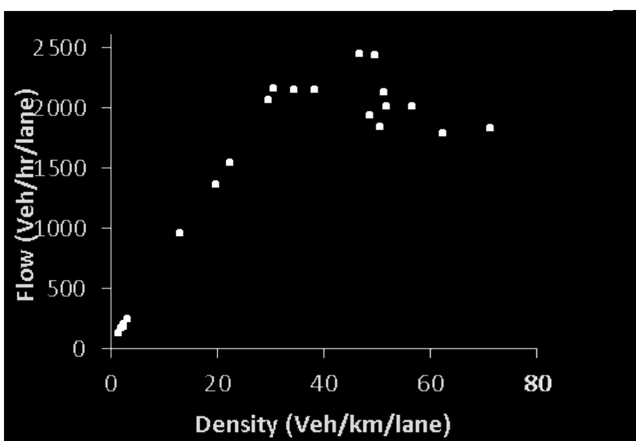
10% R– 0% C – 90% A



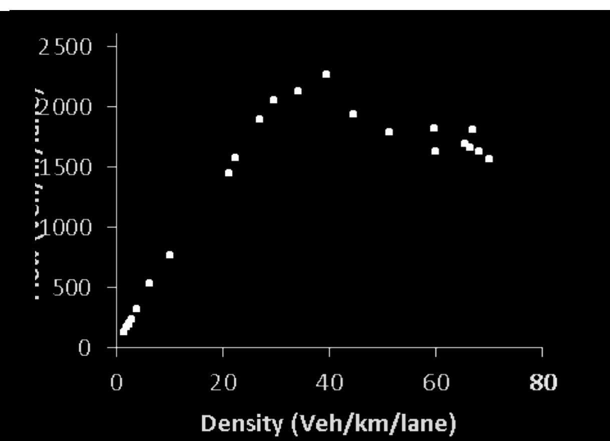
10% R– 20% C – 70% A



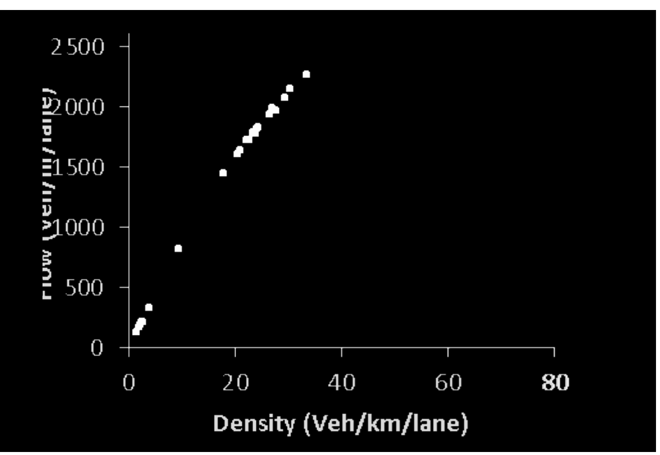
10% R– 40% C – 50% A



10% R– 50% C – 40% A



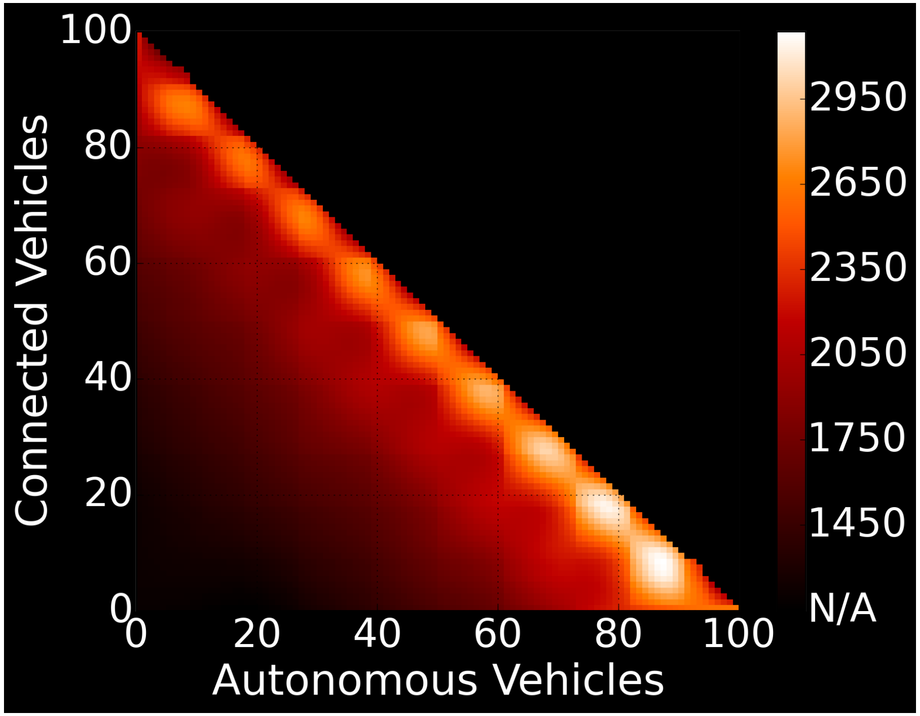
10% R– 70% C – 20% A



10% R– 90% C – 0% A

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

Conclusion (Traffic flow aspects)

The presented acceleration framework is string stable; greater autonomous vehicle penetration increases stability (faster decay of perturbations).

Connected Vehicles / Autonomous 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.

From eliminating/delaying breakdown formation stand point:

Autonomous Vehicles are more effective than Connected Vehicles

Important Caveat

THERE ARE MANY DIFFERENT WAYS OF IMPLEMENTING THE TECHNOLOGIES, ESPECIALLY WITH REGARD TO DRIVING AND FLOW CONTROL.

Simulation testbeds can help evaluate alternatives and examine implications.

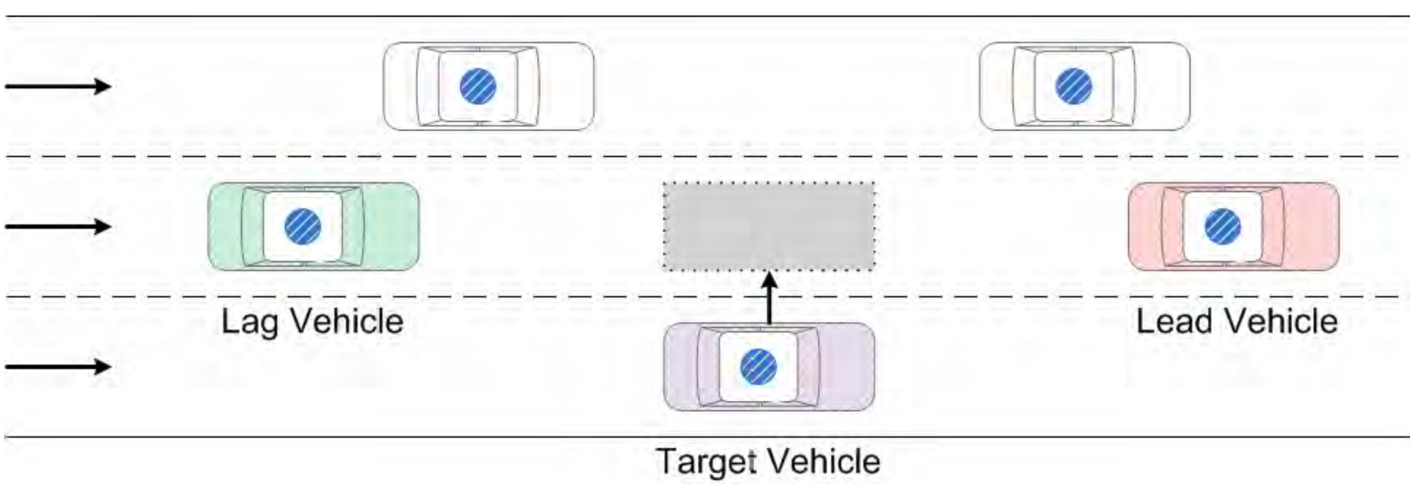
Lane-Changing Framework

It is assumed that V2V can provide information about the nature of lane-changing maneuvers:

Discretionary lane-changing vs. Mandatory lane-changing

A game-theoretical approach is adopted with the following pure strategies:

- Lag vehicle: Accelerate, Decelerate, Change Lane
- Target Vehicle : Change Lane, Do not Change Lane



Lane-Changing Framework

Inactive V2V Communications

Without information, drivers are uncertain about the nature of other drivers' lane-changing maneuvers.

*Two-person non-zero-sum non-cooperative game under **incomplete information**.*

"Harsanyi Transformation" is used to solve the game with incomplete information:

- "Harsanyi Transformation" transforms the lag vehicle's *incomplete* information about the nature of each lane-changing maneuver into *imperfect* information about the move by nature.

- "Nature" as a player chooses the type of each lane-changing maneuver.
  - *Lane-changing is mandatory with probability p and discretionary with probability (1-p)*

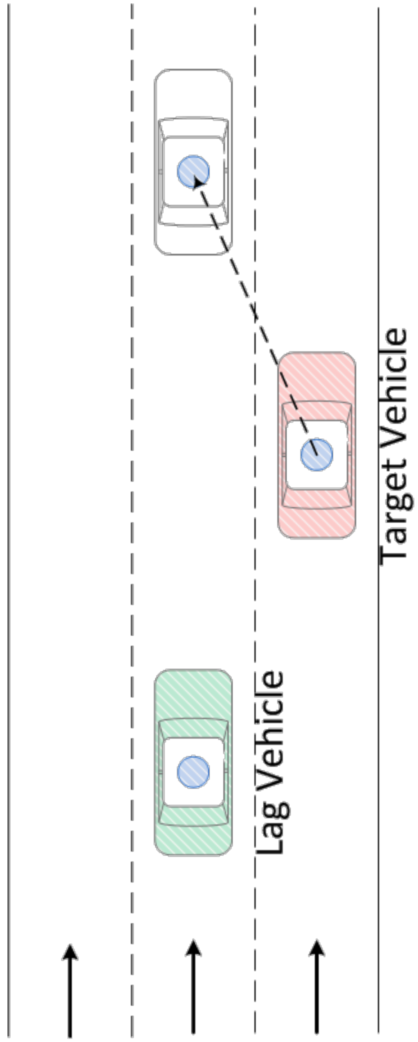
Lane-Changing Framework
Inactive V2V Communications

Discretionary lane-changing game in normal form

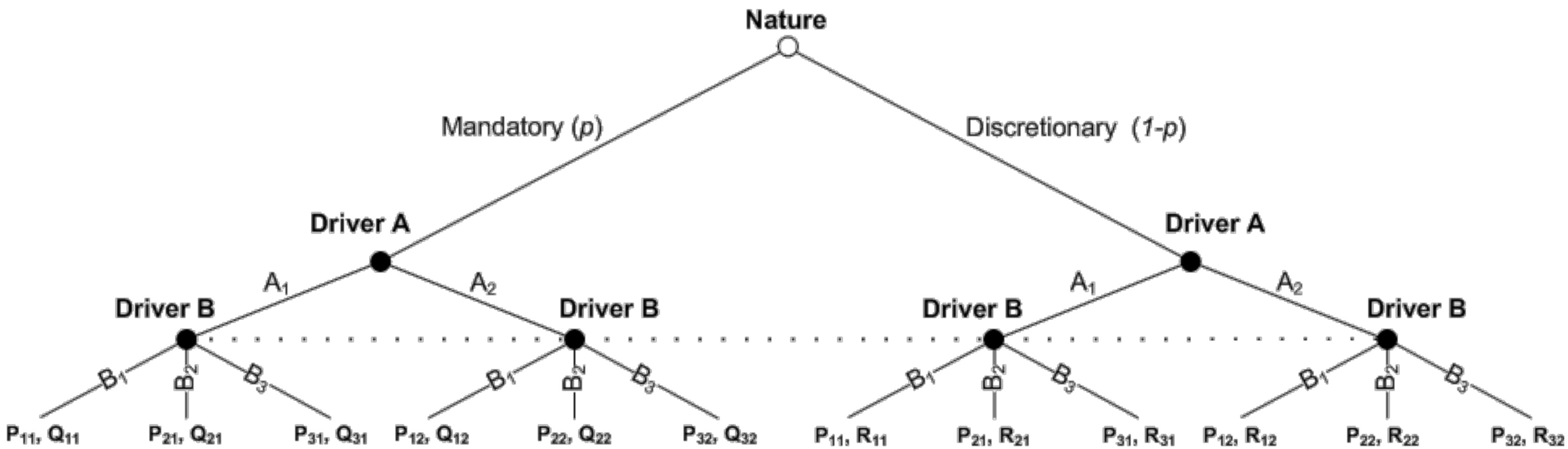
ACTION		Target Vehicle	
		A_1 (Change Lane)	A_2 (Do not Change Lane)
Lag Vehicle	B_1 (Accelerate)	(P_{11}, R_{11})	(P_{12}, R_{12})
	B_2 (Decelerate)	(P_{21}, R_{21})	(P_{22}, R_{22})
	B_3 (Change Lane)	(P_{31}, R_{31})	(P_{32}, R_{32})

Mandatory lane-changing game in normal form

ACTION		Target Vehicle	
		A_1 (Change Lane)	A_2 (Do not Change Lane)
Lag Vehicle	B_1 (Accelerate)	(P_{11}, Q_{11})	(P_{12}, Q_{12})
	B_2 (Decelerate)	(P_{21}, Q_{21})	(P_{22}, Q_{22})
	B_3 (Change Lane)	(P_{31}, Q_{31})	(P_{32}, Q_{32})



Lane-Changing Framework
Inactive V2V Communications



ACTION		Target Vehicle			
		$A_1^M A_1^D$	$A_1^M A_2^D$	$A_2^M A_1^D$	$A_2^M A_2^D$
Lag Vehicle	B_1 (Accelerate)	$(P_{11},\ pQ_{11}+(1-p)R_{11})$	$(pP_{11}+(1-p)P_{21},\ pQ_{11}+(1-p)R_{21})$	$(pP_{12}+(1-p)P_{11},\ pQ_{12}+(1-p)R_{11})$	$(P_{12},\ pQ_{12}+(1-p)R_{12})$
	B_2 (Decelerate)	$(P_{21},\ pQ_{21}+(1-p)R_{21})$	$(pP_{21}+(1-p)P_{22},\ pQ_{21}+(1-p)R_{22})$	$(pP_{22}+(1-p)P_{21},\ pQ_{22}+(1-p)R_{21})$	$(P_{22},\ pQ_{22}+(1-p)R_{22})$
	B_3 (Change Lane)	$(P_{31},\ pQ_{31}+(1-p)R_{31})$	$(pP_{31}+(1-p)P_{32},\ pQ_{31}+(1-p)R_{32})$	$(pP_{32}+(1-p)P_{31},\ pQ_{32}+(1-p)R_{31})$	$(P_{32},\ pQ_{32}+(1-p)R_{32})$

Lane-Changing Framework
Active V2V Communications

With information, drivers are certain about the nature of other drivers' lane-changing maneuvers.

Two-person non-zero-sum non-cooperative game under *complete* information**.**

ACTION		Target Vehicle	
		A_1 (Change Lane)	A_2 (Do not Change Lane)
Lag Vehicle	B_1 (Accelerate)	$(P_{11}, Q_{11} or R_{11})$	$(P_{12}, Q_{12} or R_{12})$
	B_2 (Decelerate)	$(P_{21}, Q_{21} or R_{21})$	$(P_{22}, Q_{22} or R_{22})$
	B_3 (Change Lane)	$(P_{31}, Q_{31} or R_{31})$	$(P_{32}, Q_{32} or R_{32})$

Lane-Changing Framework
Payoff Functions

Payoff matrix of the target vehicle

ACTION		Target Vehicle	
		A_1 (Change Lane)	A_2 (Do not Change Lane)
Lag Vehicle	B_1 (Accelerate)	$\eta_1.Acc^{C}_{Target} + \eta_2.\Delta V + \varepsilon_{11}$	$0 + \varepsilon_{12}$
	B_2 (Decelerate)	$\eta_1.Acc^{C}_{Target} + \eta_2.\Delta V + \varepsilon_{21}$	$0 + \varepsilon_{22}$
	B_3 (Change Lane)	$\eta_2.\Delta V + \varepsilon_{31}$	$0 + \varepsilon_{32}$

Payoff matrix of the lag vehicle

ACTION		Target Vehicle	
		A_1 (Change Lane)	A_2 (Do not Change Lane)
Lag Vehicle	B_1 (Accelerate)	$\eta_3.Acc^{C}_{Target} + \delta_{11}$	$\eta_3.Acc^{C}_{Lead} + \delta_{12}$
	B_2 (Decelerate)	$\eta_4.Acc^{Y}_{Target} + \delta_{21}$	$\eta_4.Acc^{Y}_{Lead} + \delta_{22}$
	B_3 (Change Lane)	$\eta_1.Acc^{C}_{Target} + \eta_2.\Delta V + \delta_{31}$	

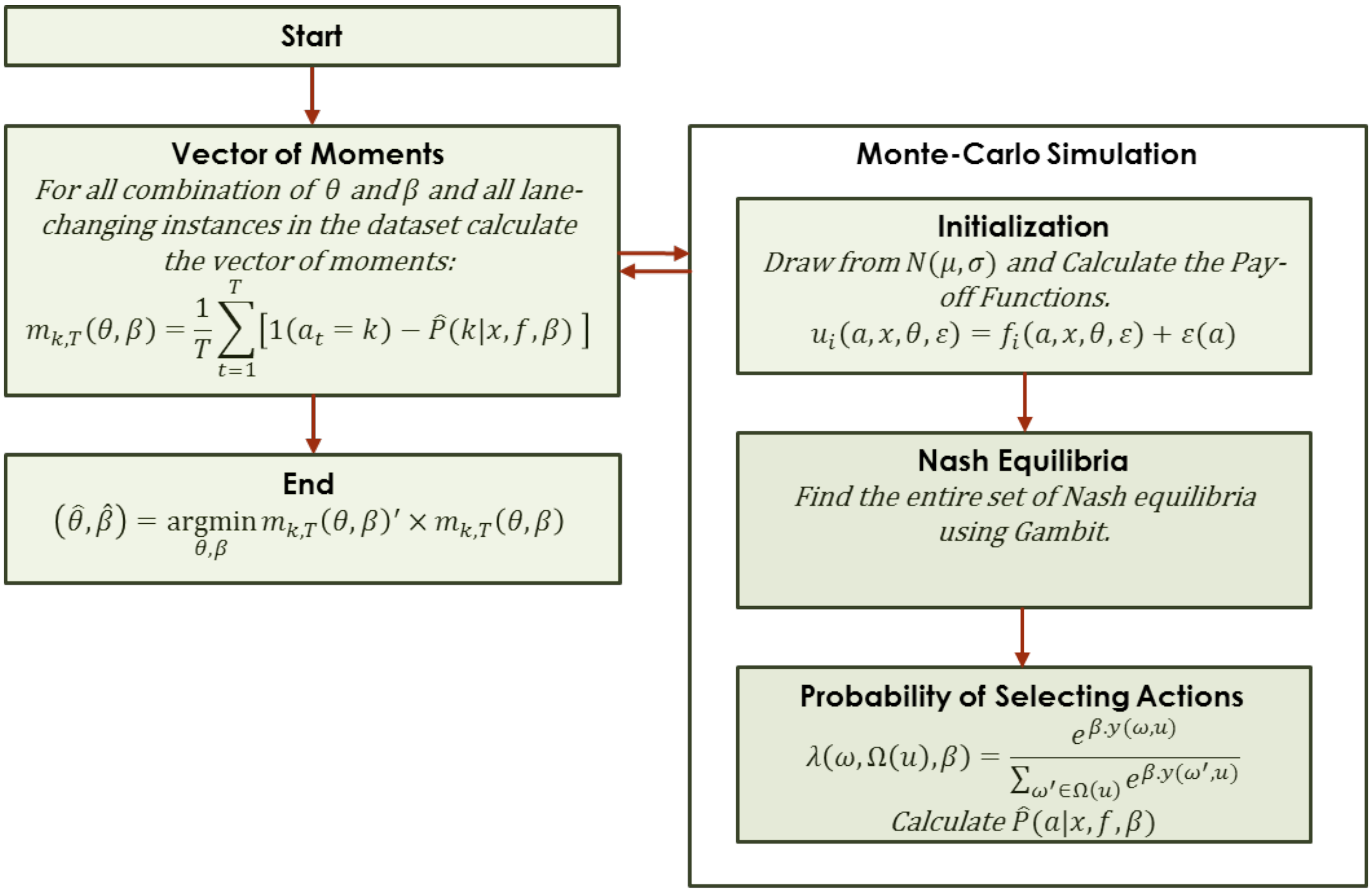
Acc^{C}_{Target} : Acceleration to prevent collision for the lag vehicle considering the target vehicle as the leader.

Acc^{Y}_{Lead} : -3.05 m/s²

ΔV : Speed difference between the old leader and the new leader

Lane-Changing Framework

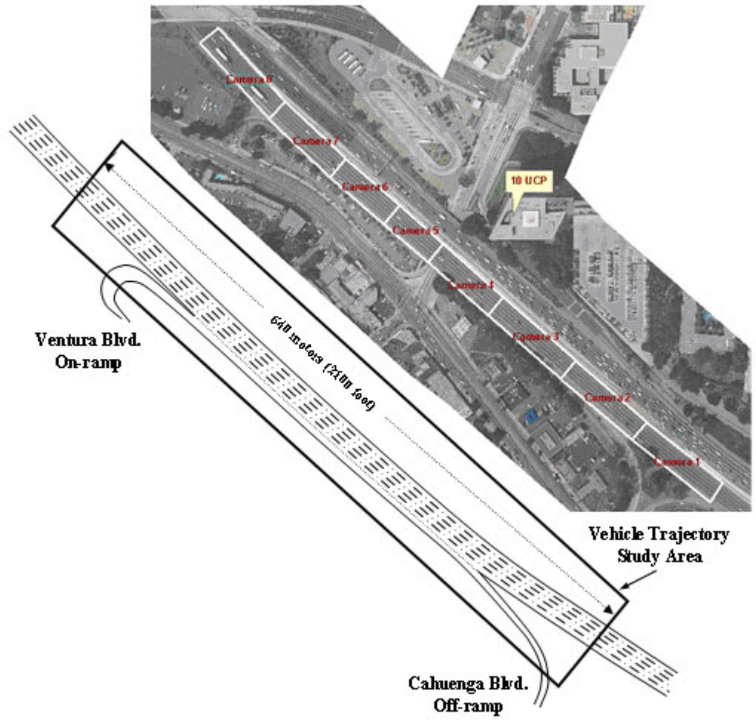
Calibration – Method of Simulated Moments



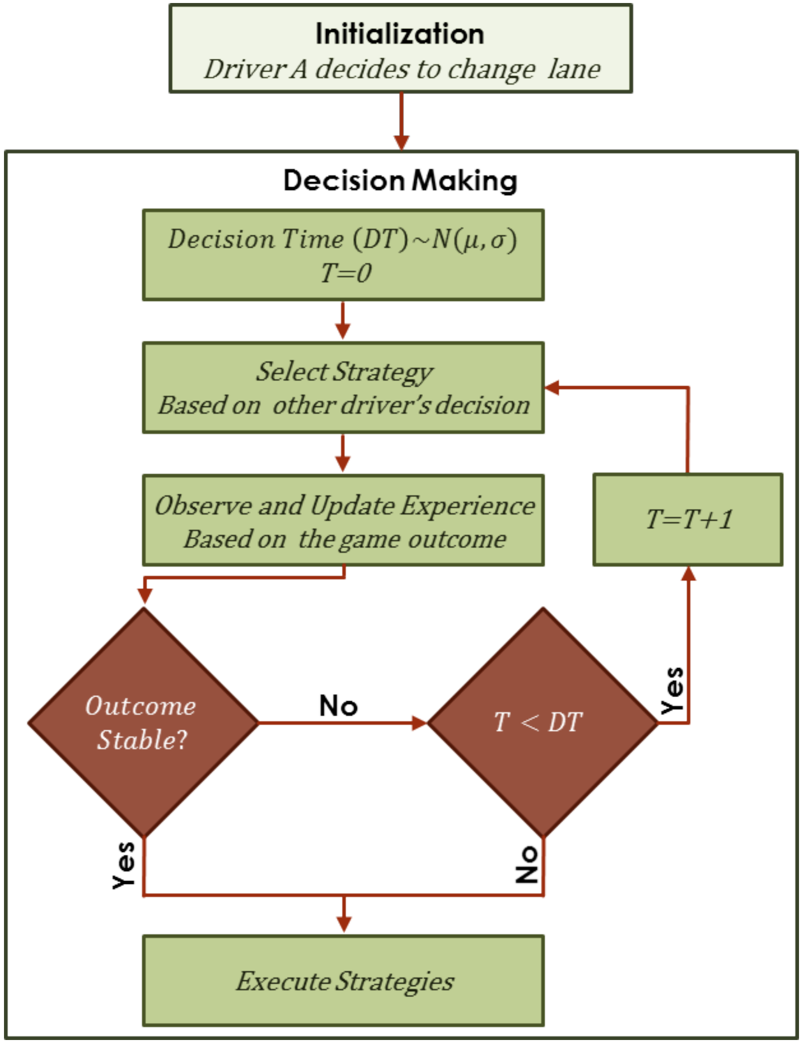
Lane-Changing Framework
Calibration Results

Discretionary Lane-changing	
Parameter	**Calibrated Value**
η_1	-0.750
η_2	0.875
η_3	-0.750
η_4	0.125
β	1.000
Mean Absolute Error (MAE)	0.383

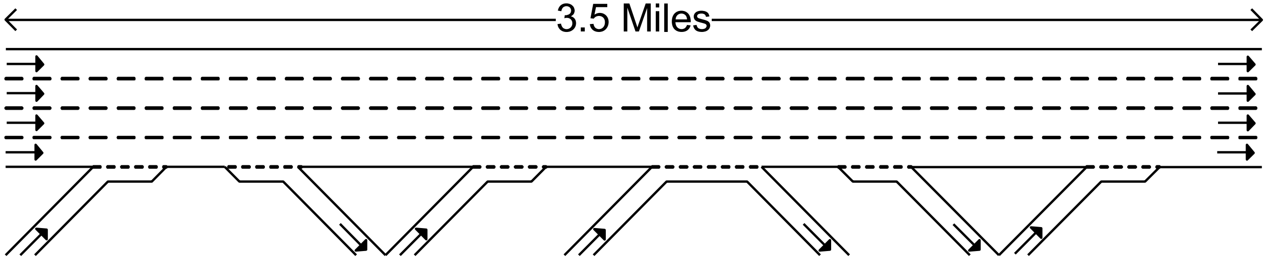
Mandatory Lane-changing	
Parameter	**Calibrated Value**
η_1	-0.875
η_2	0.375
η_3	-0.625
η_4	0.25
β	1.000
Mean Absolute Error (MAE)	0.059



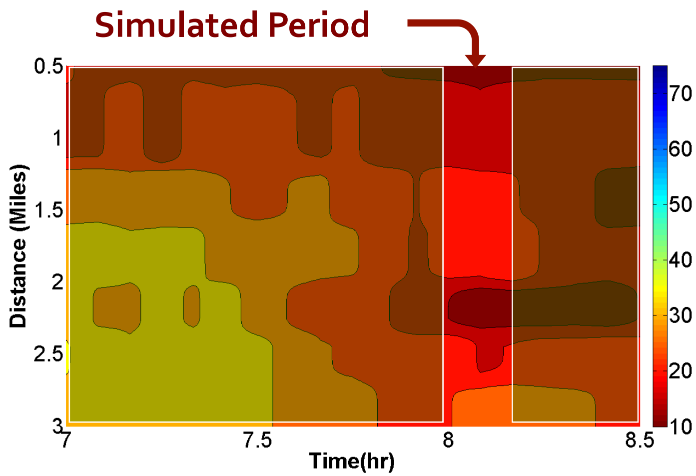
Lane-Changing Framework
Simulation – Fictitious Play



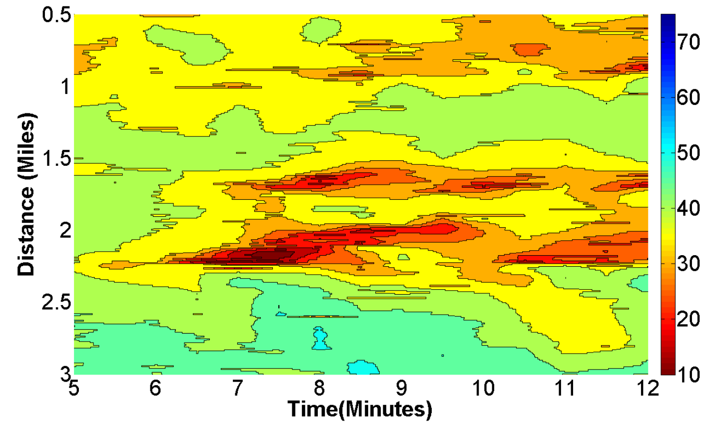
Lane-Changing Framework
Simulation Segment



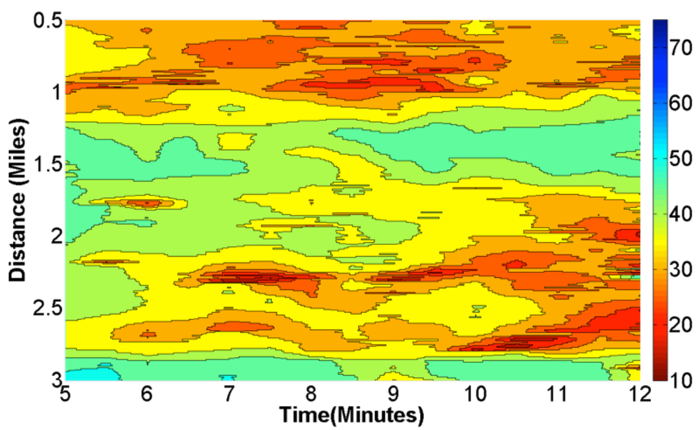
Lane-Changing Framework
Simulation Results



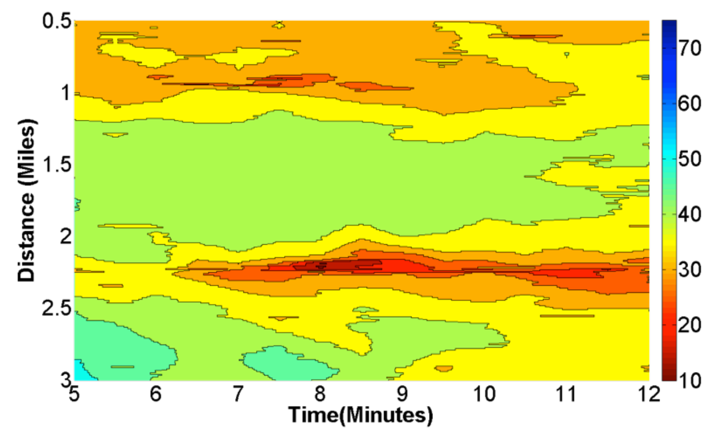
Loop Detector Data



MOBIL



Gap-Acceptance Model



Game Theory Based Model

ARE WE THERE YET? WHO IS READY?

1. Technology is here and now; "Big Tech" and "New Tech" is in the lead– ready to market within 3-5 years.

2. Automotive players– wide range ("*waiting on standards*")
   - Connectivity in vehicles here and now;
   - Driver-assist features already in high-end vehicles;
   - Semi-autonomous in 3~5 yrs.
   - Fully-autonomous: Special uses (freight, internal transit) by 2020

3. System Integrators: more hype than deployment; not quite there yet.

4. Insurance, Legal: surprisingly nimble

5. LEAST READY: Government agencies; biggest hurdles on system aspects, public sector side

6. Many challenges ahead, and many more opportunities

We Love Feedback

Questions/Comments

Email: masmah@northwestern.edu

Follow Me

Twitter @b_rational

Connect with NUTC