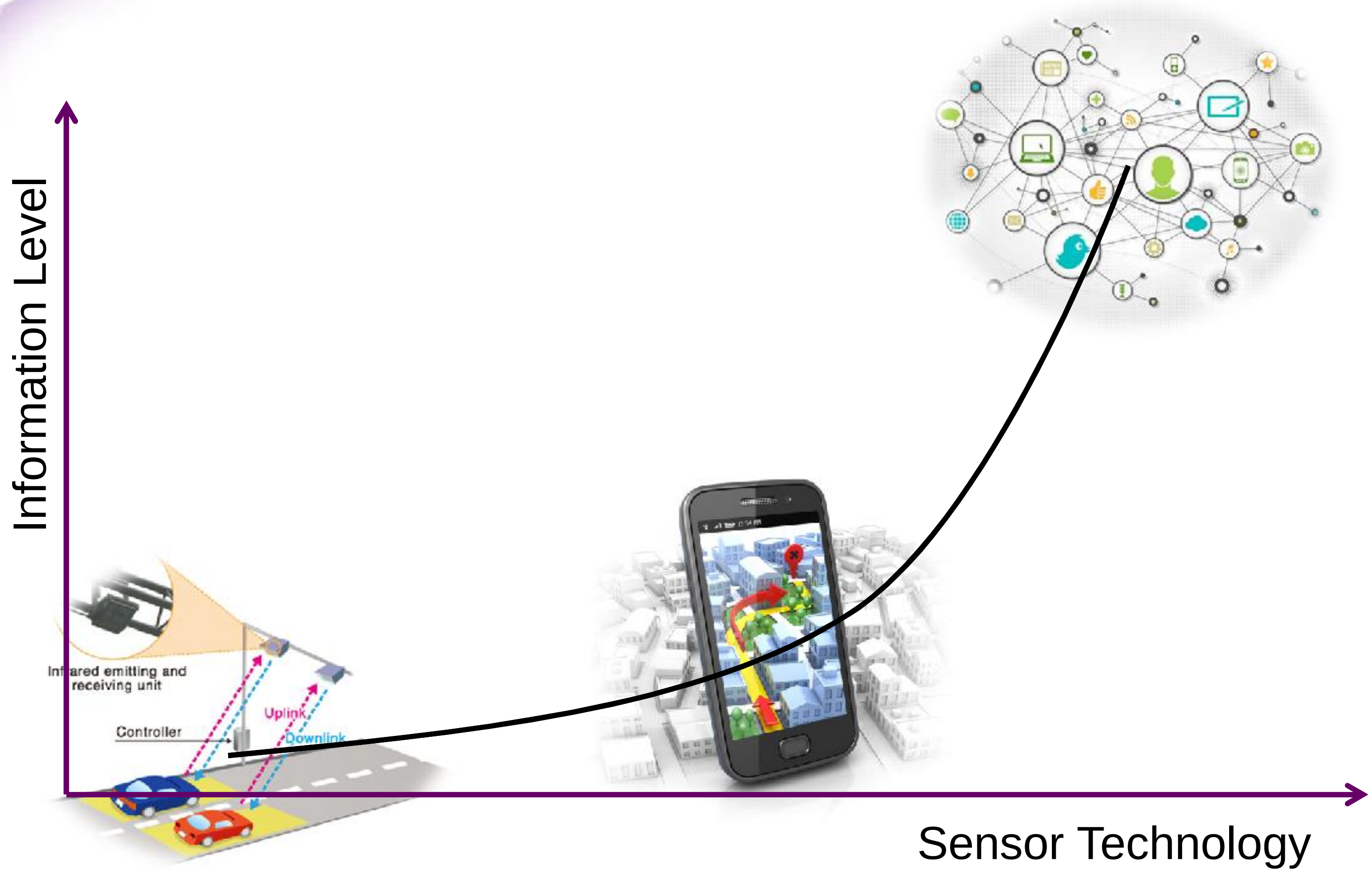
Modeling Driver Behavior in a Connected Environment
Integration of Microscopic Traffic Simulation and Telecommunication Systems

Alireza Talebpour

NORTHWESTERN UNIVERSITY

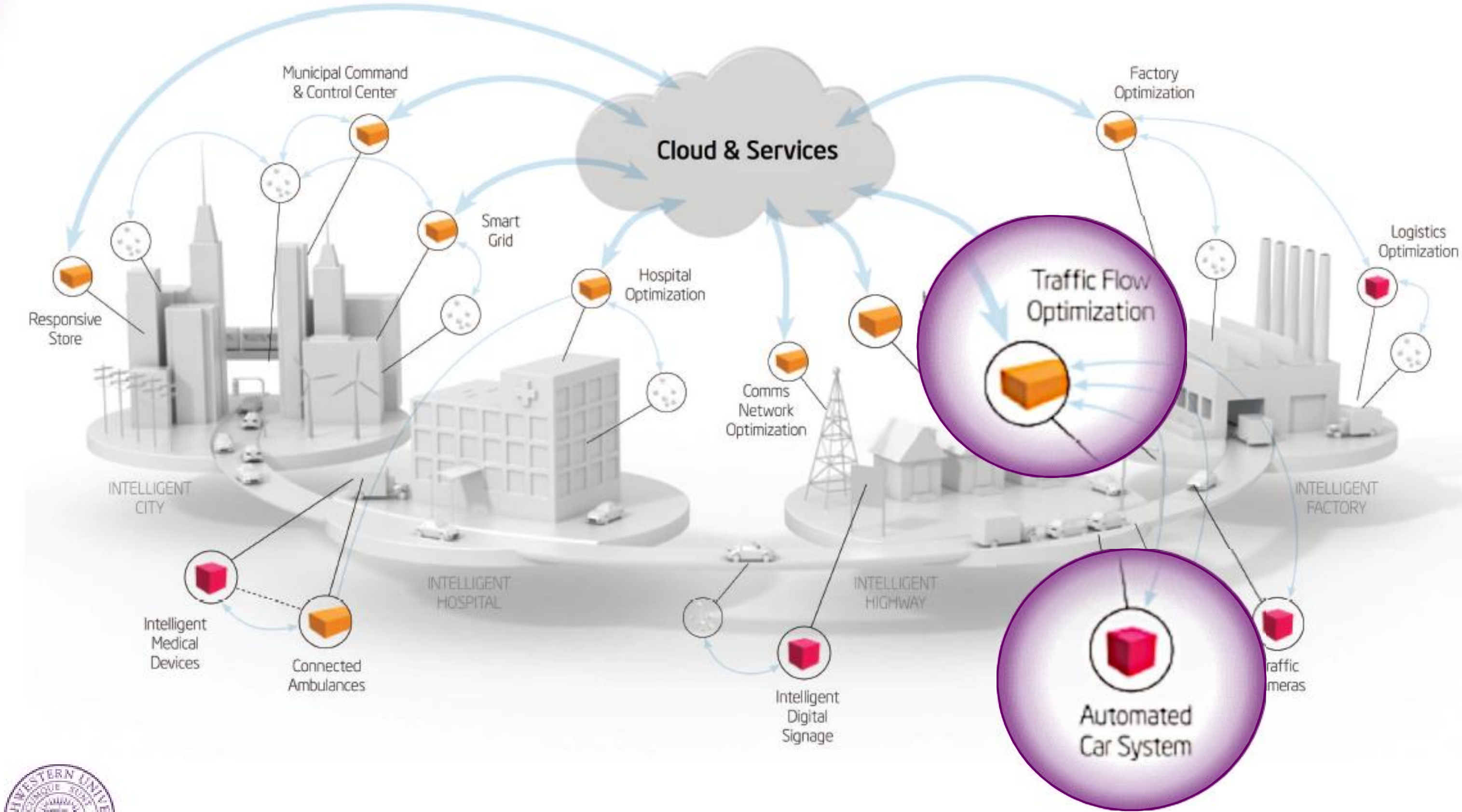
Connectivity in the Modern Age



NORTHWESTERN UNIVERSITY

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

Smart Cities Vision



NORTHWESTERN UNIVERSITY

Image Powered by Intel

Automated vs. Connected

Vehicle Operation

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

CONNECTIVITY

- Improve drivers' strategic and operational decisions.

Vehicle-to-Vehicle (V2V) Communications

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

Vehicle-to-Infrastructure (V2I) Communications

- Improve drivers' strategic decisions.

NORTHWESTERN UNIVERSITY

Automated vs. Connected

Vehicle Operation

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

CONNECTIVITY

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

Vehicle-to-Vehicle (V2V) Communications

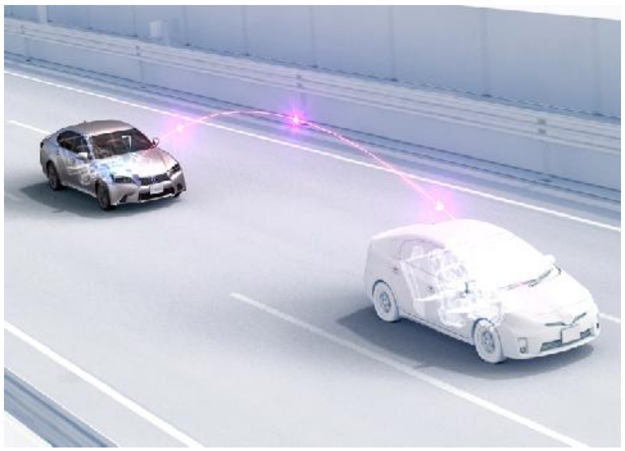
- Improve vehicles' operational decisions.

Vehicle-to-Infrastructure (V2I) Communications

- Improve vehicles' strategic decisions.

NORTHWESTERN UNIVERSITY

Applications for Connectivity



Vehicle-to-Vehicle (V2V) Communications

- Emergency Break Light Warning
- Forward Collision Warning
- Intersection Movement Assist
- Blind Spot and Lane Change Warning

Vehicle-to-Infrastructure (V2I) Communications

- Speed Harmonization
- Intelligent Traffic Signals
- Enable Traveler Information
- Transit Connection
- Incident Management

- Eco-Routing
- Smart Parking
- AFV Charging Stations

NORTHWESTERN UNIVERSITY

Image Source: Lexus and Mercedes

Motivation

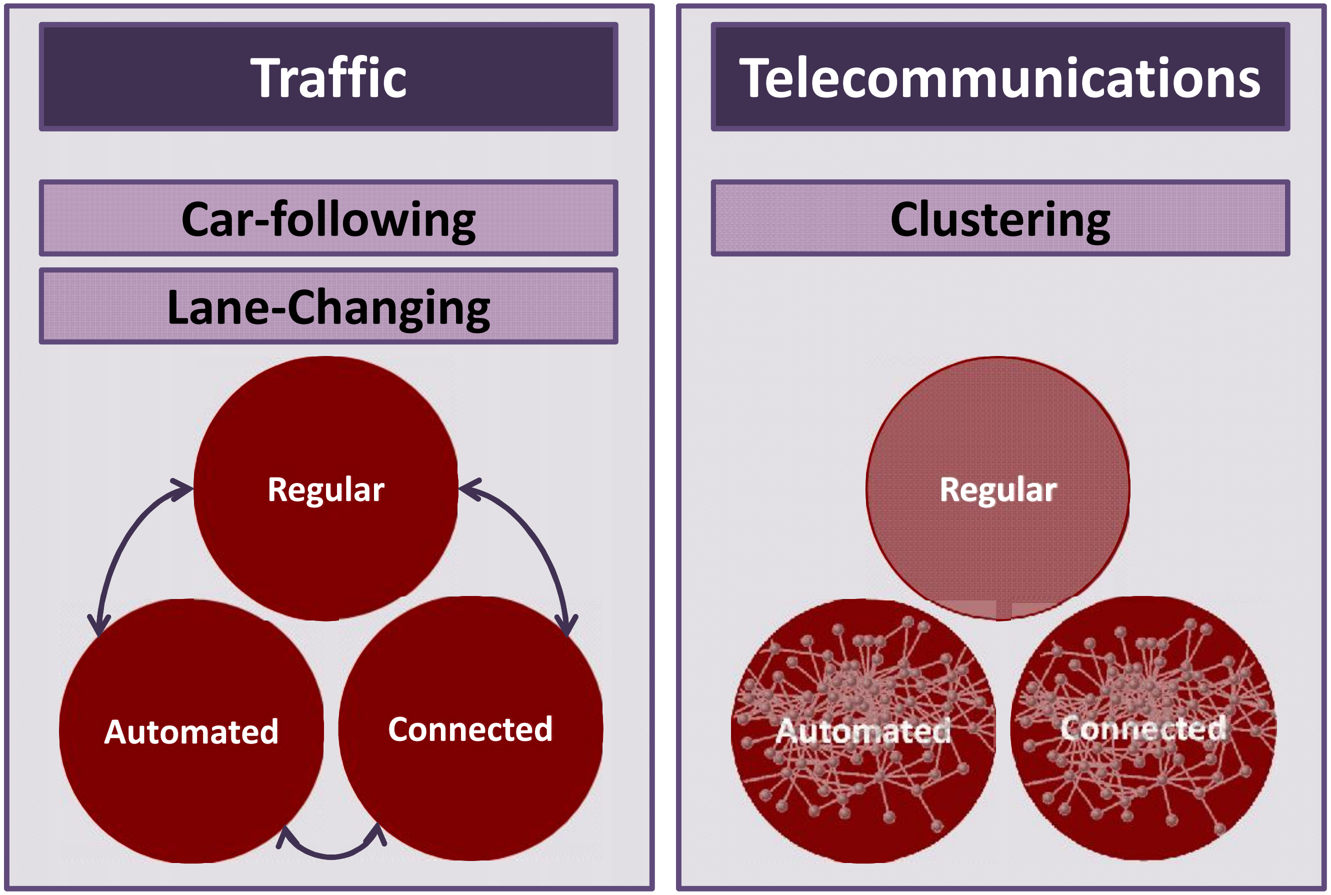
Connected Vehicles technology and Vehicle Automation are two emerging technologies that will change the driving environment and consequently drivers' behavior.

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

However, the extent of these improvements are unknown.

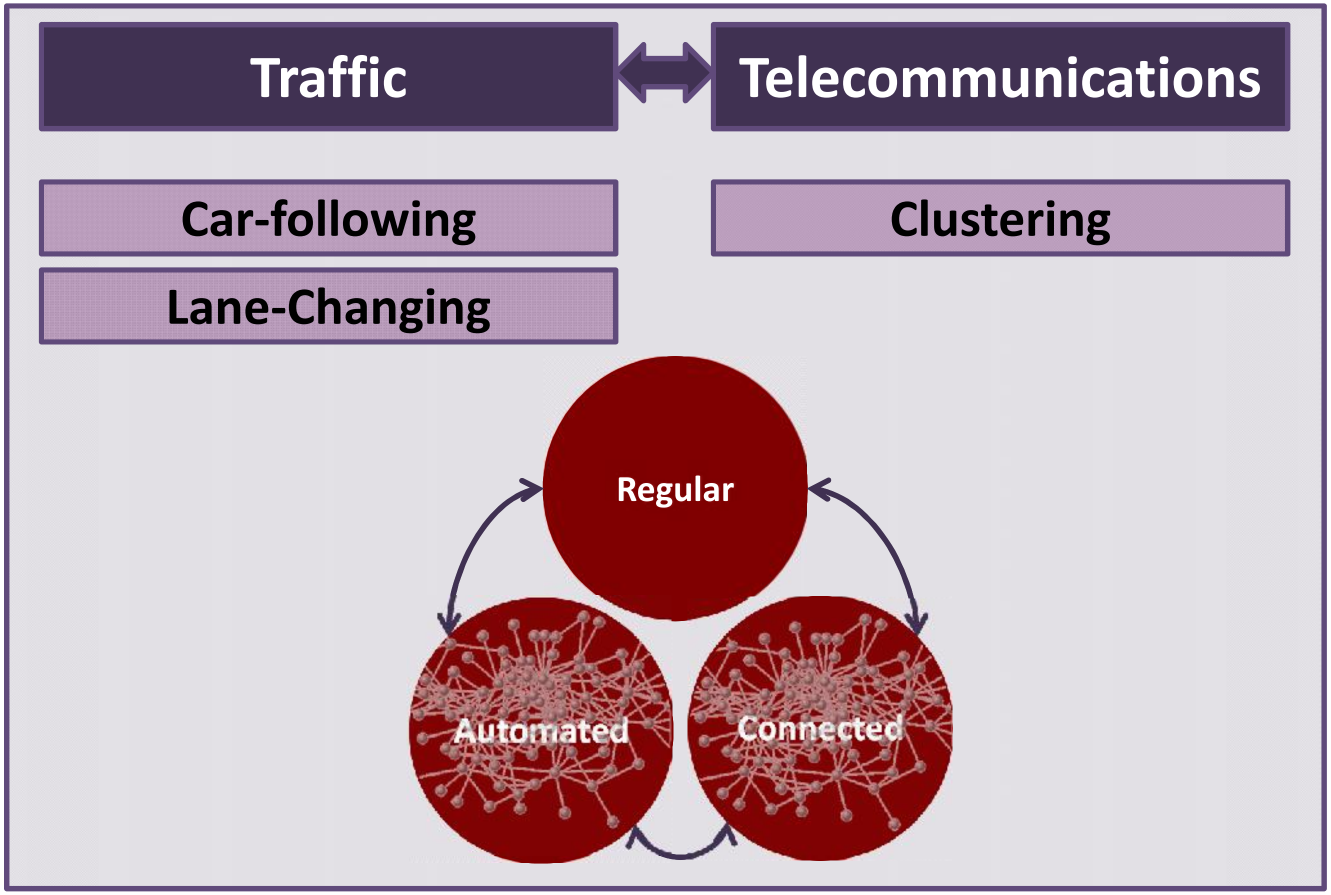
NORTHWESTERN UNIVERSITY

Framework



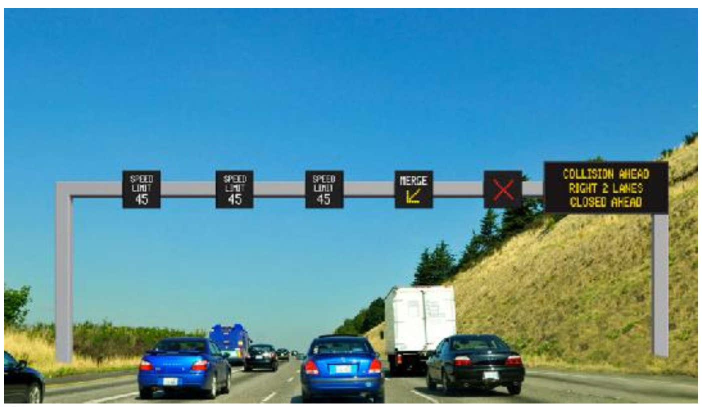
NORTHWESTERN
UNIVERSITY

Framework



NORTHWESTERN
UNIVERSITY

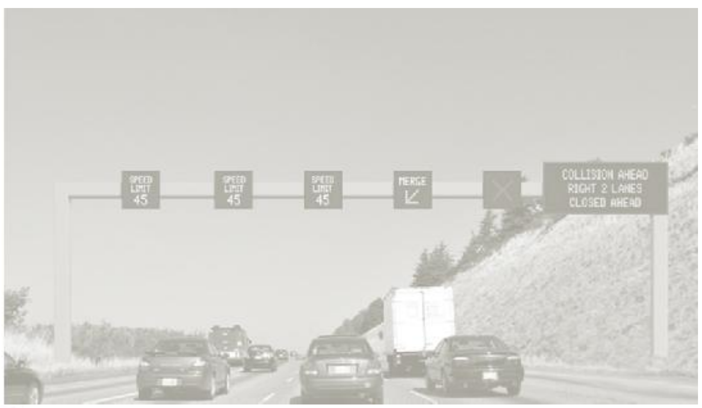
Outline



NORTHWESTERN UNIVERSITY

Image Source: Volvo, Lexus, and USDOT

Outline



NORTHWESTERN UNIVERSITY

Image Source: Volvo, Lexus, and USDOT

Acceleration Framework

No Automation
Not Connected

No Automation
Connected

Self-Driving
Not Connected

NORTHWESTERN
UNIVERSITY

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

NORTHWESTERN UNIVERSITY

Talebpour, A., Mahmassani, H., Hamdar, S., 2011. Multiregime Sequential Risk-Taking Model of Car-Following Behavior. *Transportation Research Record: Journal of the Transportation Research Board* 2260,

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.

NORTHWESTERN UNIVERSITY

Treiber, M., Hennecke, A., Helbing, D., 2000. Congested traffic states in empirical observations and microscopic simulations. *Physical Review E* 62(2), 1805-1824.

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".

NORTHWESTERN
UNIVERSITY

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

NORTHWESTERN UNIVERSITY

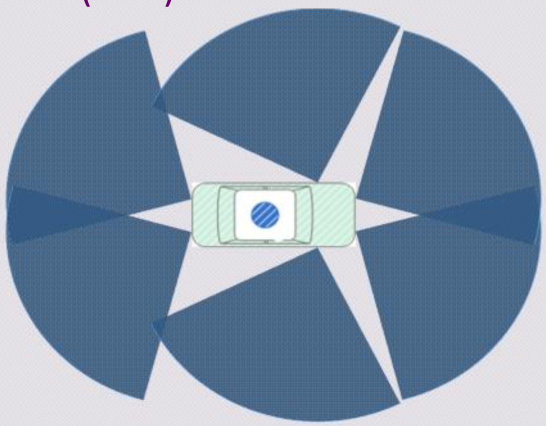
Acceleration Framework

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).



NORTHWESTERN
UNIVERSITY

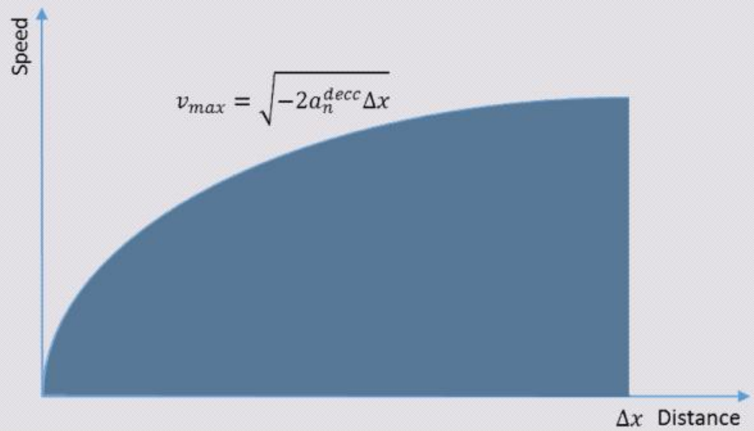
Acceleration Framework

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[1] and Arem, Driel, Visser, 2006[2]).



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

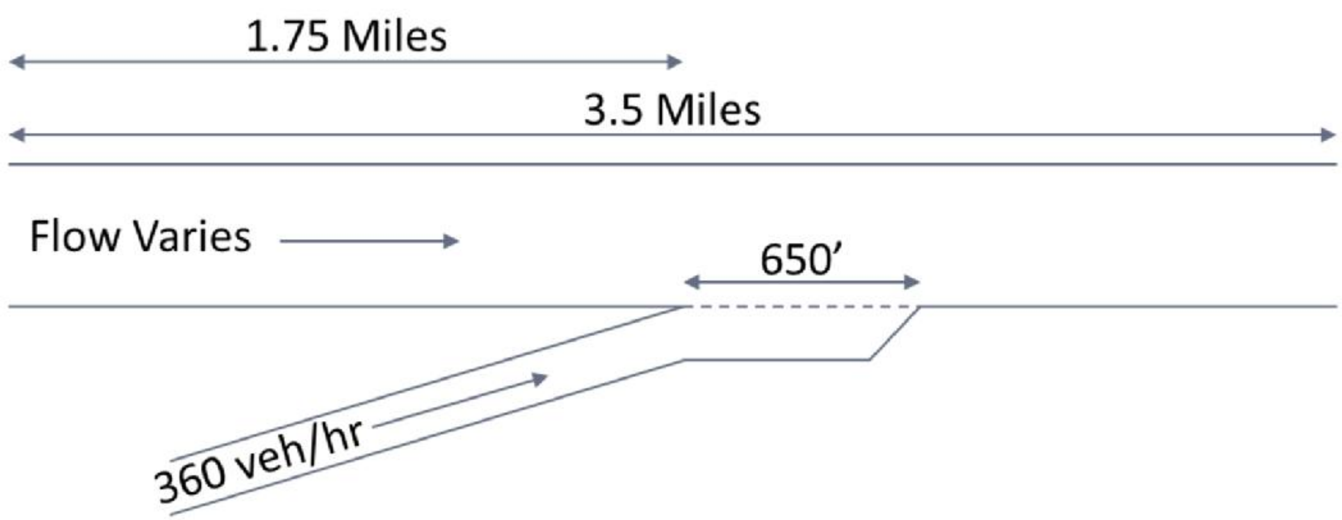
$$\begin{aligned} a_n^d(t) = {} & k_a a_{n-1}(t-\tau) + \\ & k_v(v_{n-1}(t-\tau) - v_n(t-\tau)) + \\ & k_d(s_n(t-\tau) - s_{ref}) \end{aligned}$$

NORTHWESTERN UNIVERSITY

1. Reece, D.A., Shafer, S.A., 1993. A computational model of driving for autonomous vehicles. *Transportation Research Part A: Policy and Practice* 27(1), 23-50.
2. Van Arem, B., van Driel, C.J.G., Visser, R., 2006. The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics. *Intelligent Transportation Systems, IEEE Transactions on* 7(4), 429-436.

Throughput Analysis
Simulation Segment

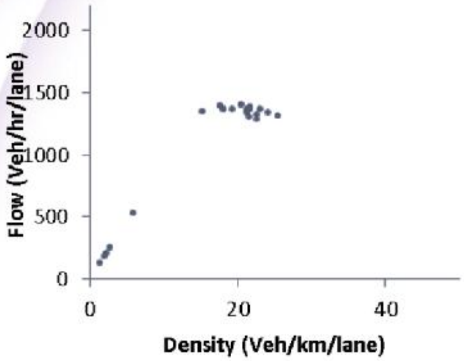
The average breakdown flow in a series of simulations is considered as the bottleneck capacity.



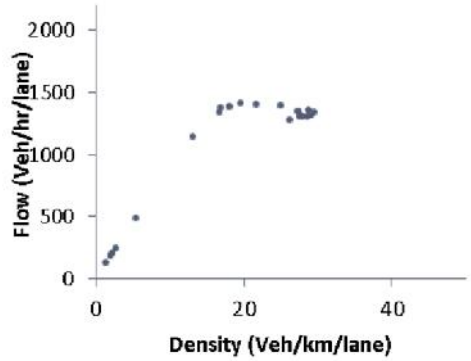
NORTHWESTERN UNIVERSITY

Throughput Analysis

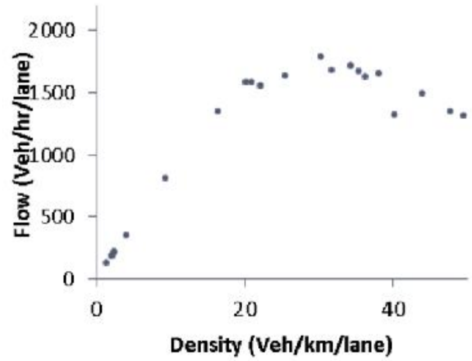
Sensitivity Analysis – Connected Vehicles



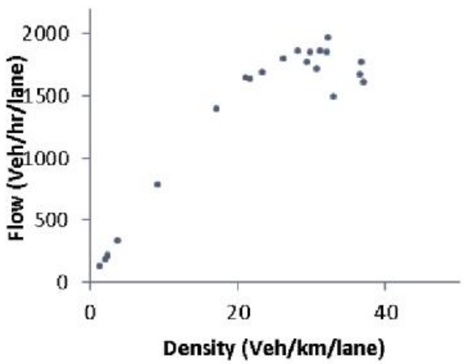
0% MPR



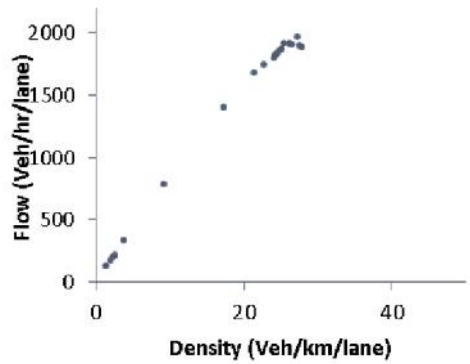
10% MPR



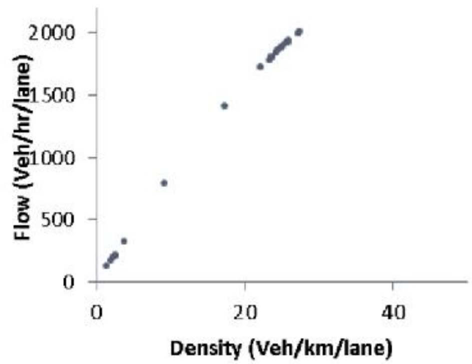
50% MPR



70% MPR



90% MPR

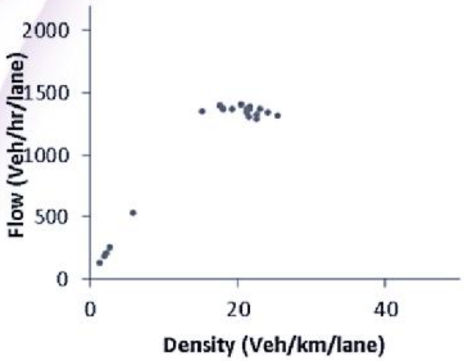


100% MPR

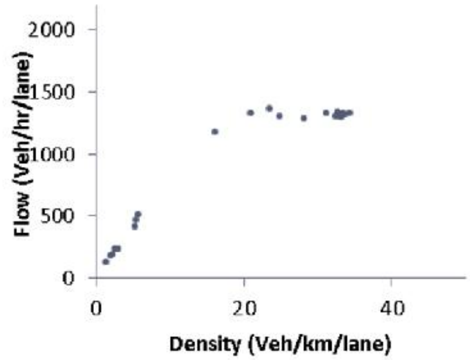
NORTHWESTERN UNIVERSITY

Throughput Analysis

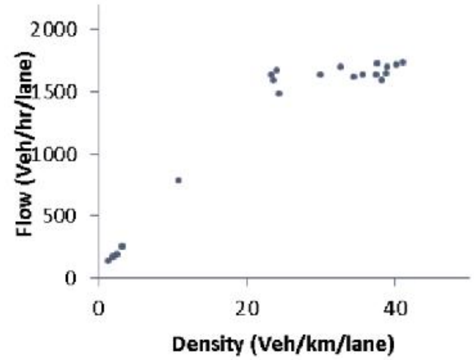
Sensitivity Analysis – Automated Vehicles



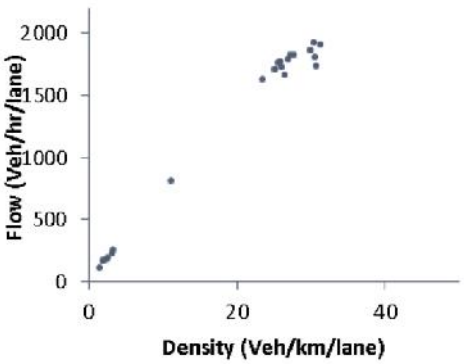
0% MPR



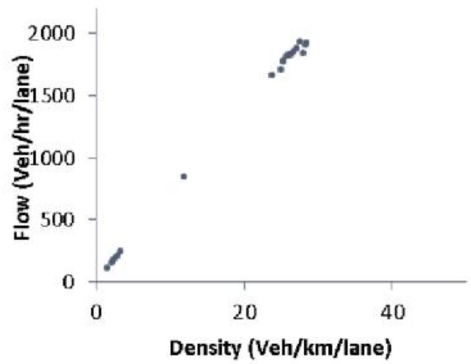
10% MPR



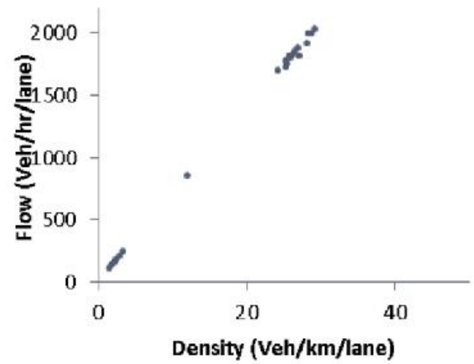
50% MPR



70% MPR



90% MPR

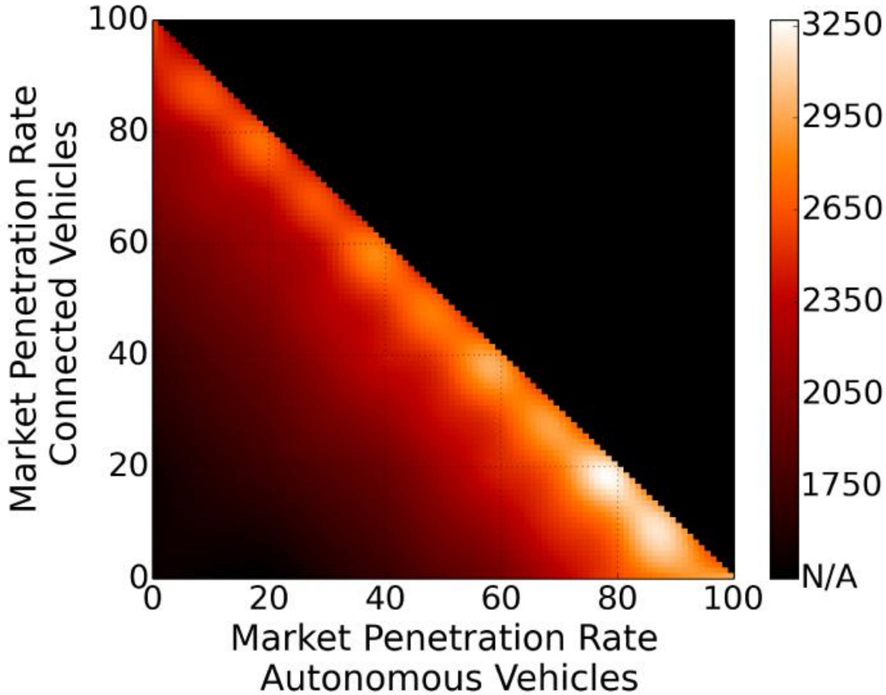


100% MPR

NORTHWESTERN
UNIVERSITY

Throughput Analysis
Simulation Results

- Low market penetration rates of automated and connected vehicles do not result in a significant increase in bottleneck capacity.
- Automated vehicles have more positive impact on capacity compared to connected vehicles.
- Capacities over 3000 veh/hr/lane can be achieved by using automated vehicles.



Automated, Connected, and Regular Vehicles

NORTHWESTERN UNIVERSITY

Throughput Analysis
Summary

Connected Vehicles / Automated vehicles:

- Low penetration rate increases the scatter in fundamental diagram.
- High penetration rate reduces the scatter in fundamental diagram.
- Capacity increases as market penetration rate increases.

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

NORTHWESTERN
UNIVERSITY

Stability Analysis

A car-following model can be formulated as:

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

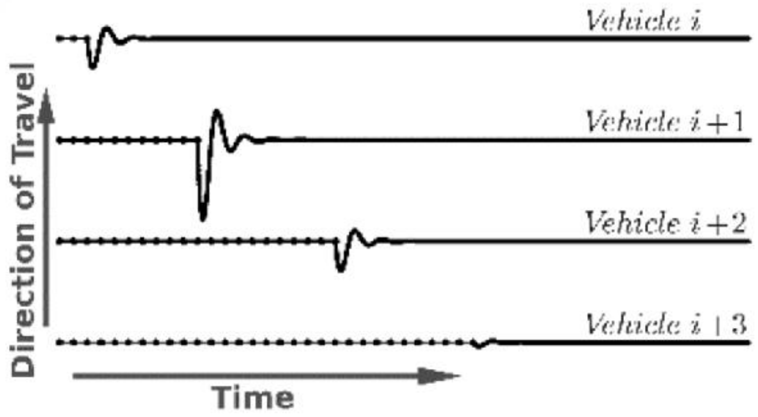
Empirical observations suggest that there exists an equilibrium speed-spacing relationship:

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

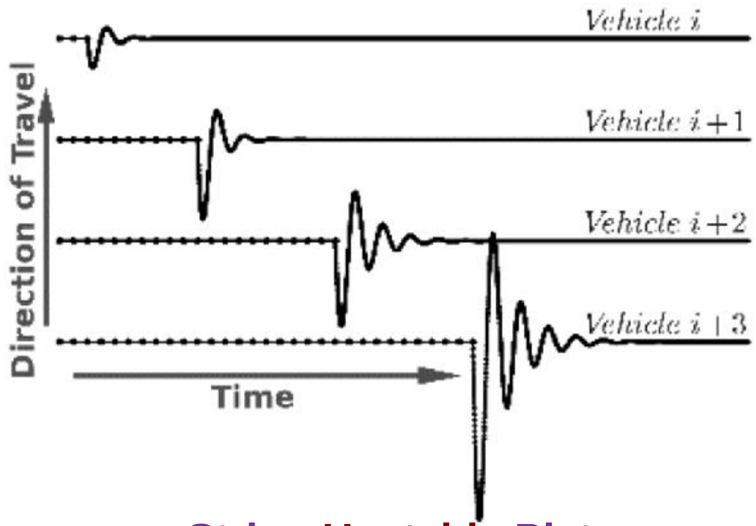
A platoon of infinite vehicles is string stable if a perturbation from equilibrium decays as it propagates upstream.

NORTHWESTERN UNIVERSITY

Stability Analysis



String Stable Platoon



String Unstable Platoon

Stability Analysis

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

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

where

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

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

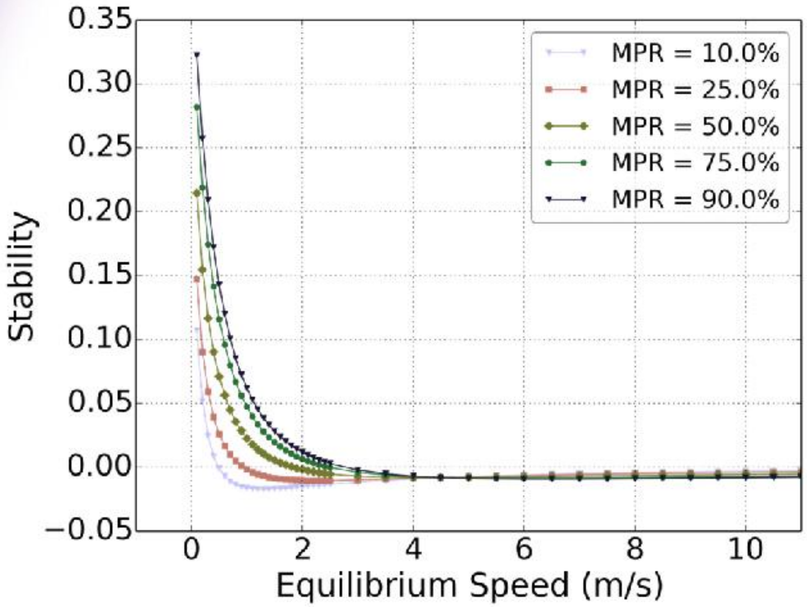
NORTHWESTERN UNIVERSITY

Ward, J.A., 2009. Heterogeneity, Lane-Changing and Instability in Traffic: A Mathematical Approach, *Department of Engineering Mathematics*. University of Bristol, Bristol, United Kingdom, p. 126.

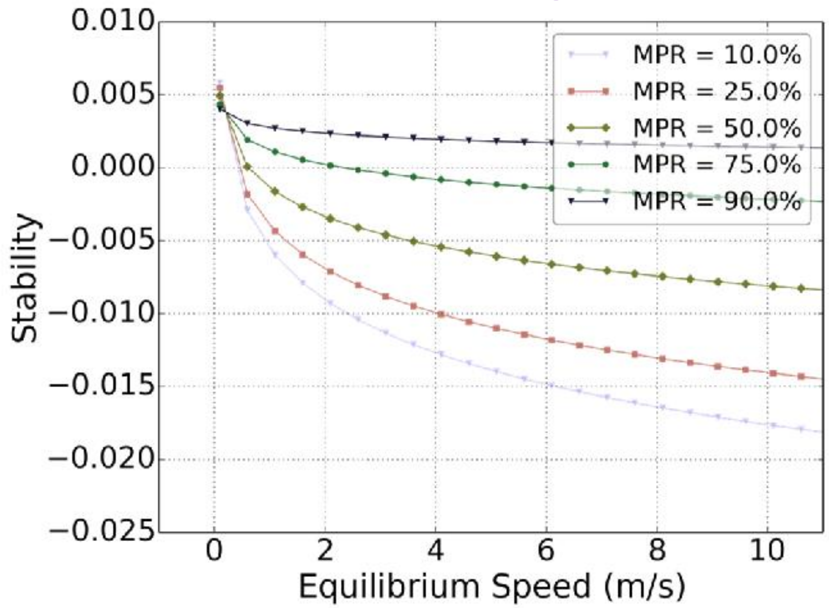
Stability Analysis

Heterogeneous Traffic Flow

Connected and Regular Vehicles



Automated and Regular Vehicles



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

NORTHWESTERN UNIVERSITY

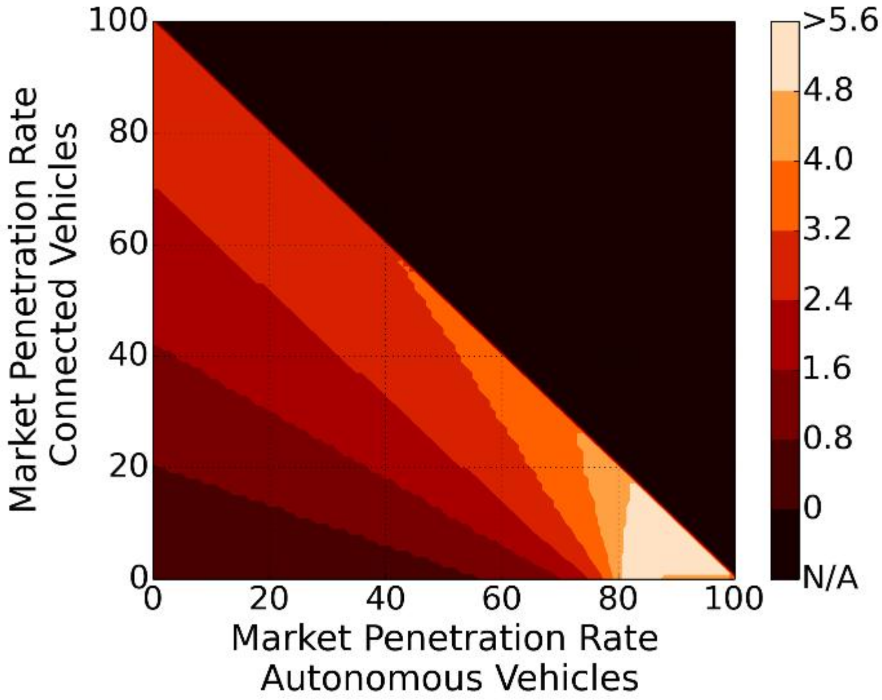
Stability Analysis

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

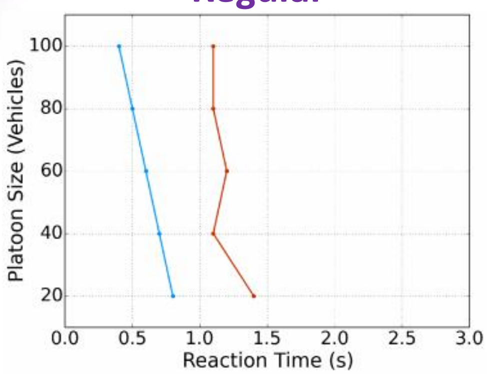
NORTHWESTERN UNIVERSITY

Stability Analysis
Simulation Results

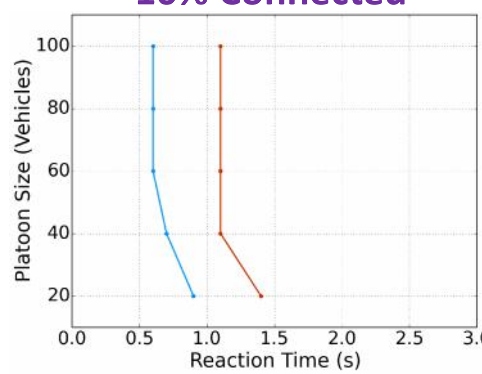
A one-lane highway with an infinite length is simulated.

String Stability as a Function of Reaction Time and Platoon Size is investigated.

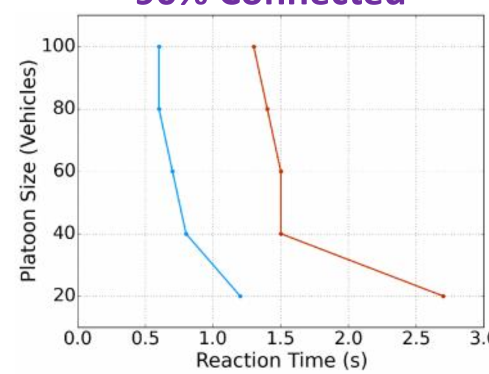
Regular



10% Connected



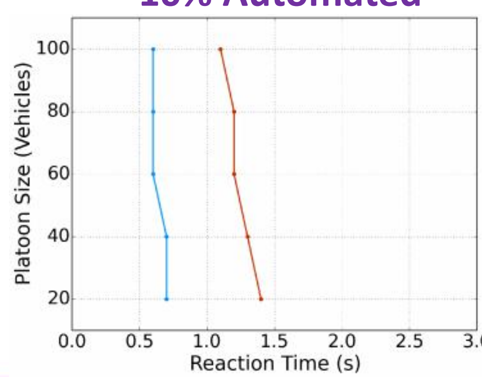
90% Connected



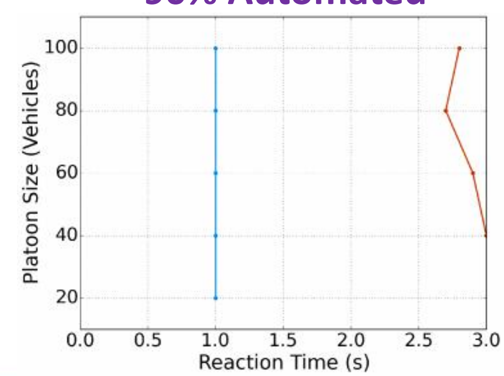
Oscillation Regime

Collision Regime

10% Automated



90% Automated



NORTHWESTERN UNIVERSITY

Stability Analysis
Summary

The presented acceleration framework is string stable.

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

- Improvements are observed at low market penetration rates of connected vehicles (unlike automated vehicles).
- At high market penetration rates, automated vehicles have more positive impact on stability compared to connected vehicles.

NORTHWESTERN UNIVERSITY

Stability Analysis
Summary

Simulation results revealed that

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

NORTHWESTERN UNIVERSITY

Outline

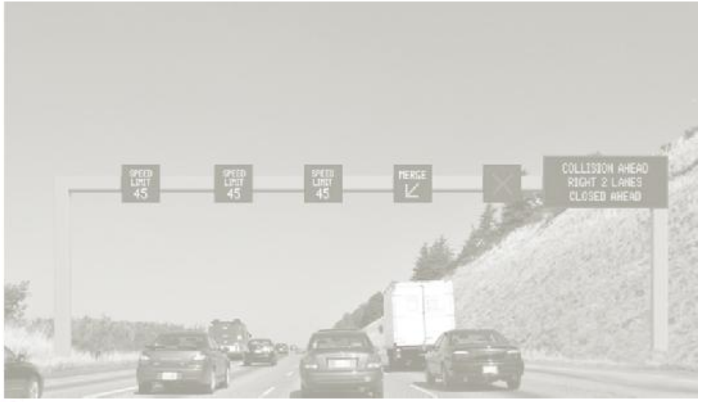


Image Source: Volvo, Lexus, and USDOT

V2V Communications Model
Background

Algorithms can be categorized into two groups,

- Topological methods

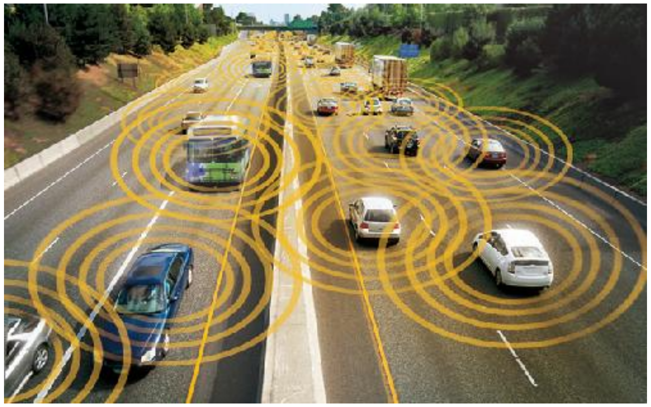
  Use network topology to select nodes.
  Network topology changes rapidly; therefore,
  Topological date should be transmitted at a high rate

- Statistical methods

  Use local measures (e.g. transmission distance).

Topological methods are more accurate.

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



NORTHWESTERN UNIVERSITY

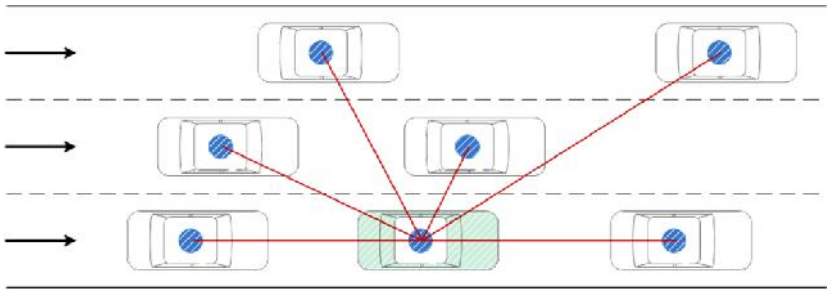
Image Source: USDOT

V2V Communications Model

Background – What is a Cluster?

Each cluster consists of,

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



Cluster members can only communicate with the cluster head (1-hop communication between cluster members).

A cluster head can communicate with cluster members and other cluster heads from other clusters.

Having stable clusters is the key to reduce signal interference.

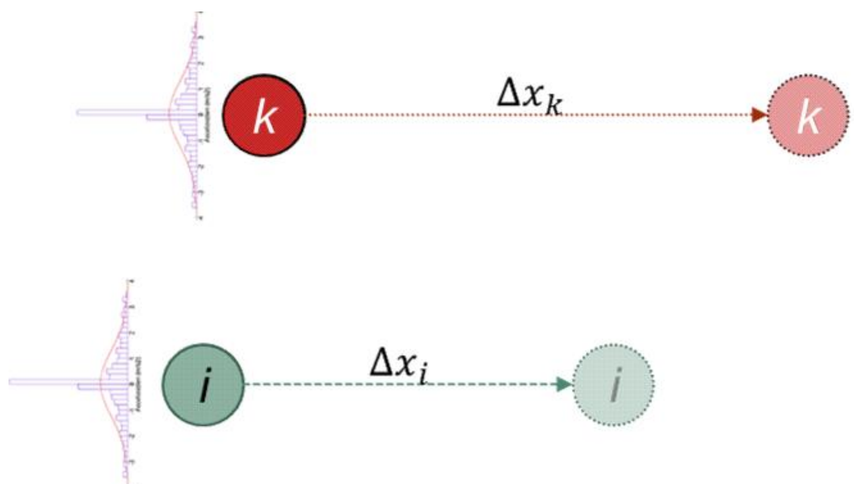
NORTHWESTERN UNIVERSITY

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.



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

NORTHWESTERN UNIVERSITY

1. Hassanabadi, B., C., Shea, L., Zhang, and S., Valaee, 2014. Clustering in Vehicular Ad Hoc Networks using Affinity Propagation. Ad Hoc Networks Part B, Vol. 13, pp. 535-548.
2. Frey, B.J. and D., Dueck, 2007. Clustering by Passing Messages Between Data Points, Science 315, pp.972–976.

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 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)

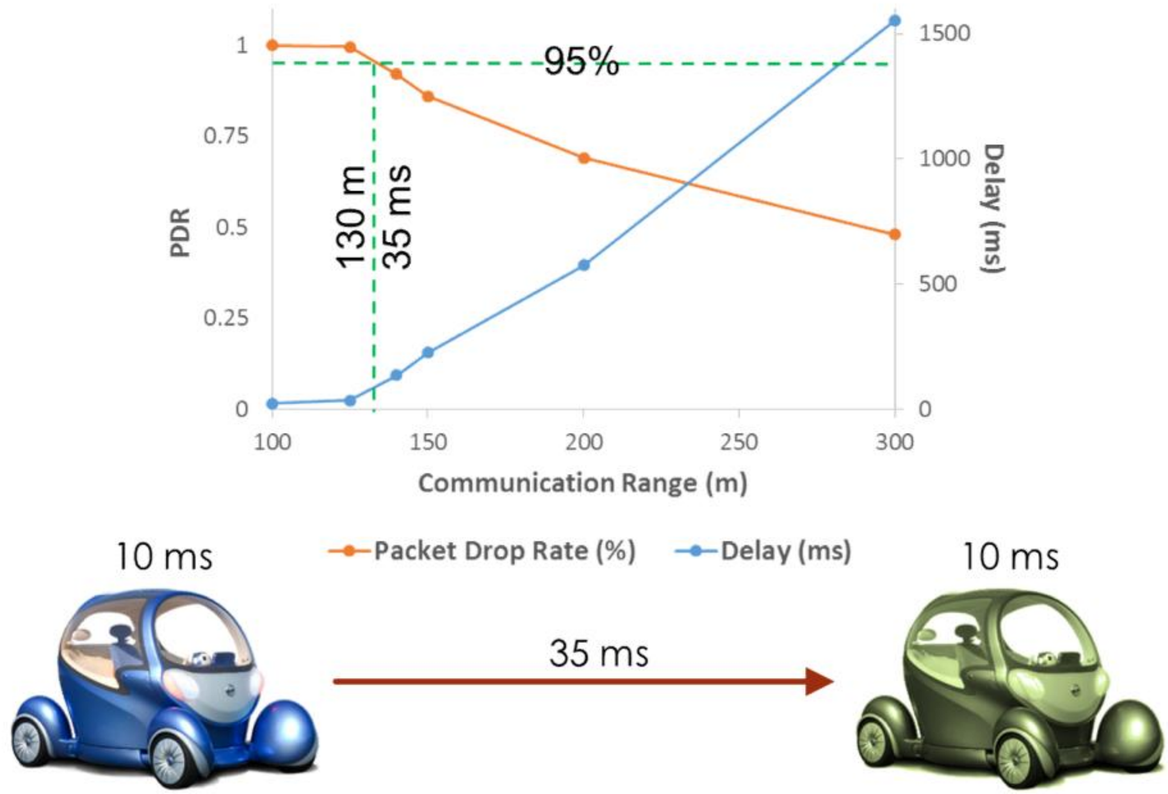
NORTHWESTERN
UNIVERSITY

V2V Communications Model

NS3 Implementation – Clustering Frequency

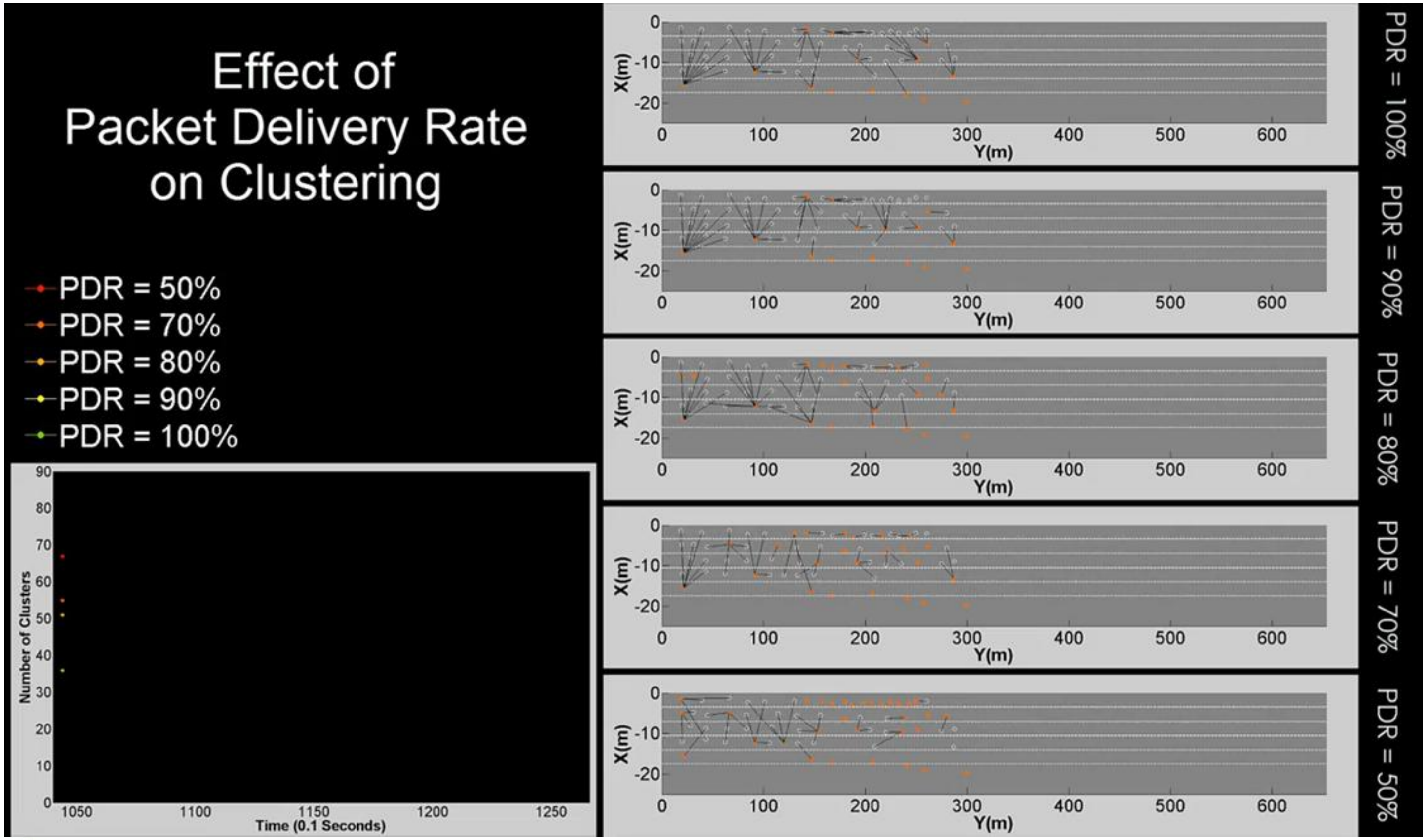
Packet size = 50 byte: Location, speed, acceleration

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



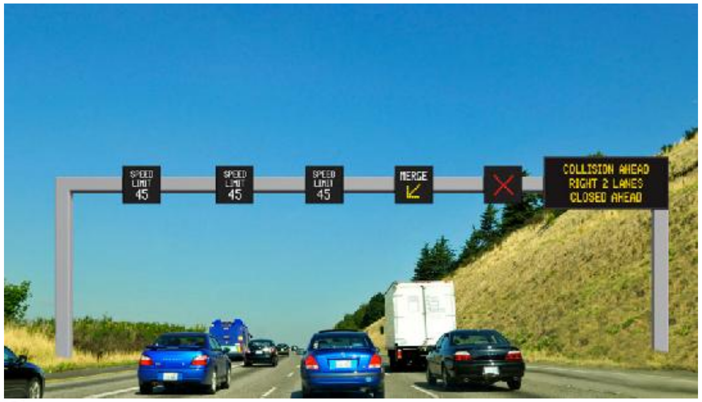
V2V Communications Model

NS3 Implementation – Packet Delivery



NORTHWESTERN UNIVERSITY

Outline



NORTHWESTERN UNIVERSITY

Image Source: Volvo, Lexus, and USDOT

SPD-HARM Simulation
Definition

Speed Harmonization

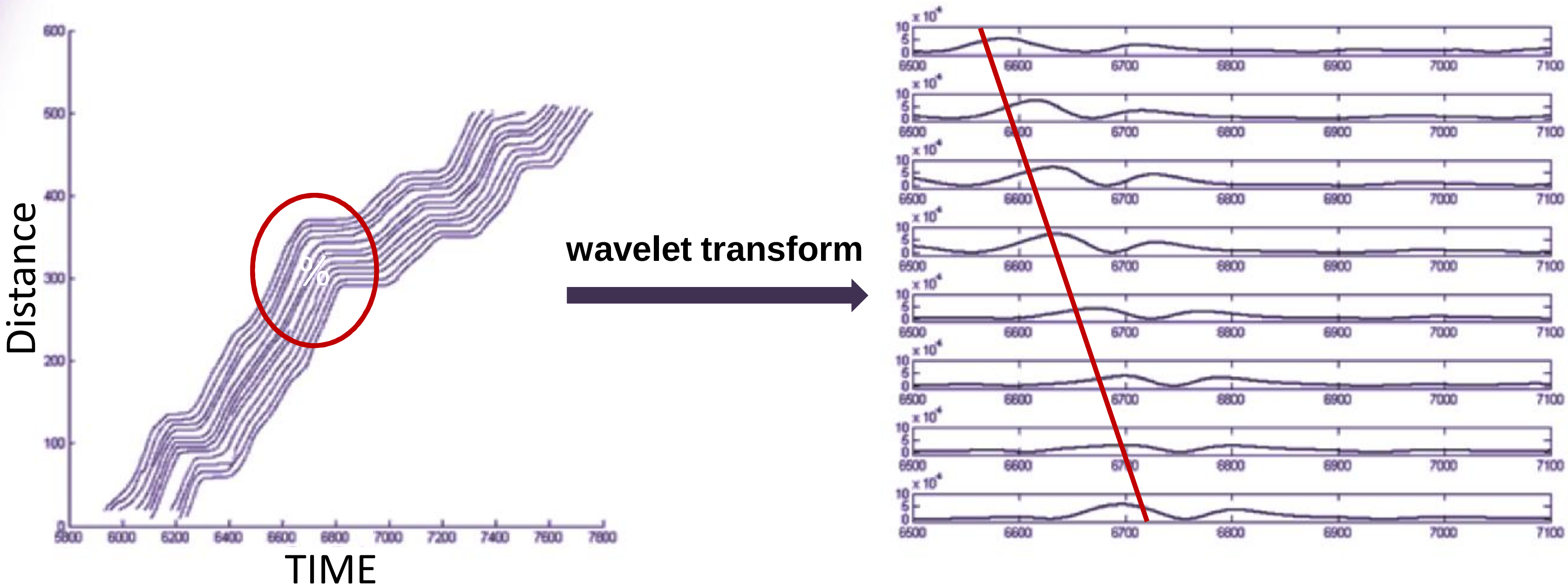
- Dynamically adjusts and coordinates maximum speed limit based on
  Prevailing traffic state
  Road surface condition
  Weather

Objectives

- Avoid or delay flow breakdown by reducing speed variance
- Smooth out shock waves
- Improve flow quality and throughput
- Reduce delay and improve reliability
- Safety?

SPD-HARM Simulation

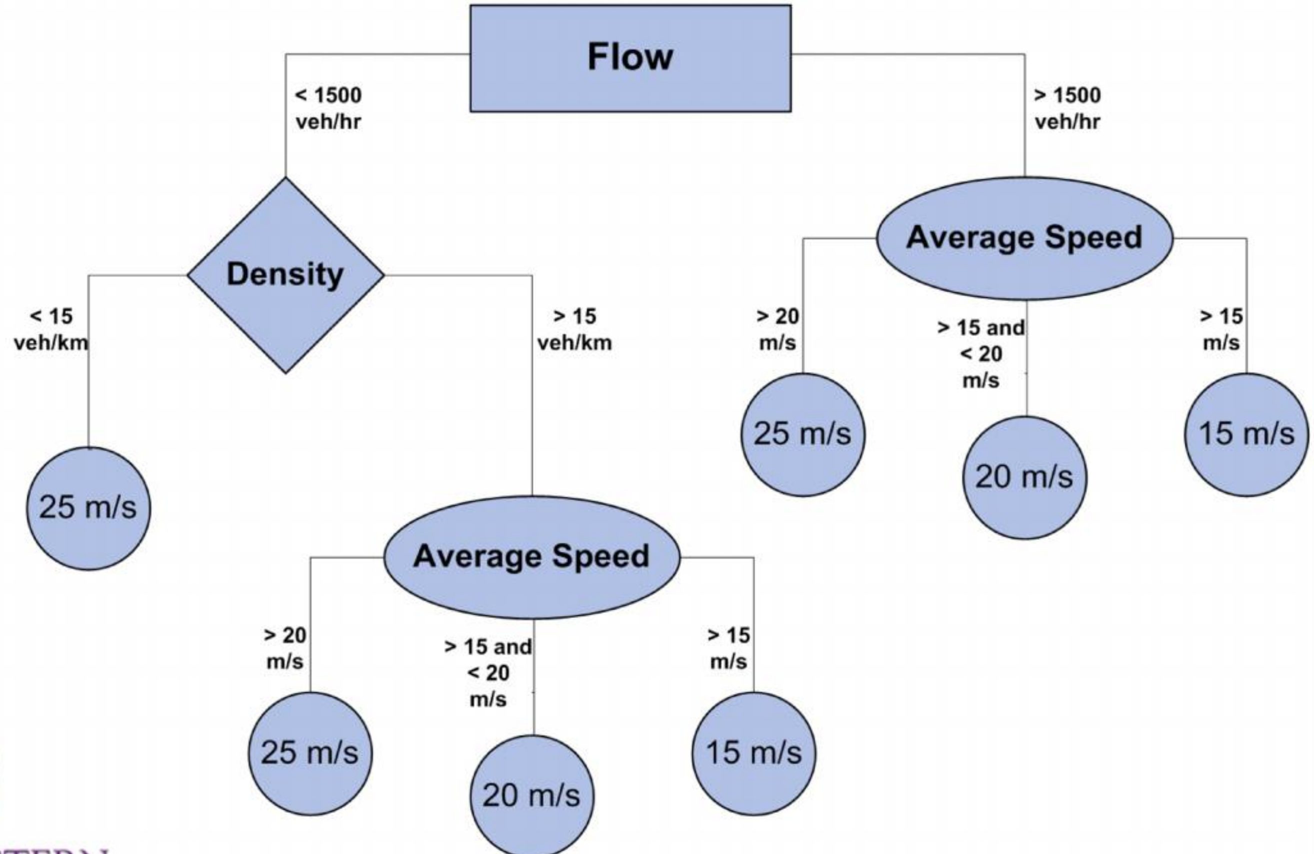
Shockwave Detection



NORTHWESTERN UNIVERSITY

SPD-HARM Simulation
Speed Limit Selection Algorithm

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

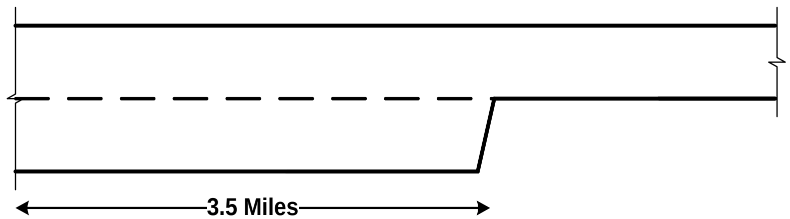


NORTHWESTERN UNIVERSITY

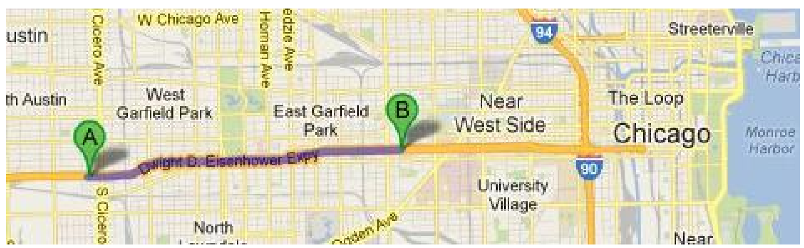
Allaby, P., B. Hellinga, M. Bullock. Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications, IEEE Transactions on Intelligent Transportation Systems, Vol. 8, No. 4, 2007, pp. 671-680.

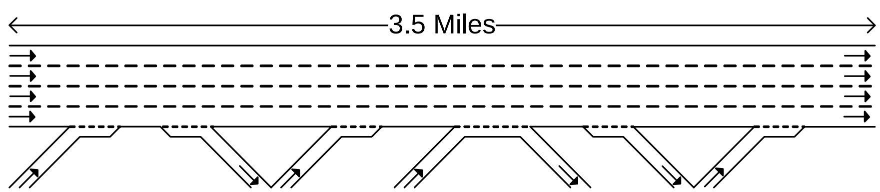
SPD-HARM Simulation
Study Segments

Hypothetical Segment



Chicago





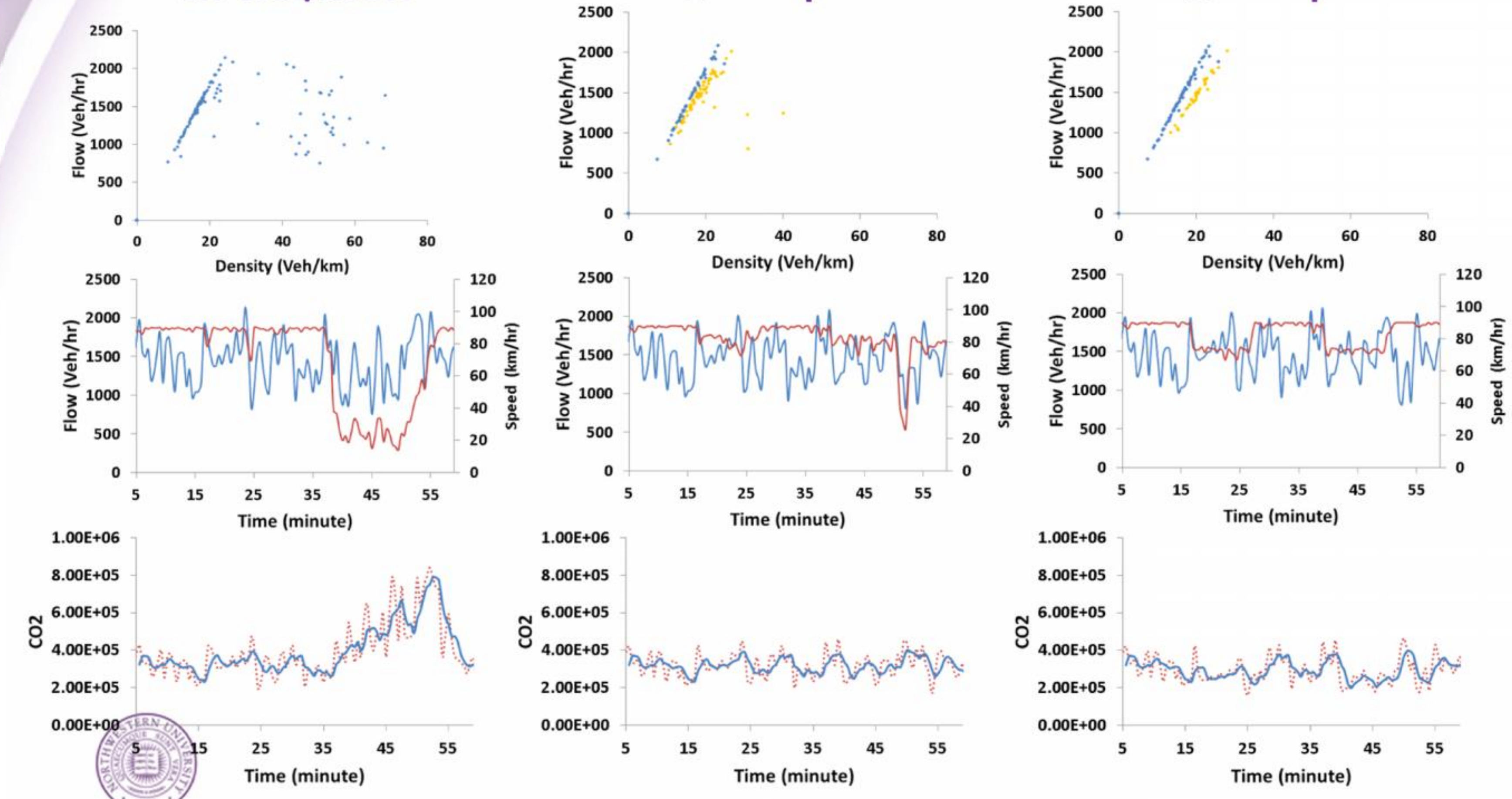
NORTHWESTERN UNIVERSITY

Image Source: Google Maps

SPD-HARM Simulation

Results: Hypothetical Segment

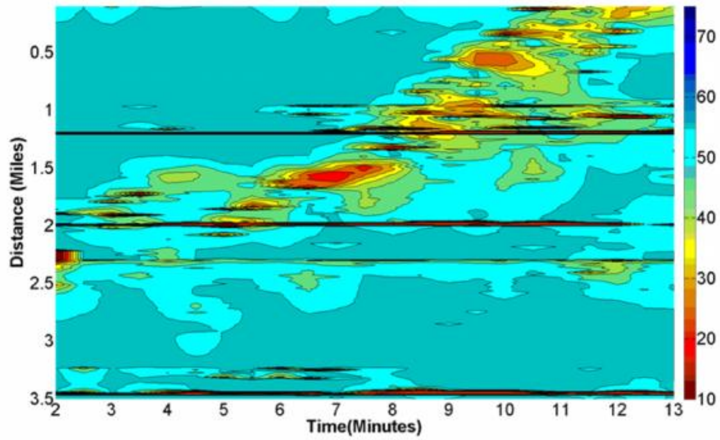
0% Compliance | **10% Compliance** | **90% Compliance**

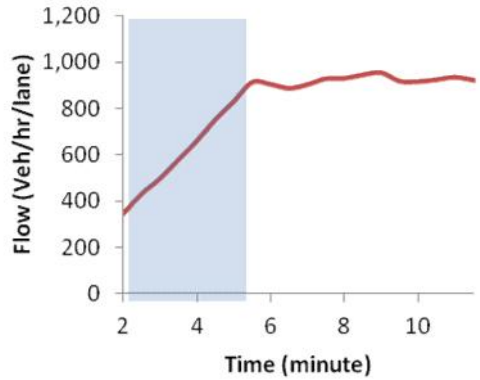


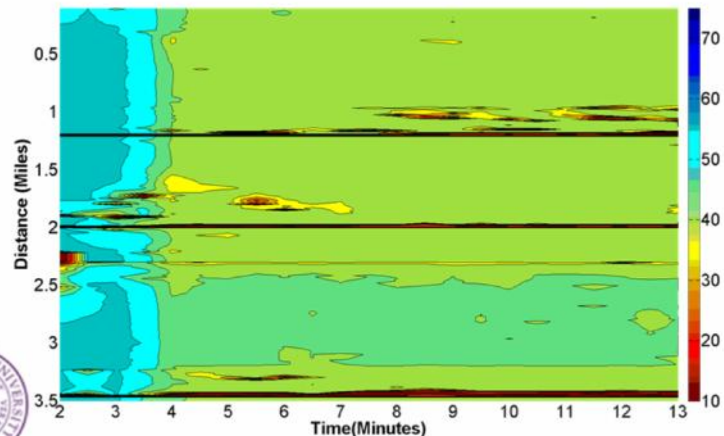
NORTHWESTERN UNIVERSITY

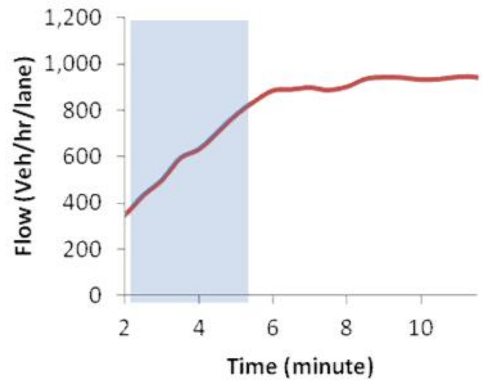
SPD-HARM Simulation

Results: Chicago









NORTHWESTERN
UNIVERSITY

Concluding Remarks

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

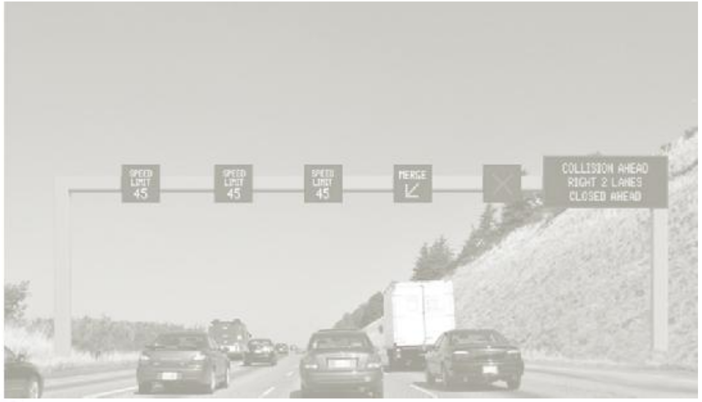
Under the assumptions of this study, mobility will improve and emissions will decrease by the addition of connected and automated vehicles.

- Automated vehicles are more effective compared to connected vehicles.

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

NORTHWESTERN UNIVERSITY

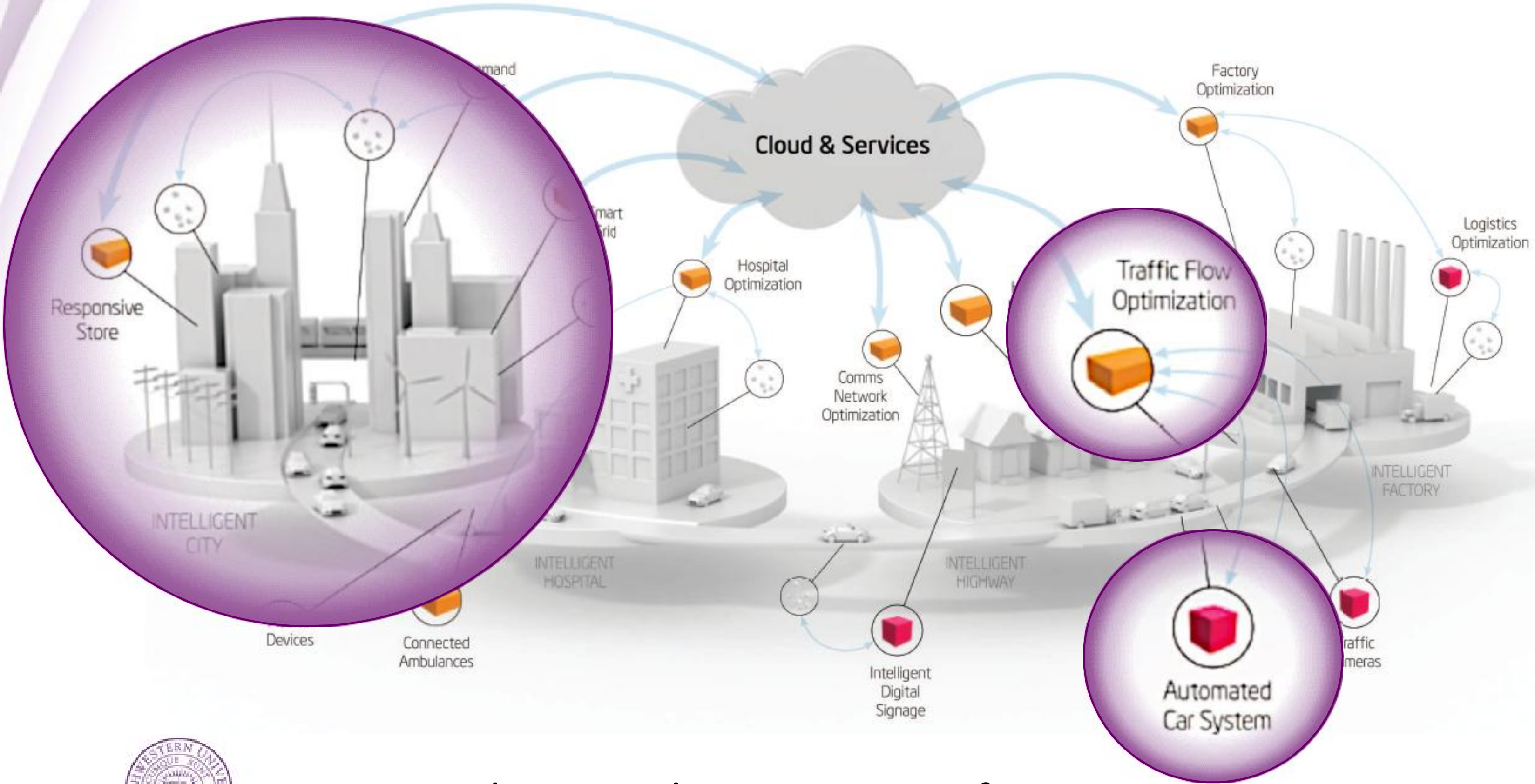
Outline



NORTHWESTERN UNIVERSITY

Image Source: Volvo, Lexus, and USDOT

What is Next?



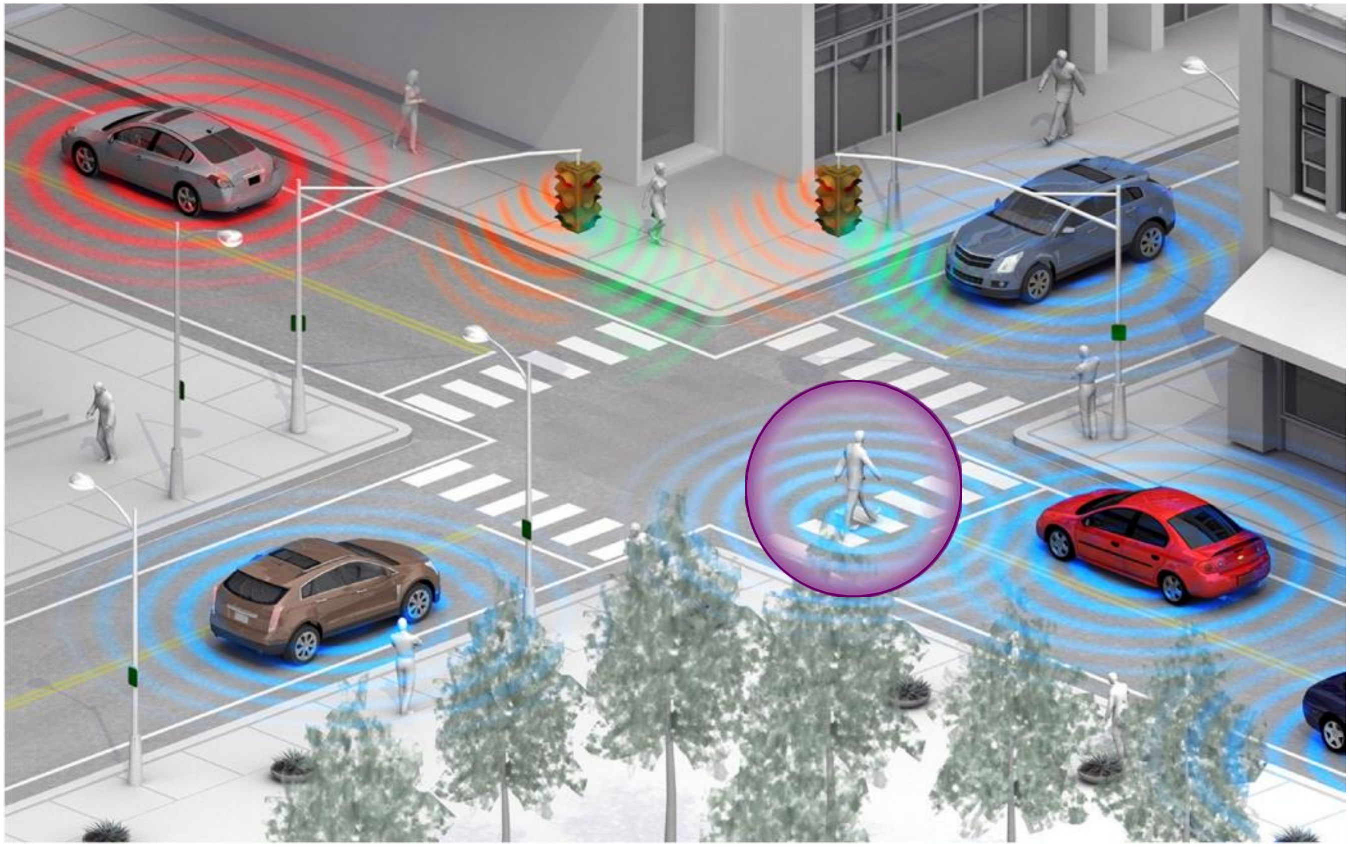
NORTHWESTERN UNIVERSITY

There is a lot more room for improvement.

There are a lot of elements to add.

Image Powered by Intel

What is Next?



New measures are required and we need to apply new data collection procedures.

NORTHWESTERN UNIVERSITY

Image Source: USDOT


Google
Google
03
MDV
GM
CAT
19
CATERPILLAR
Internet access
Connect home
Cell phone
Traffic
Laptop
Navigation system
MDV
STANFORD