Information Flow Propagation and Topologies for Control under Connected and Autonomous Vehicles

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Vehicle-to-Vehicle (V2V) Communications

http://icsw.nhtsa.gov/safercar/ConnectedVehicles/pages/v2v.html

- Vehicle itself is a dynamic sensor, transmitter, and information user
- Location, speed, braking, condition, etc.
- Vehicles can communicate with each other: DSRC, C-V2X
- Communication constraints
  - Communication range (300 m), interference, bandwidth

Analytical Modeling to Leverage V2V Communications

- Information flow propagation
  - Traffic management
  - Leverage real-time V2V data
  - Decentralized strategies

- Information flow topologies
  - Platoon control
  - Leverage real-time V2V data
  - Cooperative strategies

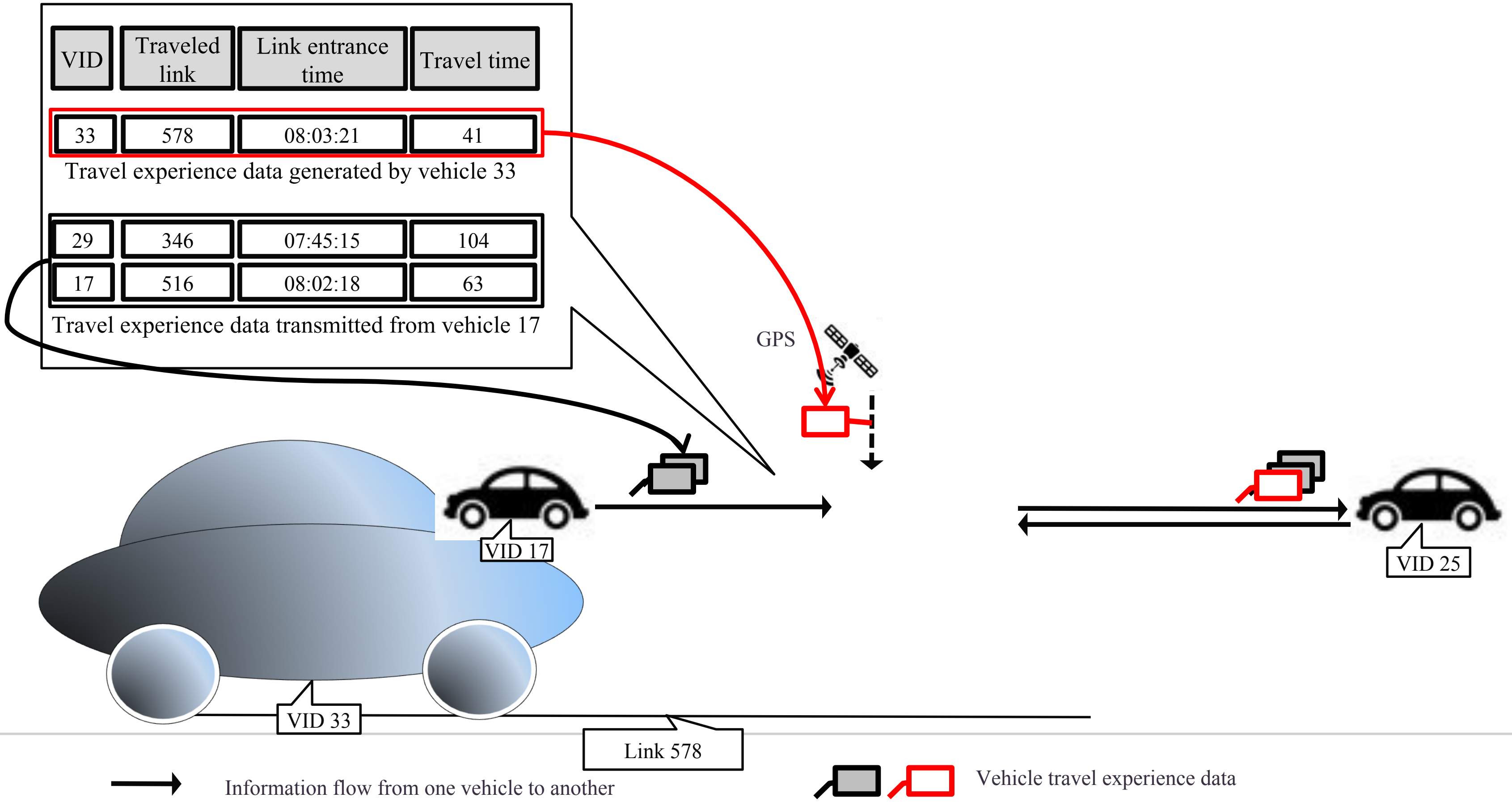
Modeling Vehicle Knowledge Evolution under V2V Communications

- Kim, Y-H. and Peeta, S. (2016). “Graph-based Modeling of Information Flow Evolution and Propagation under V2V Communications-Based Advanced Traveler Information Systems,” ***Computer-Aided Civil and Infrastructure Engineering***, Vol. 31, No. 7, pp. 499-514.

- Kim, Y-H. and Peeta, S. (2017). “Modeling of the Dynamic Flow Propagation of Multiple Units of Information under Vehicle-to-Vehicle Communications based Advanced Traveler Information Systems,” ***Journal of Intelligent Transportation Systems: Technology, Planning, and Operations***, Vol. 21, No. 4, pp. 310-323.

Vehicle Knowledge

- **Information flow:** flow of raw travel experience data between vehicles, and not data processed for ATIS
- **Vehicle knowledge:** set of spatiotemporal travel experience data on an equipped vehicle



V2V-DVKI Problem

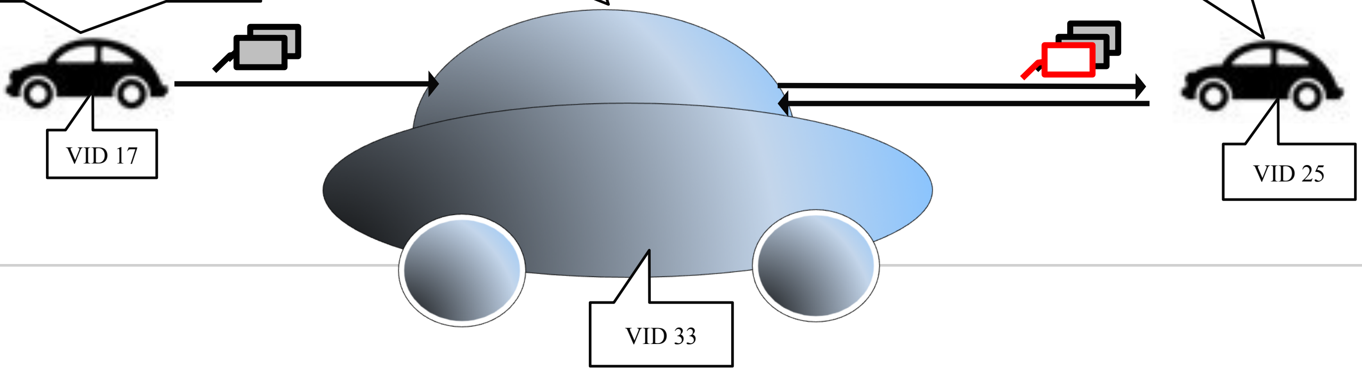
- **V2V-DVKI:** V2V-Dynamic vehicle knowledge identification problem
  - Systematic understanding of interactions among the traffic flow, inter-vehicle communication network and information flow propagation is necessary for a systematic modeling of V2V communications based traffic system:

    - to design robust V2V communications-based traffic system architectures
    - to enable active control of congested traffic networks and the rapid flow of useful information

VID	Traveled link	Link entrance time	Travel time
17	346	07:55:33	55seconds
121	231	07:45:15	104
23	516	08:02:18	87
63	531	08:03:21	41
12	98	08:13:11	63
17	332	08:03:21	55

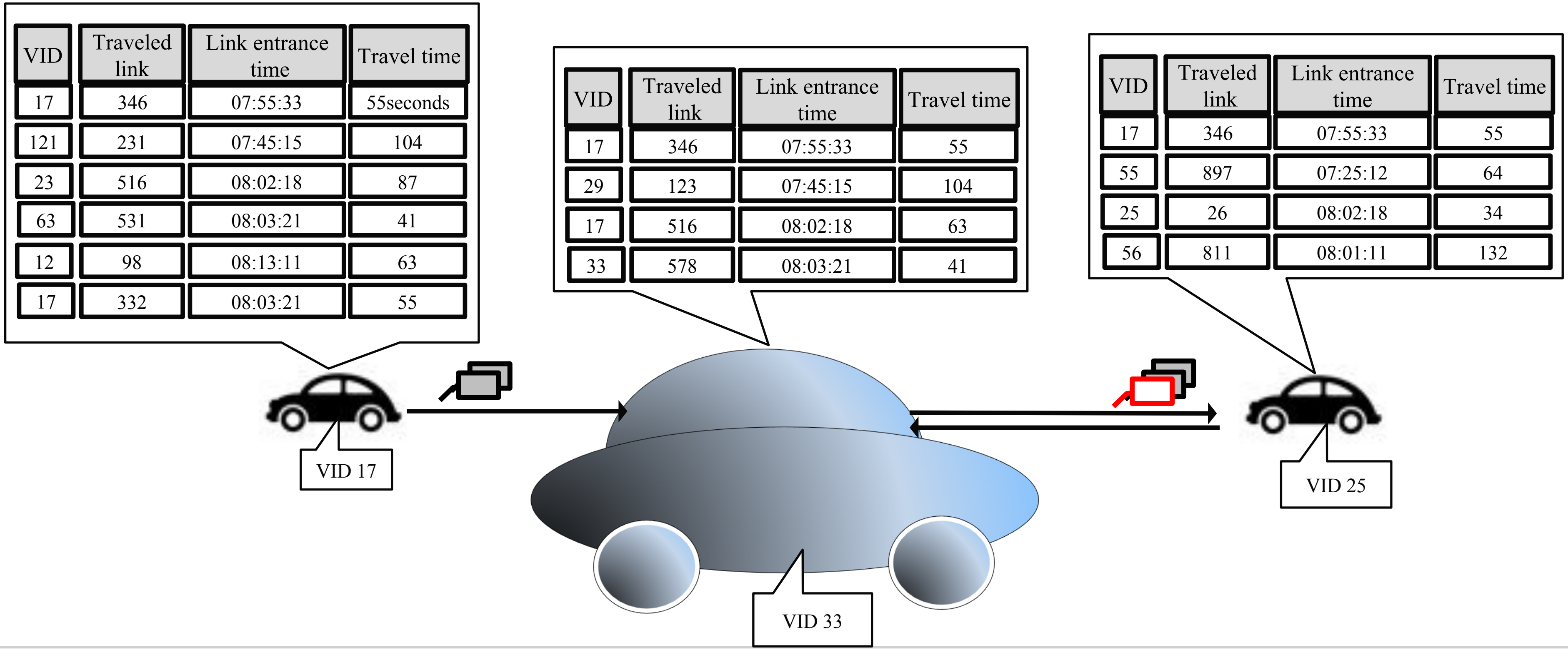
VID	Traveled link	Link entrance time	Travel time
17	346	07:55:33	55
29	123	07:45:15	104
17	516	08:02:18	63
33	578	08:03:21	41

VID	Traveled link	Link entrance time	Travel time
17	346	07:55:33	55
55	897	07:25:12	64
25	26	08:02:18	34
56	811	08:01:11	132



V2V-DVKI Problem

- **V2V-DVKI:** V2V-Dynamic vehicle knowledge identification problem
  - To model and identify V2V dynamic vehicle knowledge and the evolution of information flow propagation
  - *Integrated graph based multi-layer framework*



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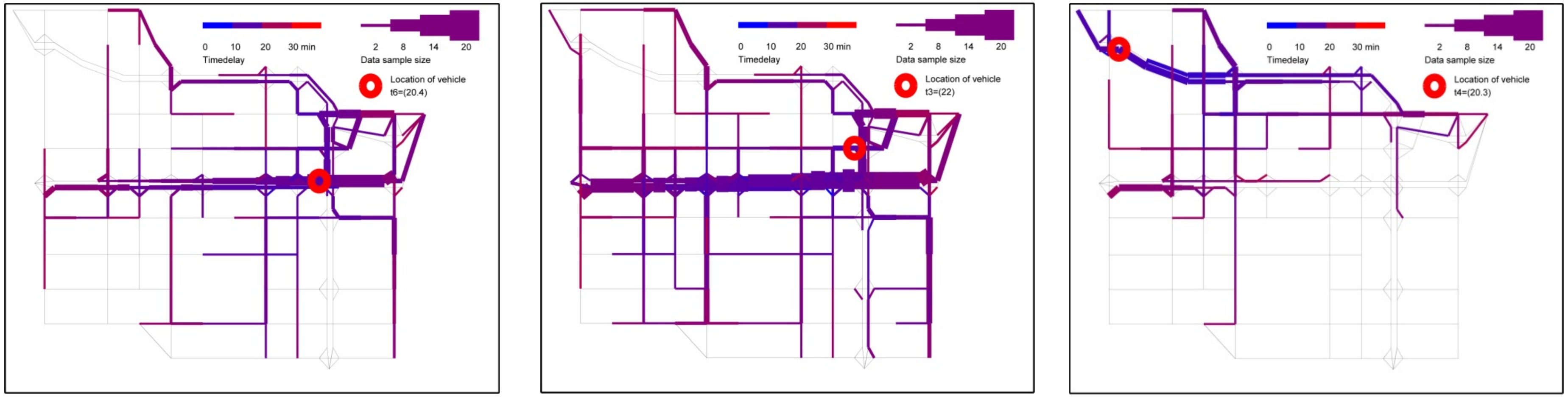
Characteristics of V2V-DVKI Problem

- Characteristics of V2V-DVKI problem
  - Spatiotemporal coverage of vehicle knowledge in an area can vary
  - Quality issues in terms of time delay (latency)
  - Quality and quantity of travel experience data can vary across links
  - Usefulness of travel experience data may vary across vehicles



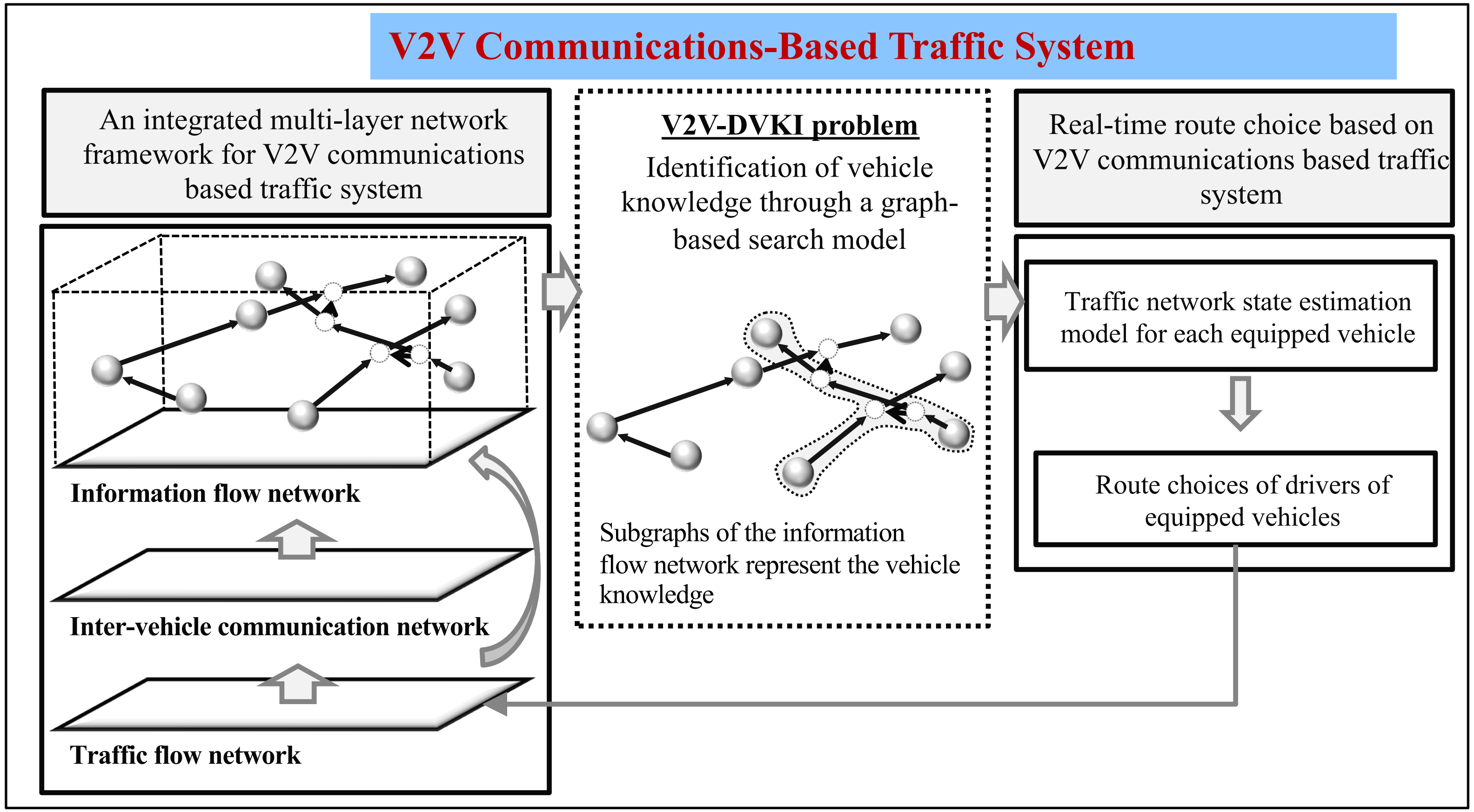
Vehicle A, at time 20.4min | Vehicle B, at time 22min | Vehicle C, at time 20.3min

Vehicle's dynamic knowledge

- Illustrates problem complexity and need for a systematic understanding of characteristics for V2V communications-based traffic system

Problem Context

- V2V-DVKI problem is a subproblem of the broader V2V communications based traffic system that seeks to address user/system objectives in congested traffic networks



Traffic Flow Network

- Physical traffic network

$G^T = (N, A)$: A traffic flow network in which vehicles have an ability to communicate with each other

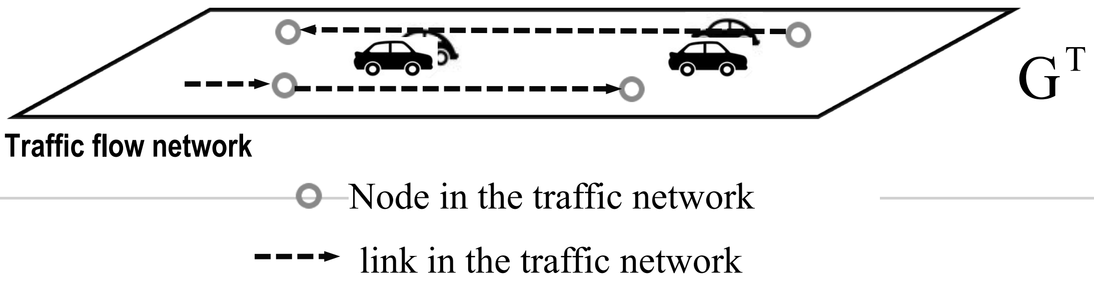
N : A set of n nodes corresponding to physical intersections or designated points

A : A set of m directed links corresponding to road links

- Dynamics of traffic flow
  - Dynamic traffic flow characteristics are observable and given
  - Time-dependent locations of vehicles determine

    - travel experience data generation

    - feasibility of inter-vehicle communication



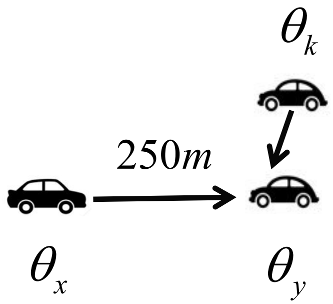
Inter-Vehicle Communication Network

- Inter-vehicle communication network

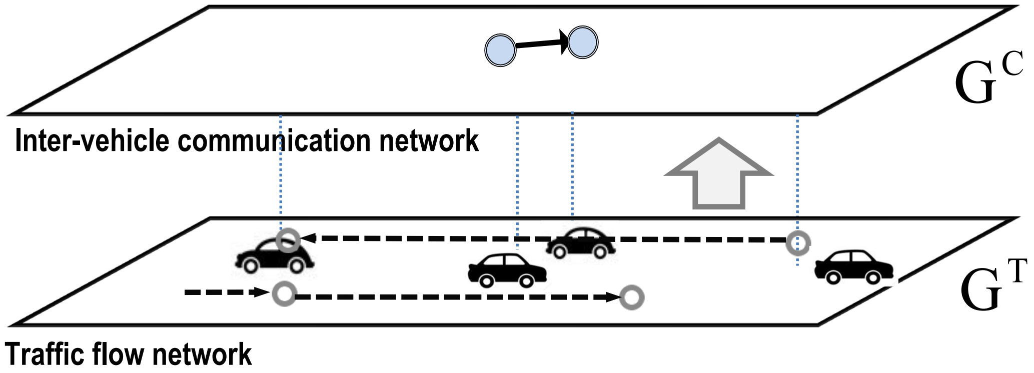
$G^C = (C, M)$: Characterize the inter-vehicle communication events

C : A virtual communication node set M : A directed communication link set

- Inter-vehicle communication related technical constraints
  - Communication range: 250m
  - Interference:
  - Bandwidth: 2Mbps rate



$$\frac{\dfrac{T_x}{\left|\theta_x - \theta_y\right|^2}}{N + \sum_{\substack{k \in X \\ k \neq x}} \dfrac{T_x}{\left|\theta_k - \theta_y\right|^2}} \geq \beta$$



θ_k θ_x θ_y : location of an equipped vehicle within communication range

T_x : signal power level

N : ambient noise power

β : signal-to-interference

Pair of inter-vehicle communication nodes

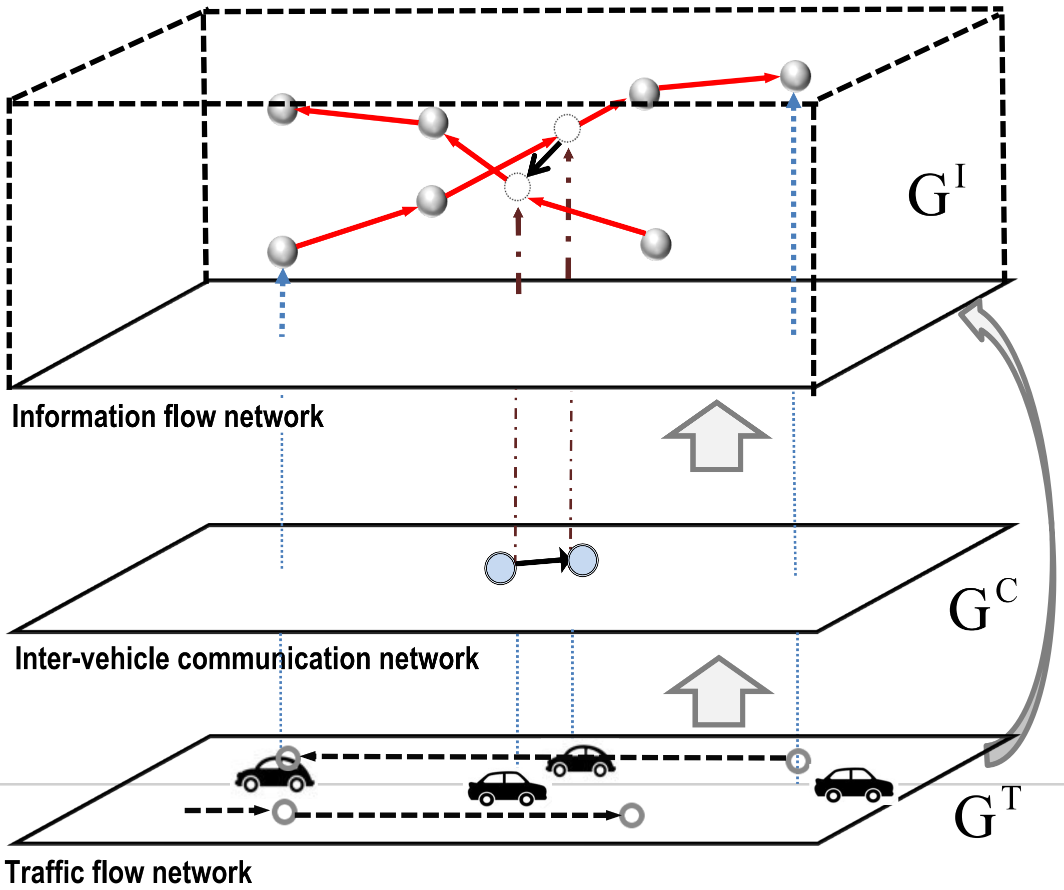
Inter-vehicle communication link

Information Flow Network

- Information flow network

$G^I = (N^I, C^I, A^I, M^I)$: Flows are a set of travel experience data

- Evolves over time in that new nodes are generated, some nodes gain new links
- Maps what/when/where information is generated and how it propagates



❑ Two sets of nodes

- TED node $\in N^I$
- VIC node $\in C^I$

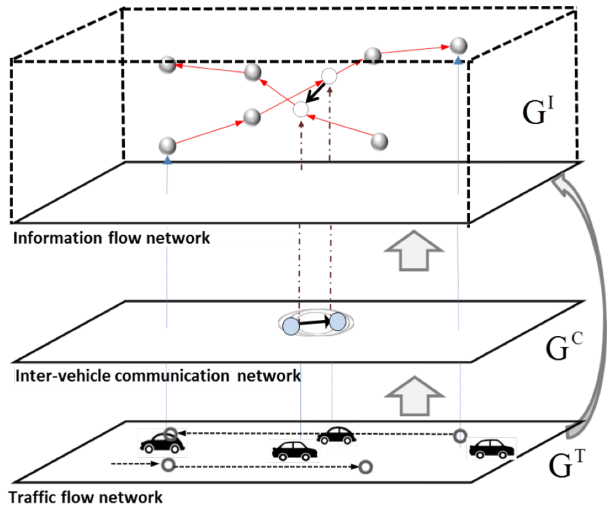
❑ Two sets of links

- T-link $\in A^I$
- I-link $\in M^I$

Corresponding node generation in the information flow network

Interdependencies of Three Network Layers

- ❑ Their structures are determined based on the physical traffic network
- ❑ Layers are linked to other layers
  - Inter-vehicle communication network is linked to the traffic flow network through dynamic vehicle trajectories
  - Information flow network is dependent on the other two layers through events
- ❑ Information flow network can be analyzed as an integrated multi-layer network framework along with the traffic flow and inter-vehicle communication through shared structural characteristics



Spatiotemporal Tracking Capabilities

- Graph based approach provides retrospective capabilities related to how information flow evolves and how vehicle knowledge is updated
- Generate a fundamental understanding of how events in the traffic flow and/or inter-vehicle communication networks can affect the information flow network
- Explicit modeling of the evolution of the vehicle knowledge/information flow propagation

Layer	**Available information**	**Information source**	
		Graph-based approach	**Simulation-based approach**
Traffic flow network	Trajectory of vehicles	TED nodes	Vehicle trajectory data
Inter-vehicle communication network	Events of inter-vehicle communication	VIC nodes	Communication events data
	Propagation chain	Graph-based shortest path algorithm from any time point	Required to memorize the propagation chain
Information flow network	DVKI problem	Graph-based reverse search algorithm from any time point	Memory space at the end of simulation time
	Information flow propagation	Graph-based forward search algorithm from any time point	Required to search the information flow propagation from all vehicles' storage locations

Modeling Information Flow Propagation under V2V Communications for Traffic Management

- Kim, Y-H., Peeta, S. and He, X. (2017). "Modeling the Information Flow Propagation Wave under Vehicle-to-Vehicle Communications," ***Transportation Research, Part C: Emerging Technologies***, Vol. 85, pp. 377-395.

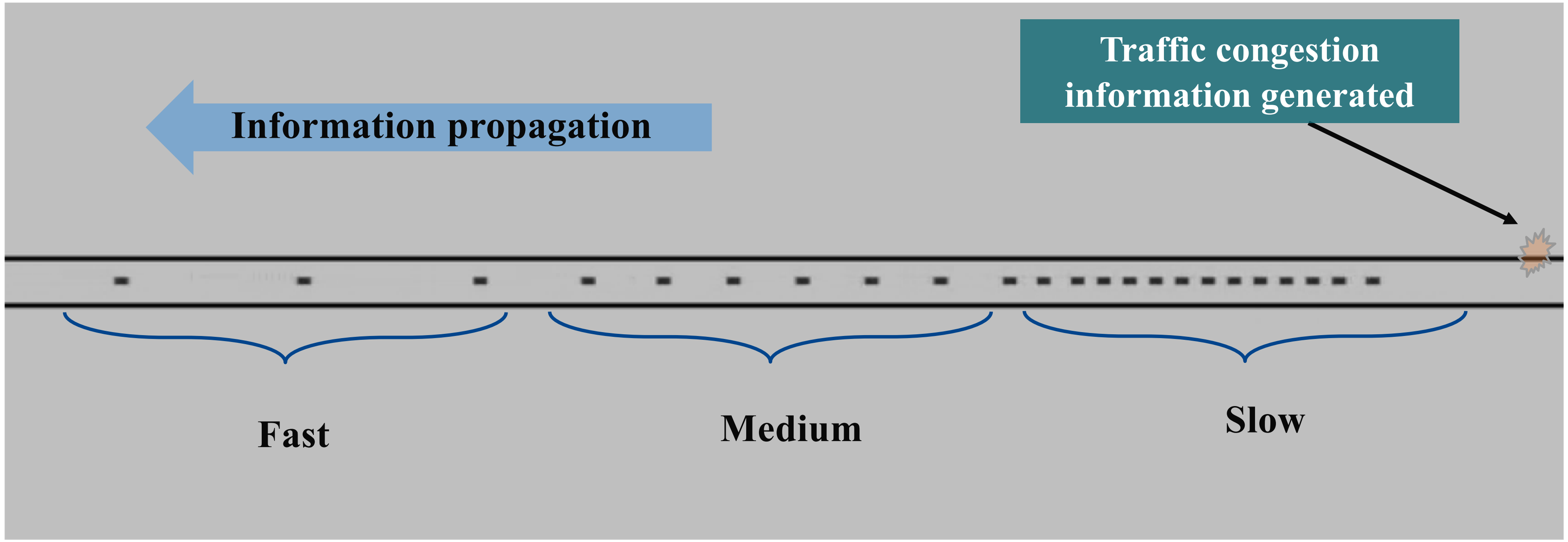
- Kim, Y-H., Peeta, S. and He, X. (2018). "An Analytical Model to Characterize the Spatiotemporal Propagation of Information under Vehicle-to-Vehicle Communications," ***IEEE Transactions on Intelligent Transportation Systems***, Vol. 19, No. 1, pp. 3-12.

- Wang, J., Kim, Y-H., He, X. and Peeta, S. (2018). "Analytical Model for Information Flow Propagation Wave under an Information Relay Control Strategy in a Congested Vehicle-to-Vehicle Communication Environment," ***Transportation Research, Part C: Emerging Technologies***, Vol. 94, pp. 1-18.

- Wang, J., Peeta, S., Lu, L. and Li, T. (2019). "Multiclass Information Flow Propagation Control under Vehicle-to-Vehicle Communication Environments," ***Transportation Research, Part B: Methodological***, Vol. 129, pp. 96-121.

Information Flow Propagation

- Understanding how information propagates in space and time is important for V2V-based applications



Problem Statement

V2V-based traffic system

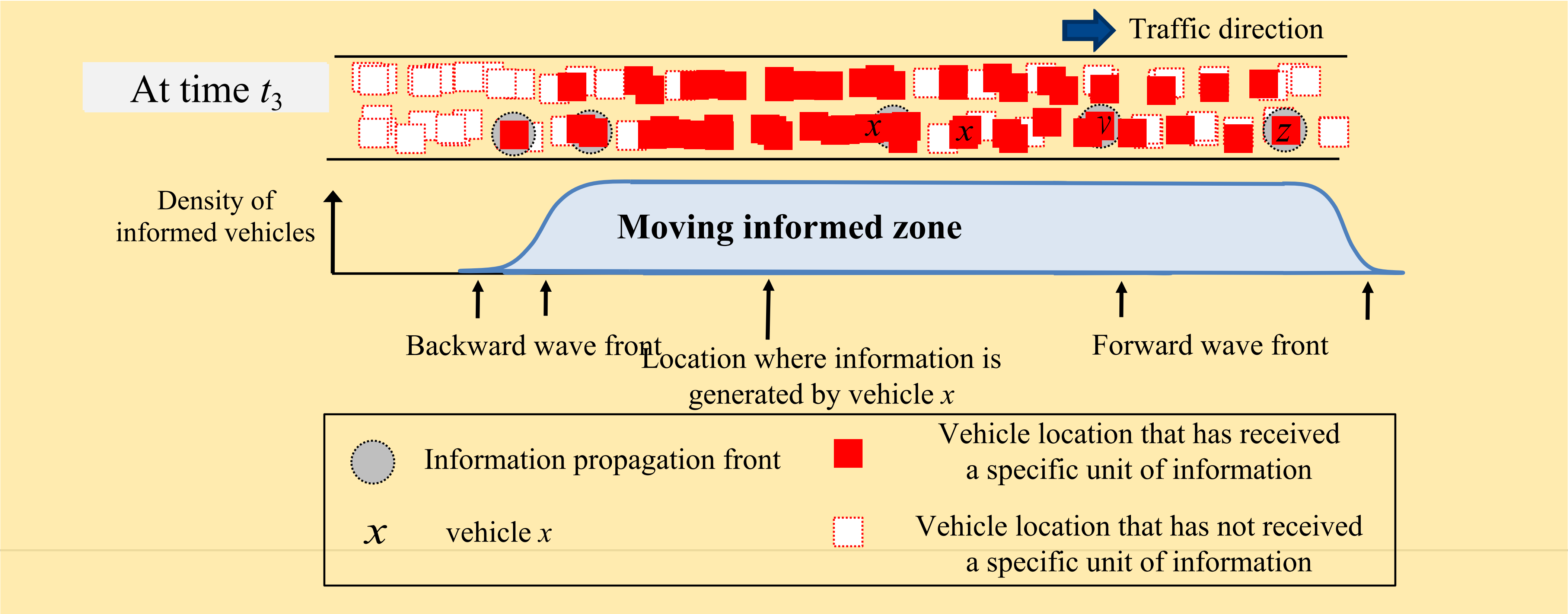
Traffic flow dynamics: speed, density	Communication constraints: distance, interference	Environmental factors: urban/rural area

- How does information propagate in space and time?

Necessary conditions	Under what traffic and communication conditions can information propagate in the network?
Speed	How quickly can information propagate?
Information density	What is the number of equipped vehicles that can receive information?

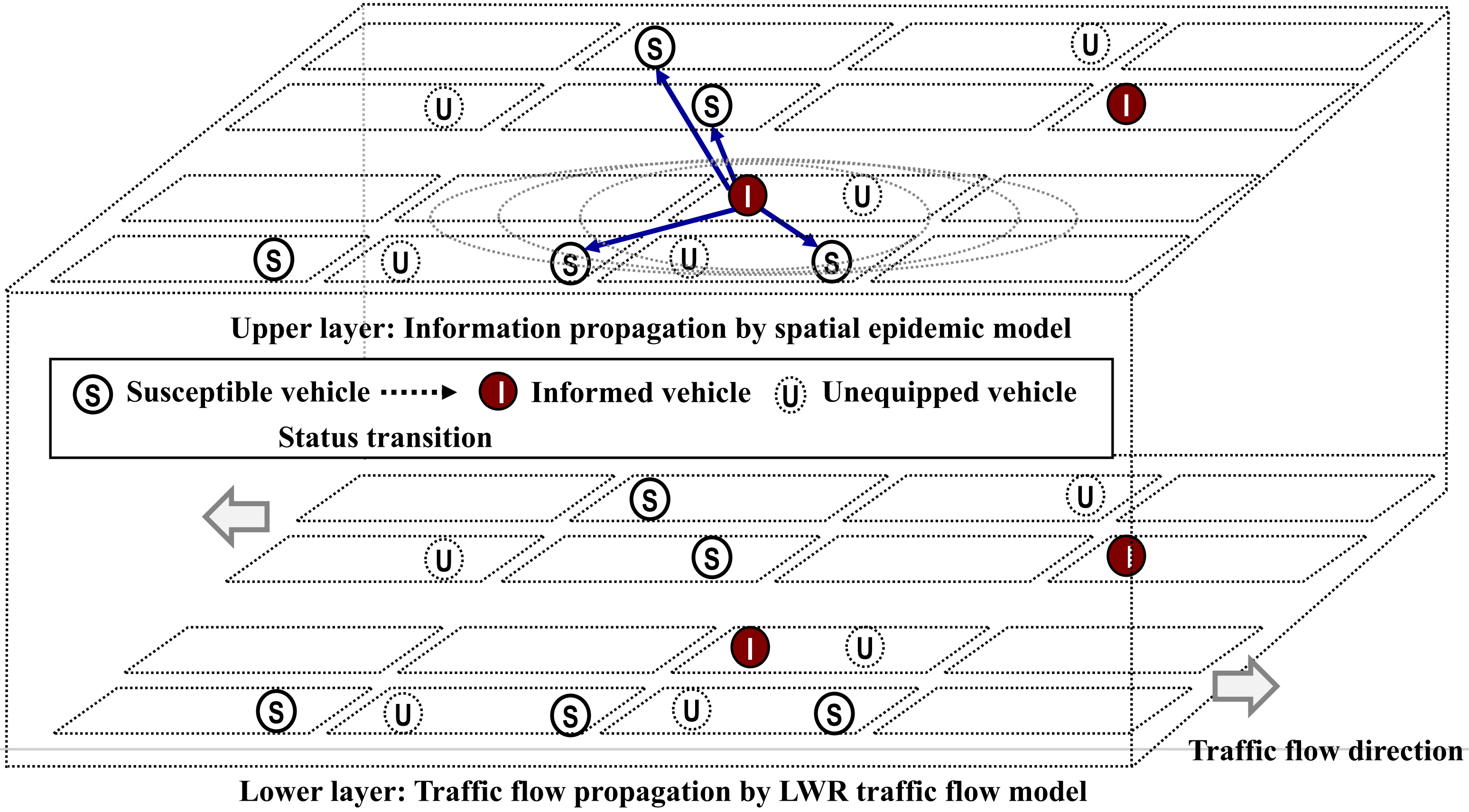
Modeling Framework: Macroscopic Model

- Information flow propagation wave (IFPW)
  - Forms a moving boundary that separates traffic flow into informed and uninformed regions, and moves towards the uninformed region
  - Can describe how density, speed, and location of vehicles lead to the evolution of dynamic information spreading

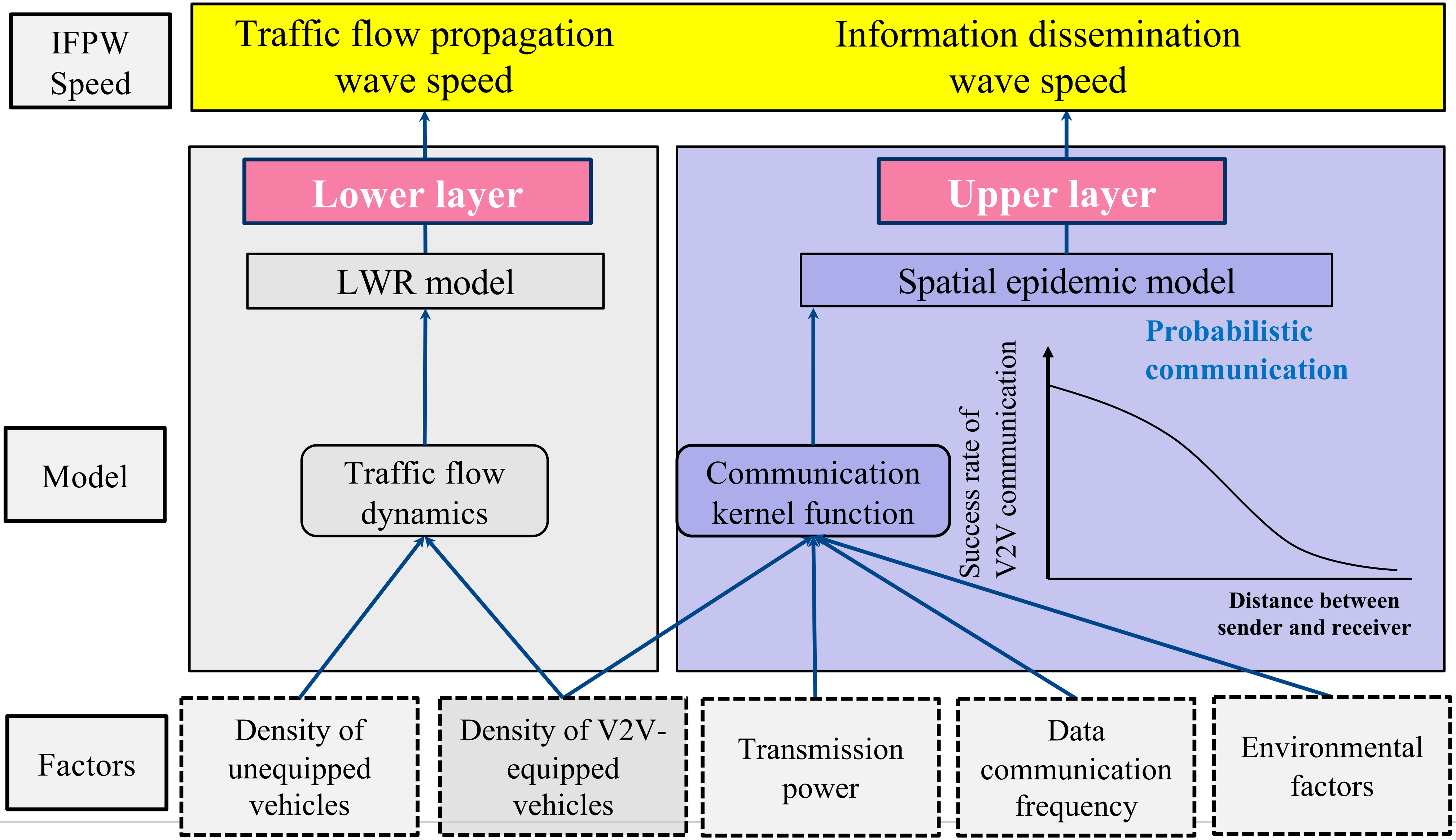


Modeling Framework: Two-layer Model

- Two-layer structure
  - Top layer describes dynamics of information propagation and bottom layer describes dynamics of traffic flow
  - Two-layer model captures interactions between upper and lower layers



Modeling Framework: Two-layer Model



Conceptual Leveraging and Modification of an Epidemic Model

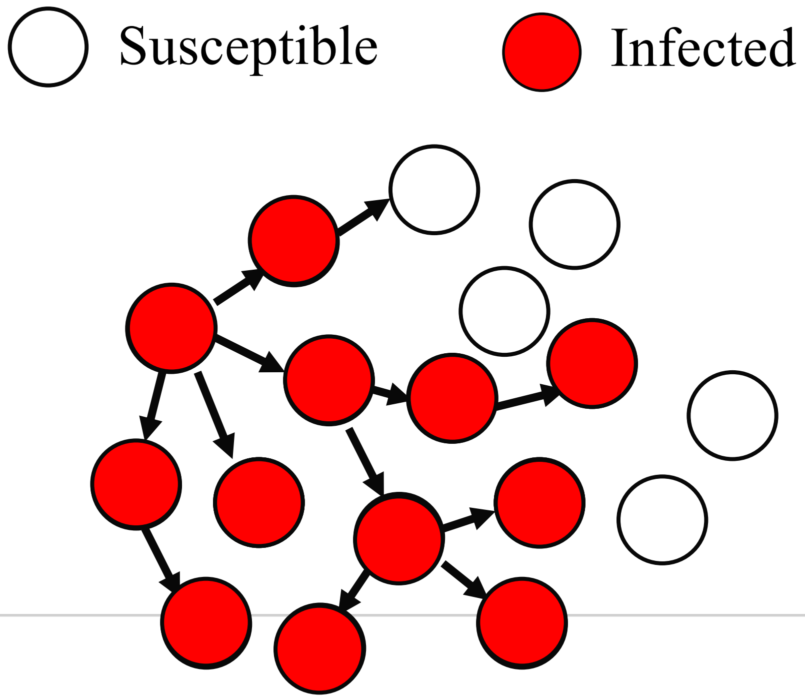
- Similarities and differences to epidemiology

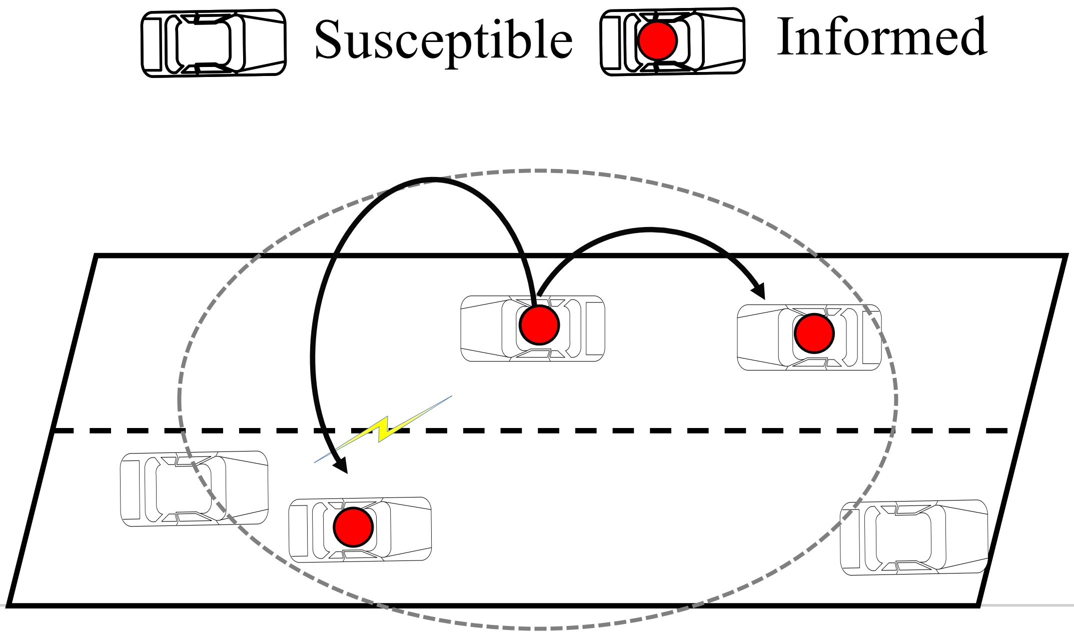
Notation	Epidemiology	V2V communications system
Network	All directions in a plane	Dynamic but geographically constrained topology
Population movement	No movement or random movement	Dynamic traffic flow
Infection rate	Fixed infection rate for a specific disease	Success rate changes with equipped vehicle density
Time resolution	Day/Month	Second
Research objective	Regulating spread of disease	Managing propagation of information

- Some similarities between the dissemination of information among V2V equipped vehicles and the transmission of infectious disease between the individuals
- Key differences exist in modeling a V2V communication system

Epidemiology and V2V communications

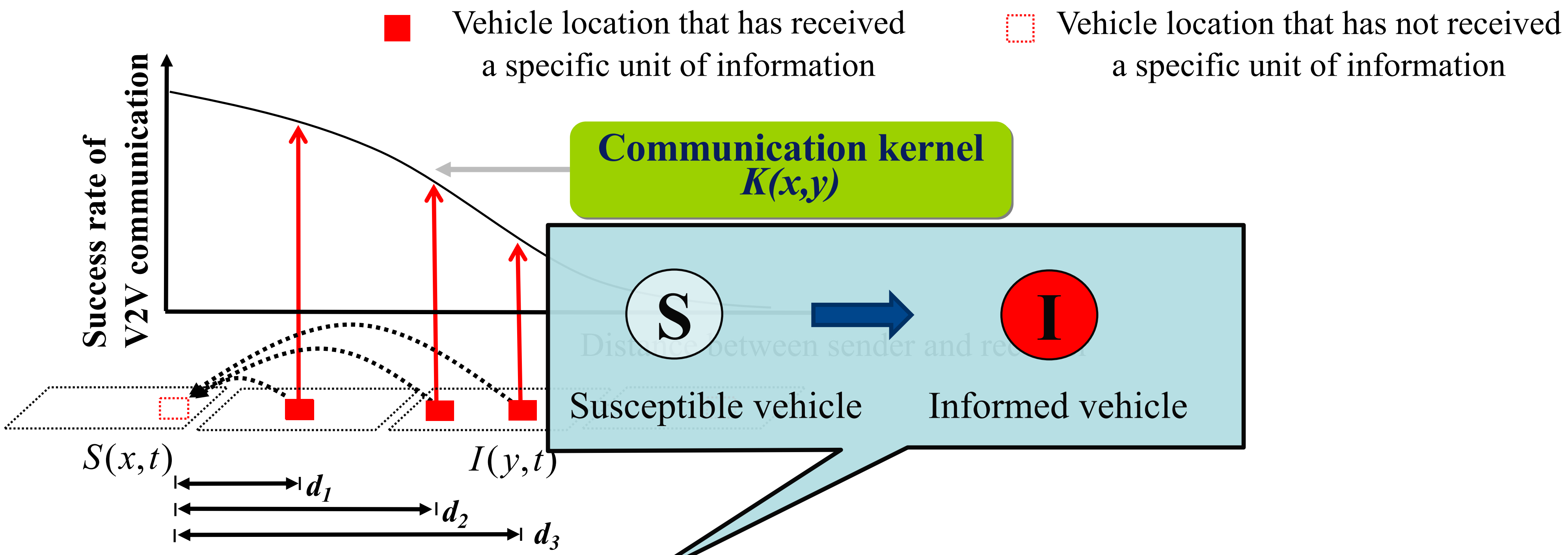
Notation	Epidemiology	V2V communications system
Susceptible (*S*)	Set of individuals susceptible to infection	Set of vehicles that potentially can receive information
Informed (*I*)	Set of infectious individuals	Set of vehicles which have information
Unequipped (*U*)	Set of vaccinated individuals	Set of unequipped vehicles





Model Formulation (Upper Layer)

- Spatial epidemic model (Integro-differential equations)



$$\frac{\partial S}{\partial t} = -\beta \cdot \left[\boxed{\int_{\Omega} K(x,y) \cdot I(y,t)\,dy} \right] \cdot S(x,t)$$

Integral in the IDEs is a weighted average over the spatial domain

$$\frac{\partial I}{\partial t} = +\beta \cdot \left[\int_{\Omega} K(x,y) \cdot I(y,t)\,dy \right] \cdot S(x,t)$$

Differential is an evolution equation specifying how the system will evolve with time

Rate at which susceptible vehicles (*S*) become informed vehicles (*I*)

Model Formulation (Lower Layer)

- Lower layer: Lighthill-Whitham-Richards (LWR) model

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0$$

Flow conservation law

$$q(x,t) = F(k,x,t)$$

Flow-density relationship

$k(x,t)$: Traffic density for cell x at time t

$q(x,t)$: Instantaneous flow

$F(k,x,t)$: Fundamental Diagram

Closed Form Solution of IFPW Speed

- Forward IFPW speed = $c_I + c_T$
- Derivation of closed form solution c_I

$$\frac{\partial I}{\partial t} = \beta \cdot E \cdot \left[\int_{\Omega} K(x,y) \cdot I(y,t) dy \right]$$

$$I(x,t) = A \cdot e^{-\theta(x - c_I t)}$$

$$I^*(x,t) = I(x - c_I t)$$

Kernel $K(u)$	c_I
Gaussian $\frac{\lambda}{\alpha\sqrt{\pi}} e^{-u^2/\alpha^2}$	$c_I = \pm\sqrt{\frac{e}{2}\alpha \cdot \beta \cdot \lambda \cdot E}$

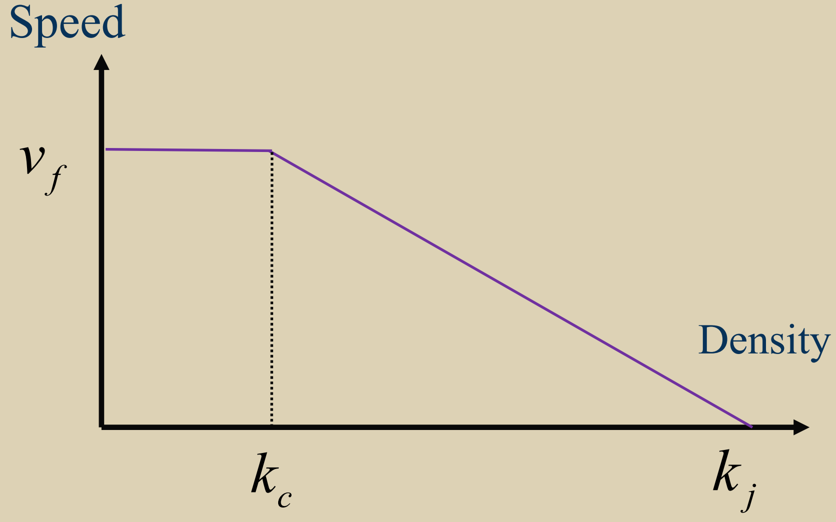
Kernel function shape

Density of equipped vehicles

Frequency of communication

- Traffic flow speed (c_T) is determined by the Fundamental Diagram

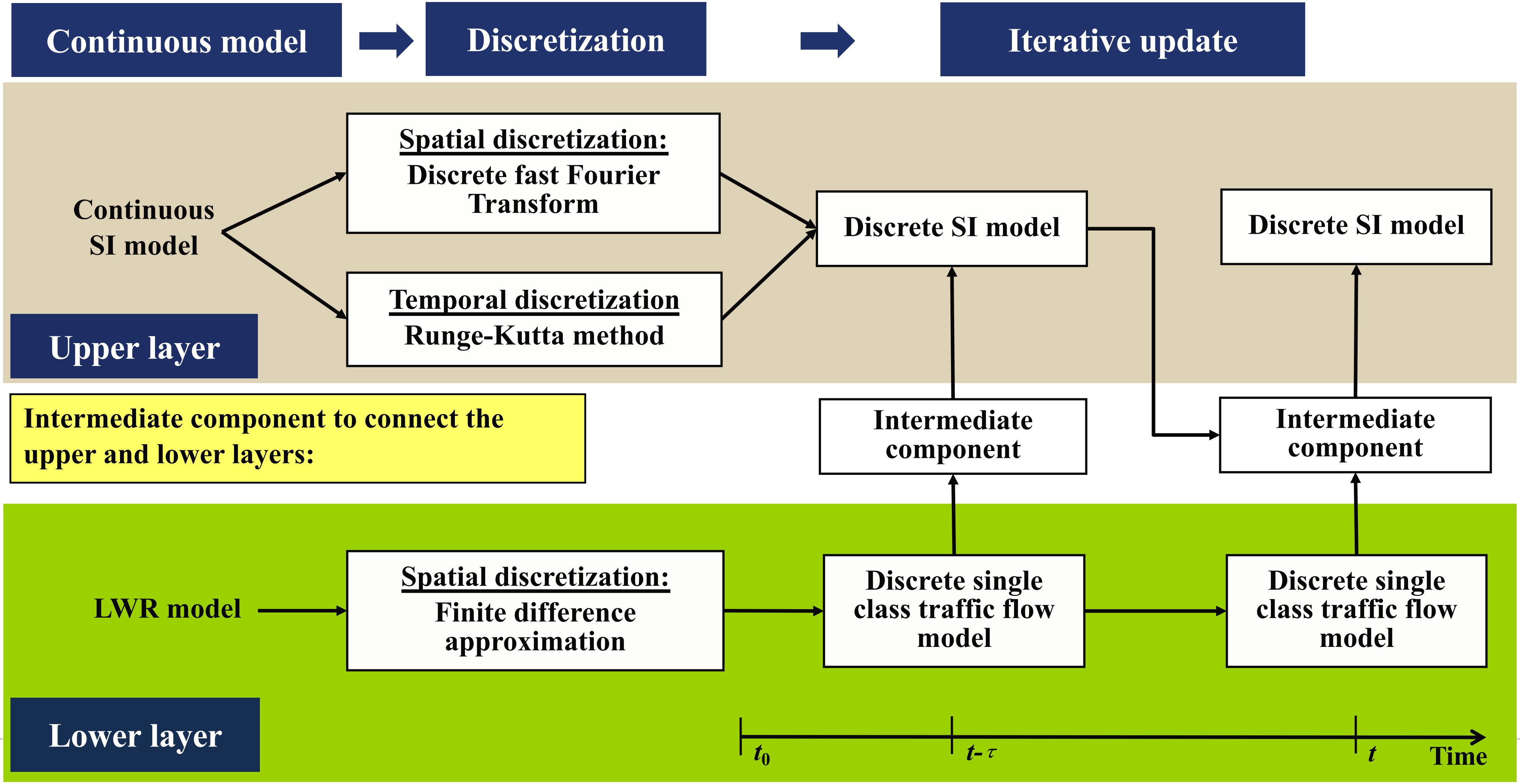
$$c_T = \begin{cases} v_f, & 0 \le k < k_c \\ \frac{k_c \cdot (k_j - k)}{(k_j - k_c) \cdot k} \cdot v_f, & k_c \le k \le k_j \end{cases}$$



v_f Free flow speed

k_c Critical density k_j Jam density

Numerical Solution Method for IFPW Speed



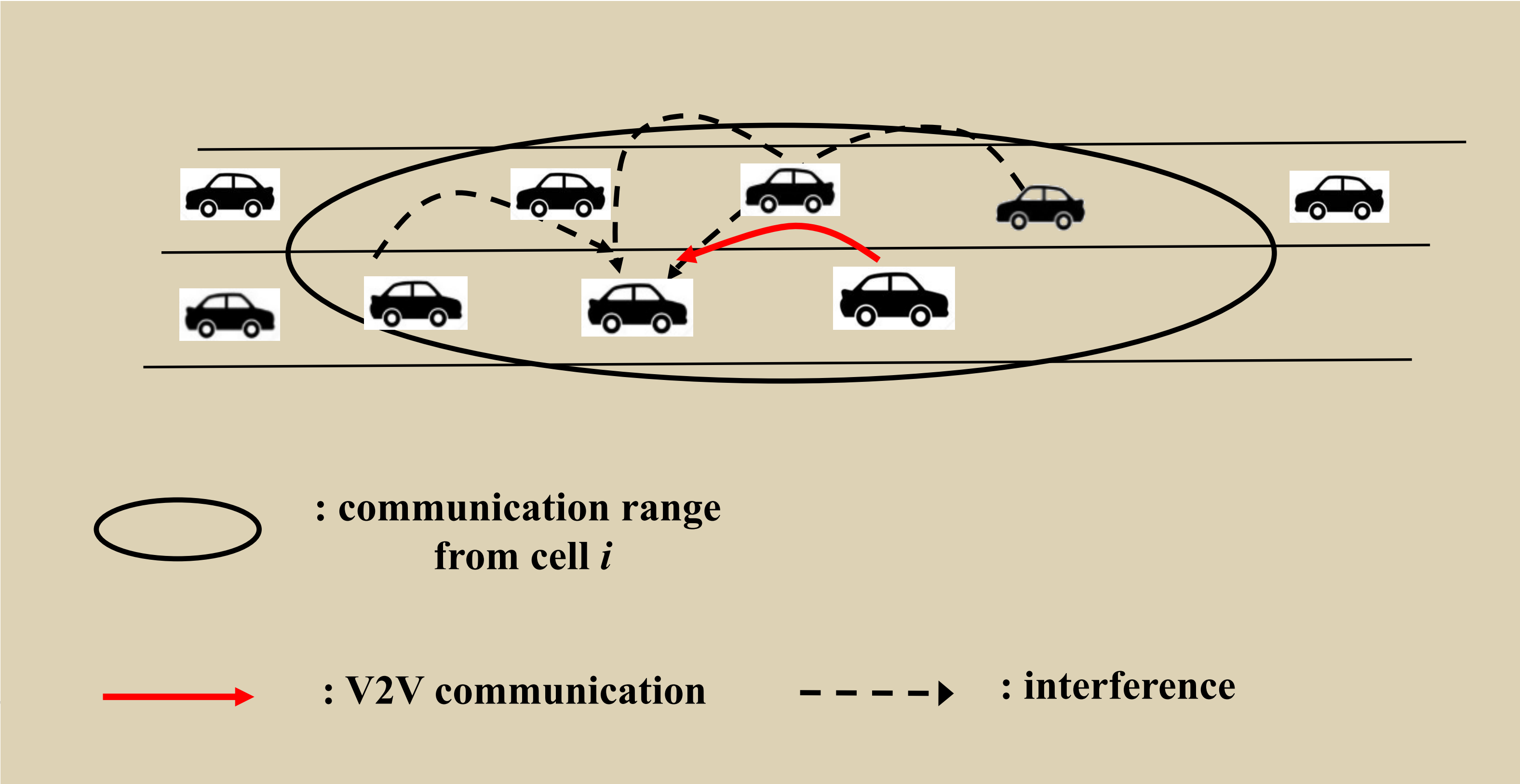
Numerical Experiments

- Experiment design
  - Test (corridor) network consists of 2000 cells which are equivalent to 30km of highway
  - Time interval (τ) is set to 0.5 seconds, consistent with communication frequency

Variables	Units	Value
Free flow speed (v_f)	(km/h)	108
Time interval (τ)	(seconds)	0.5
Grid cell length (u)	(meters)	15
Number of lanes	-	1
Market penetration rate (γ)	-	0.5
Number of cells	-	2,000
Critical density (k_c)	(vehicles/km/lane)	42
Jam density (k_j)	(vehicles/km/lane)	167
Frequency of communication (β)	(Hz)	2

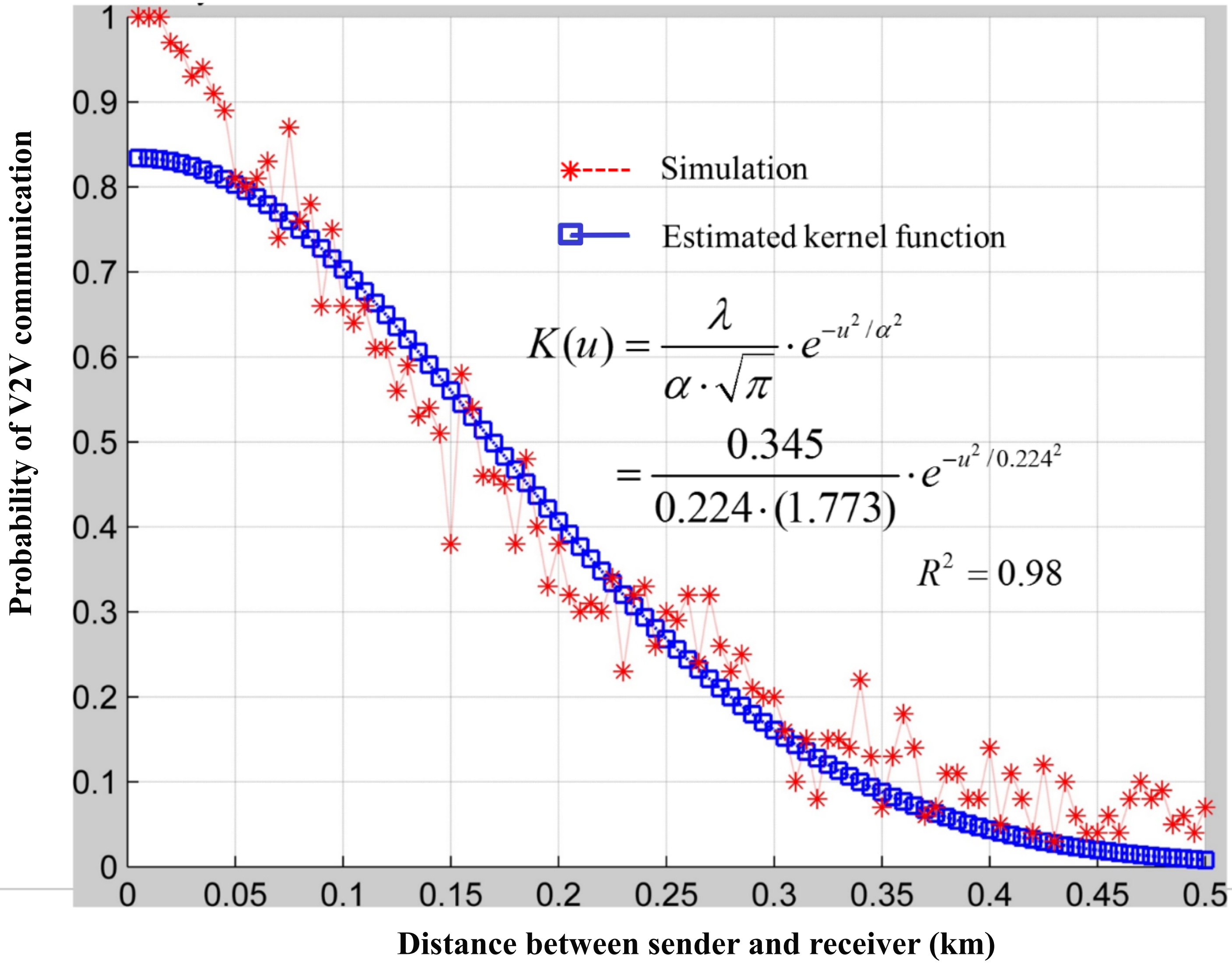
Estimation of Kernel Function

- Kernel function is estimated using a SINR model and Monte Carlo simulation
  - SINR (Signal to interference and noise ratio): [Gupta and Kumar, 2000]
  - Different densities with same market penetration rate (50%)
  - V2V communications-related constraints: communication range (500 meters)



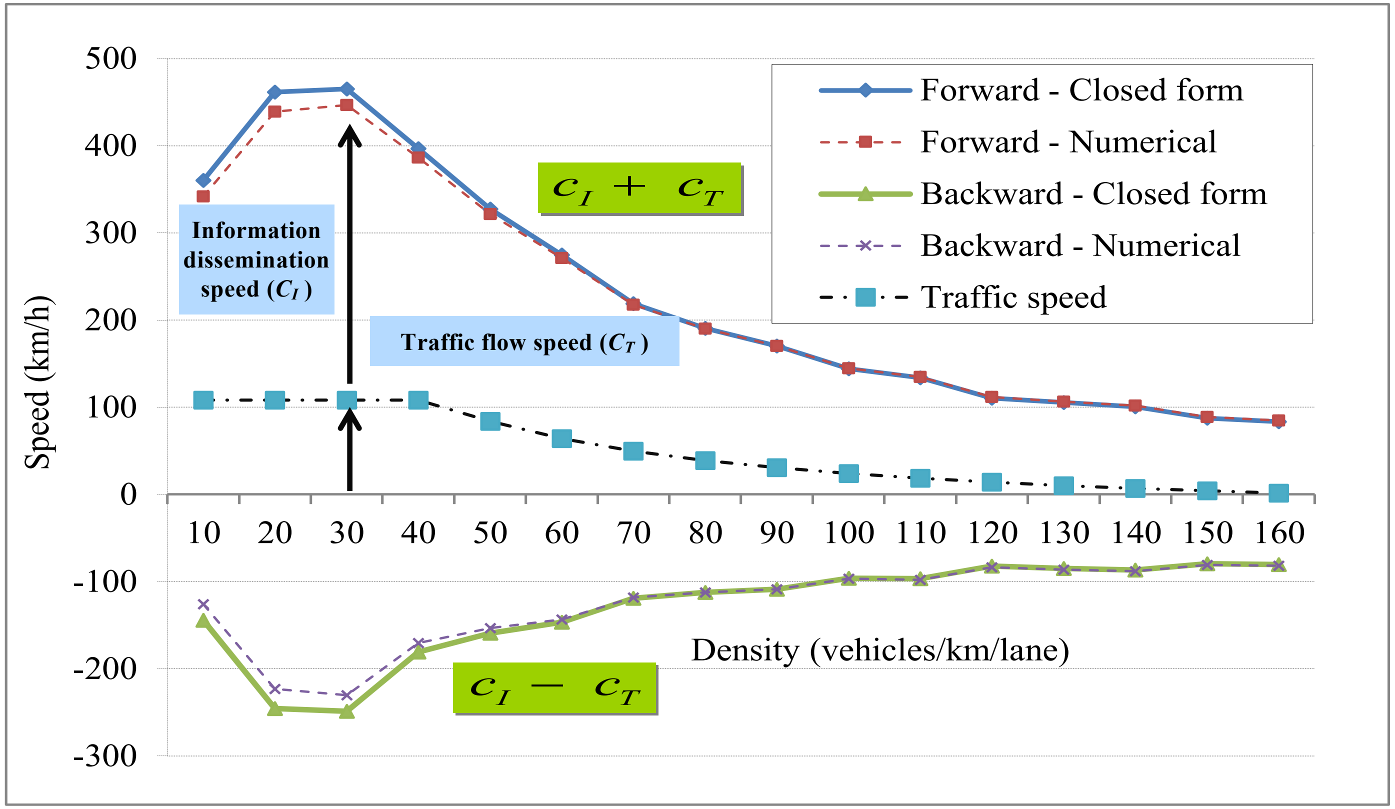
Estimation of Kernel Function

- Density (50 veh/km) and market penetration rate (50%)



Uniform Traffic Stream on Uni-directional Highway

- Comparison of closed form and numerical solution results



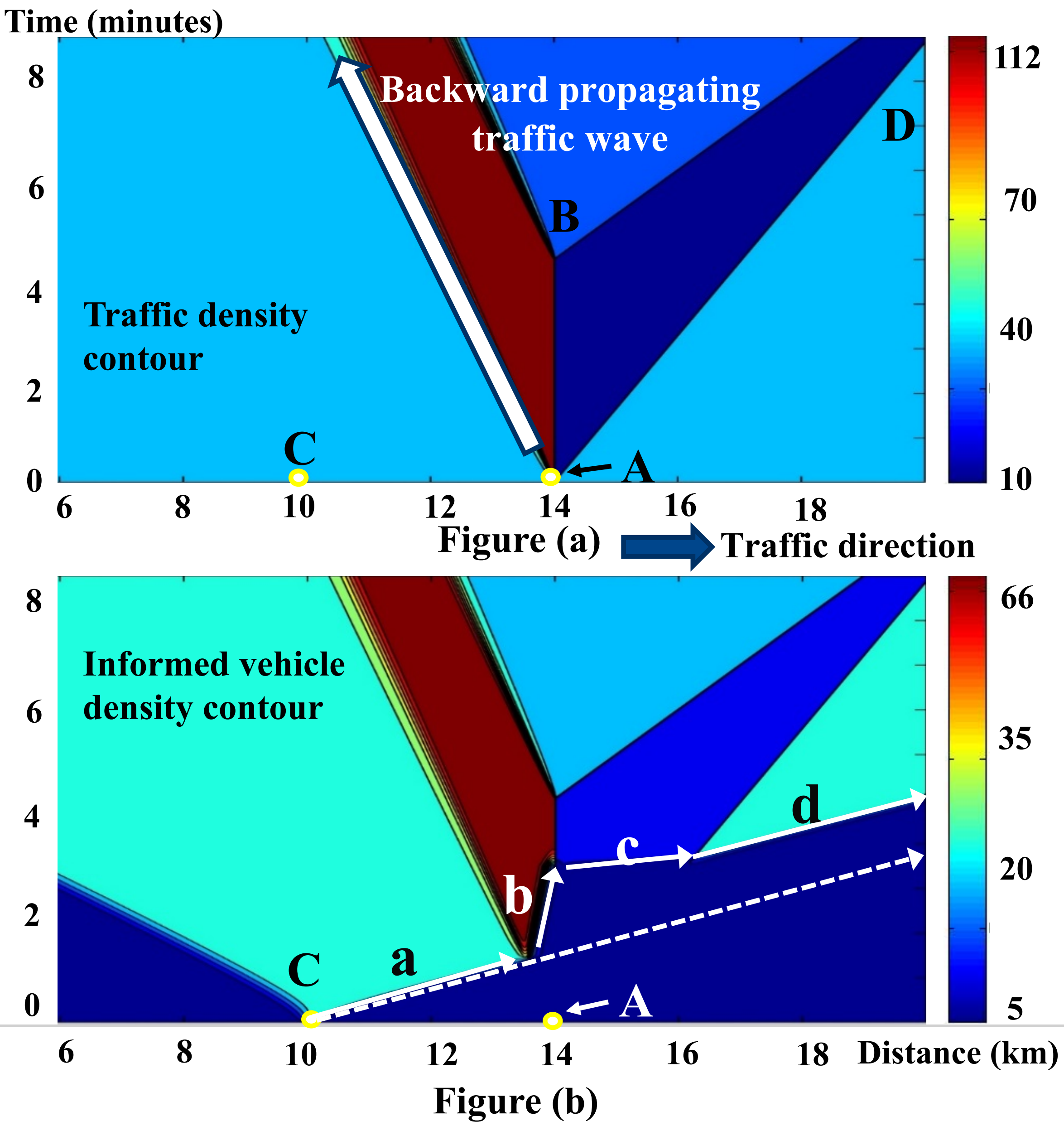
- Closed form solution results match information propagation speeds generated by numerical solution

Uniform Traffic Stream on Uni-directional Highway

- Relationship between traffic flow dynamics, V2V communications and forward propagation wave speed

Density level	Low	Low to medium	Medium	High
Information dissemination speed (Upper layer)	Medium	Maximum	Medium	Very low
Traffic flow speed (Lower layer)	Free flow speed	Free flow speed	Congested	Congested
IFPW speed (Sum)	Medium	Maximum	Medium	Very low

Non-uniform Traffic Stream



50 veh/mile/lane

A	An incident occurs
B	Capacity recovered
C	Location where information is generated
A-D	Location where discharging flow catches the tail of downstream flow

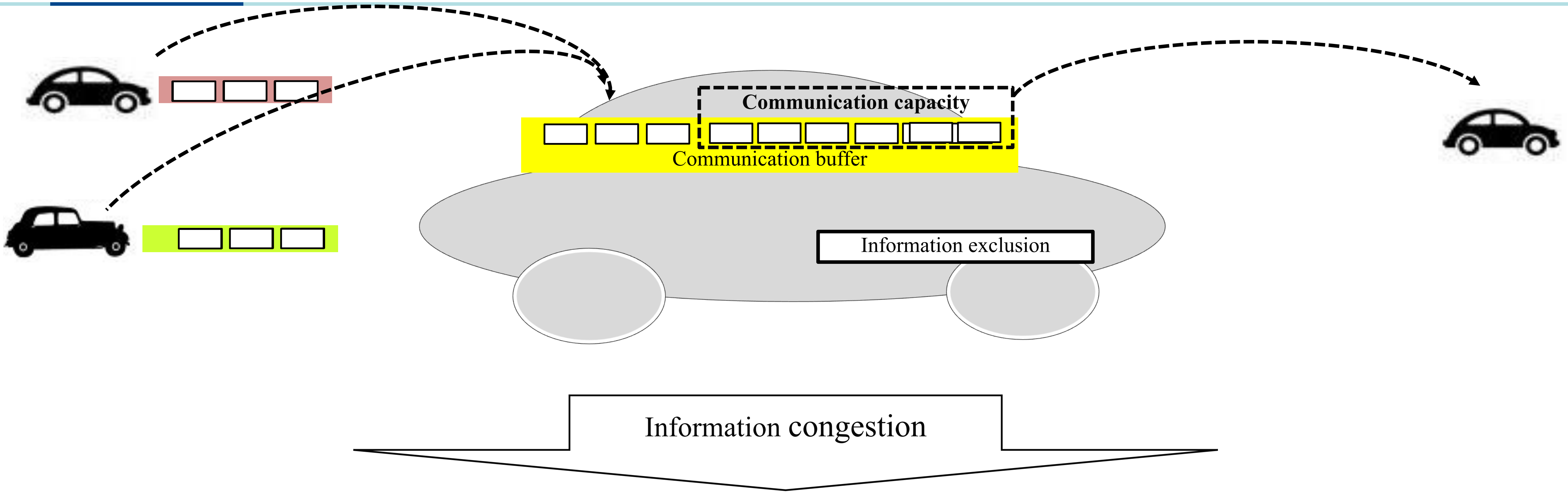
a, b, c, and d

Forward IFPW speed corresponding to downstream densities

Consideration of Information Congestion

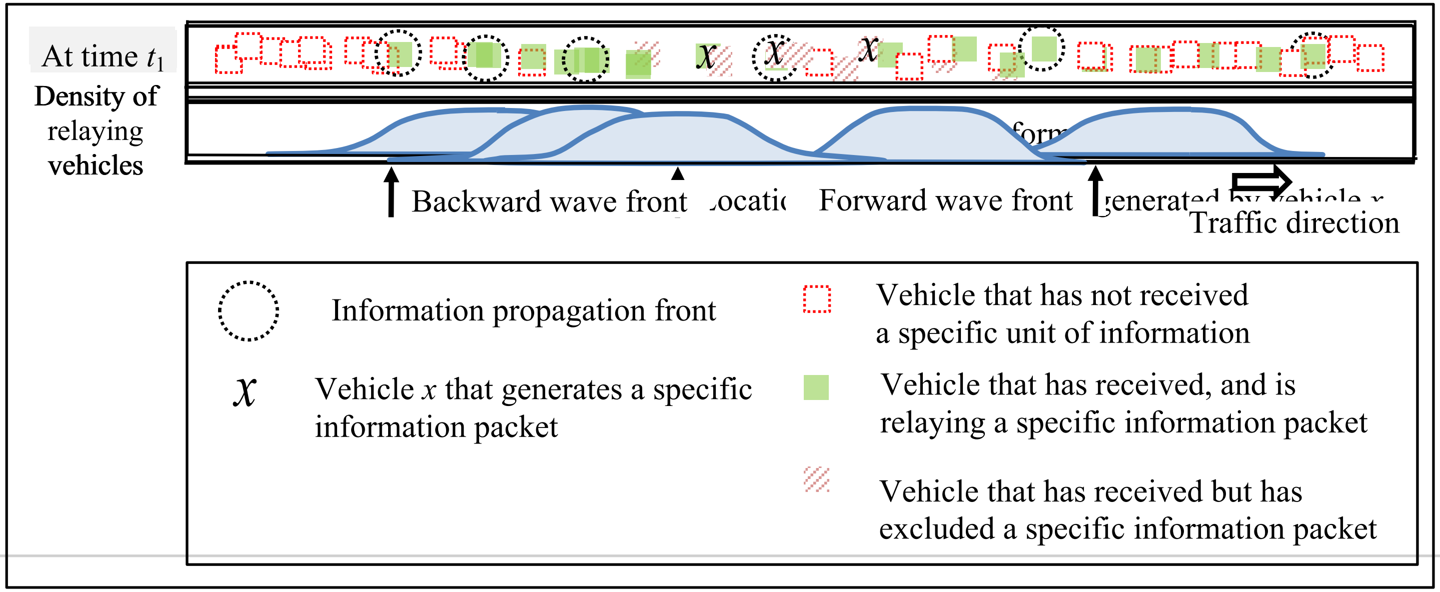
- Scenarios that can result in congestion effects for IFPW
  - Vehicular traffic congestion
  - Broadcasting storm
  - High information generation rate
- Develop information relay control strategy to address congestion effects
  - Preclude endless broadcasting of the same message
  - Reduce collisions of information packets by seeking to reduce congesting the communication network

Consideration of Information Congestion



IFPW under Information Congestion

- Susceptible vehicles become information-relay vehicles after they receive the specific information.
- Information-relay vehicles become information-exclusion vehicles when the specific information packet in the communication buffer is excluded.
- The wave forms a moving boundary that separates the traffic flow into partly informed and completely uninformed regions, and moves towards the uninformed region.



Model Formulation for IFPW

- IFPW under information congestion

$$
\begin{cases}
\dfrac{\partial S(x,t)}{\partial t} = -\beta \cdot S(x,t) \cdot \displaystyle\int_{\Omega} R(y,t) \cdot K(x,y) dy \\
\dfrac{\partial R(x,t)}{\partial t} = \beta \cdot S(x,t) \cdot \displaystyle\int_{\Omega} R(y,t) \cdot K(x,y) dy - \lambda \cdot R(x,t) \\
\dfrac{\partial X(x,t)}{\partial t} = \lambda \cdot R(x,t).
\end{cases}
$$

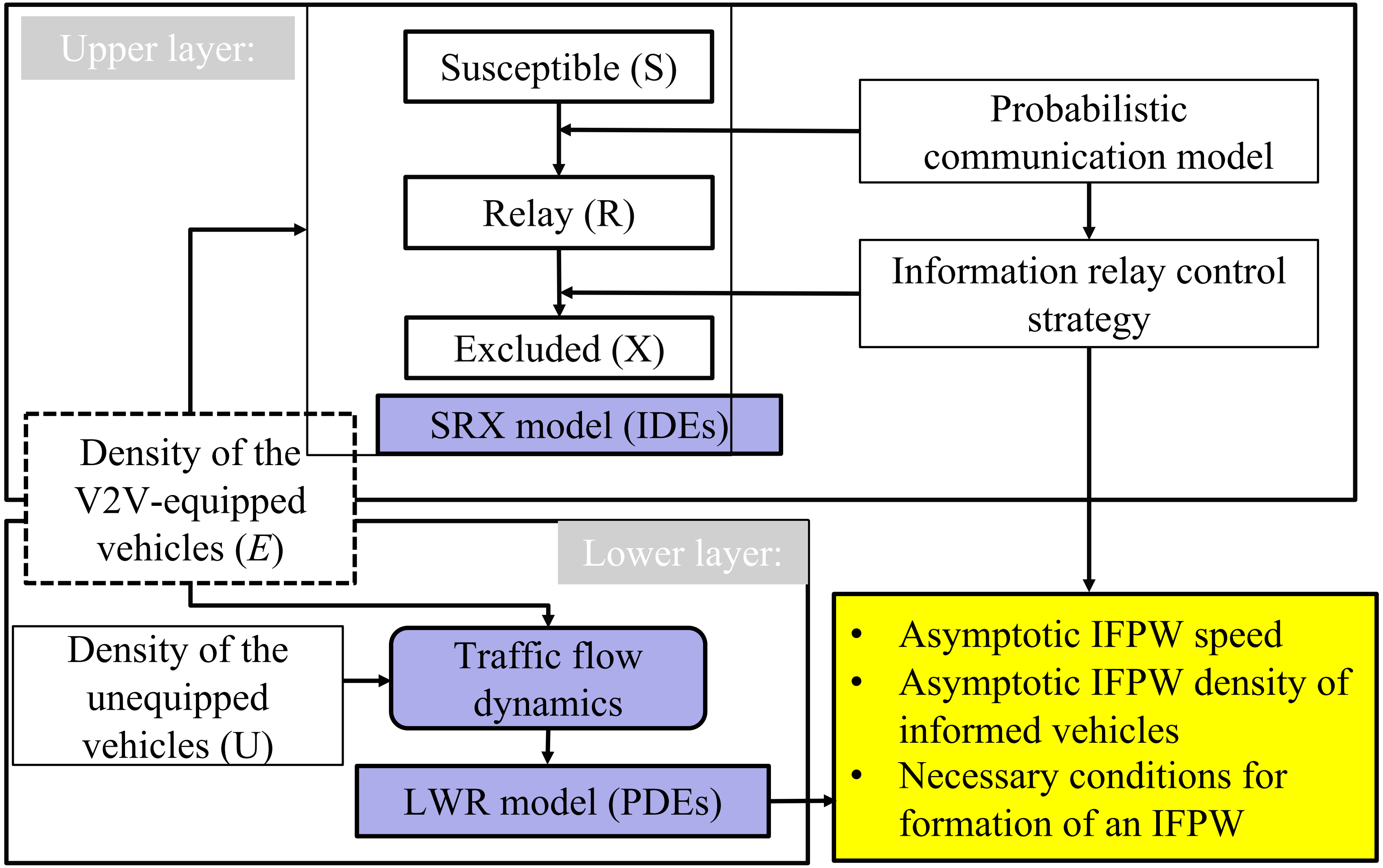
$S(x,t)$: density of susceptible vehicles at location x at time t

$R(x,t)$: density of information-relay vehicles at location x at time t

$X(x,t)$: density of information-excluded vehicles at location x at time t

λ: information exclusion rate

Modeling Framework: Congestion

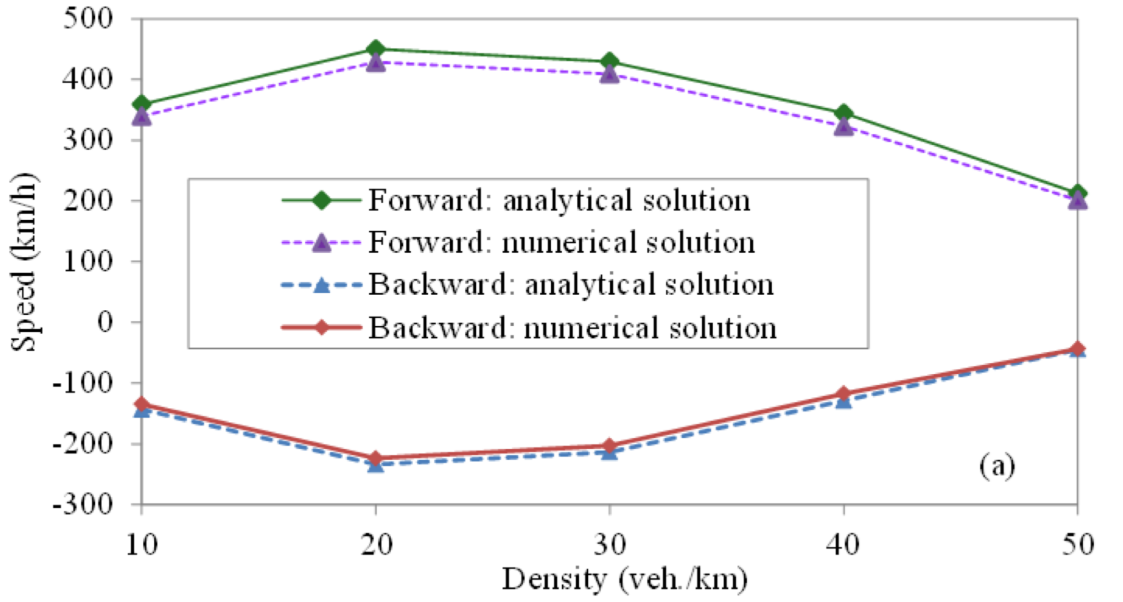


Comparison of IFPW under Uniform Traffic Density

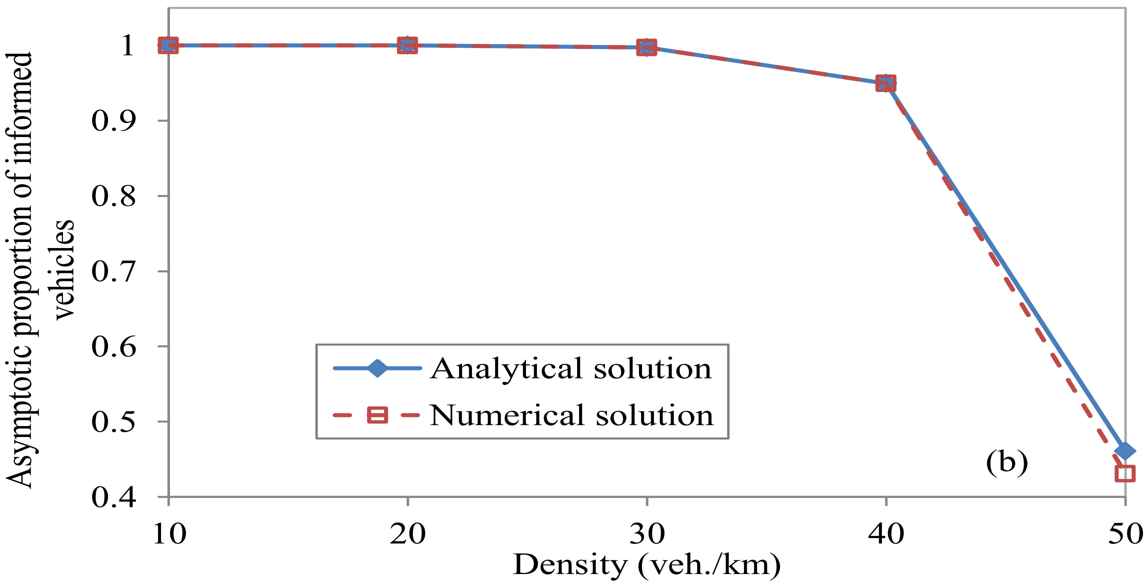
	Uncongested case	Congested case
Communication Buffer	≤Full	Full
IFPW Speed	Faster	Slower
Density of informed vehicles	100%	$\leq$ 100%

Numerical Experiment

- Asymptotic IFPW speed and proportion of informed vehicles under uniform traffic density



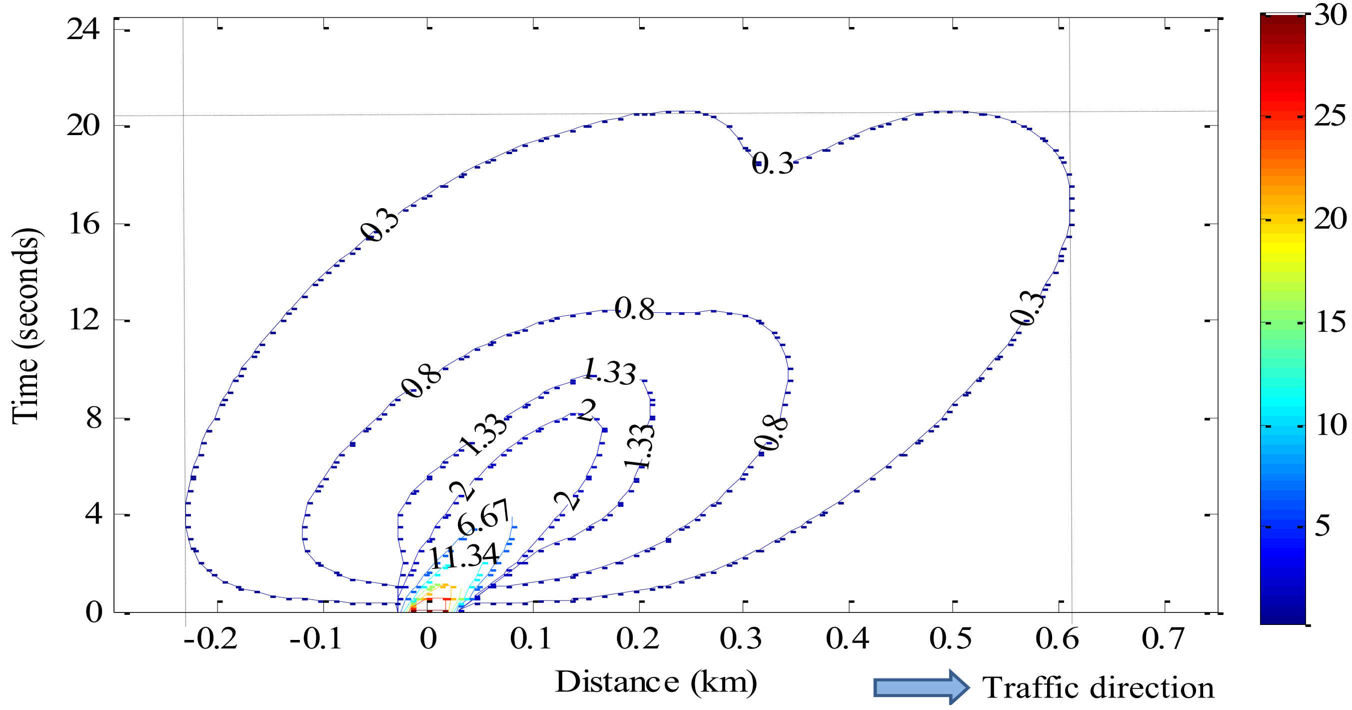
Asymptotic IFPW speed



Asymptotic proportion of informed vehicles under uniform traffic density

Numerical Experiment

- Scenario in which IFPW does not exist (information cannot be propagated far away)



Density contour of information-relay vehicles at $k = 60$ veh./km

- Density of $R(x, t)$ decrease in space and time
- Information is only propagated to area with limited range
- Information in the buffer is excluded too quickly to be propagated

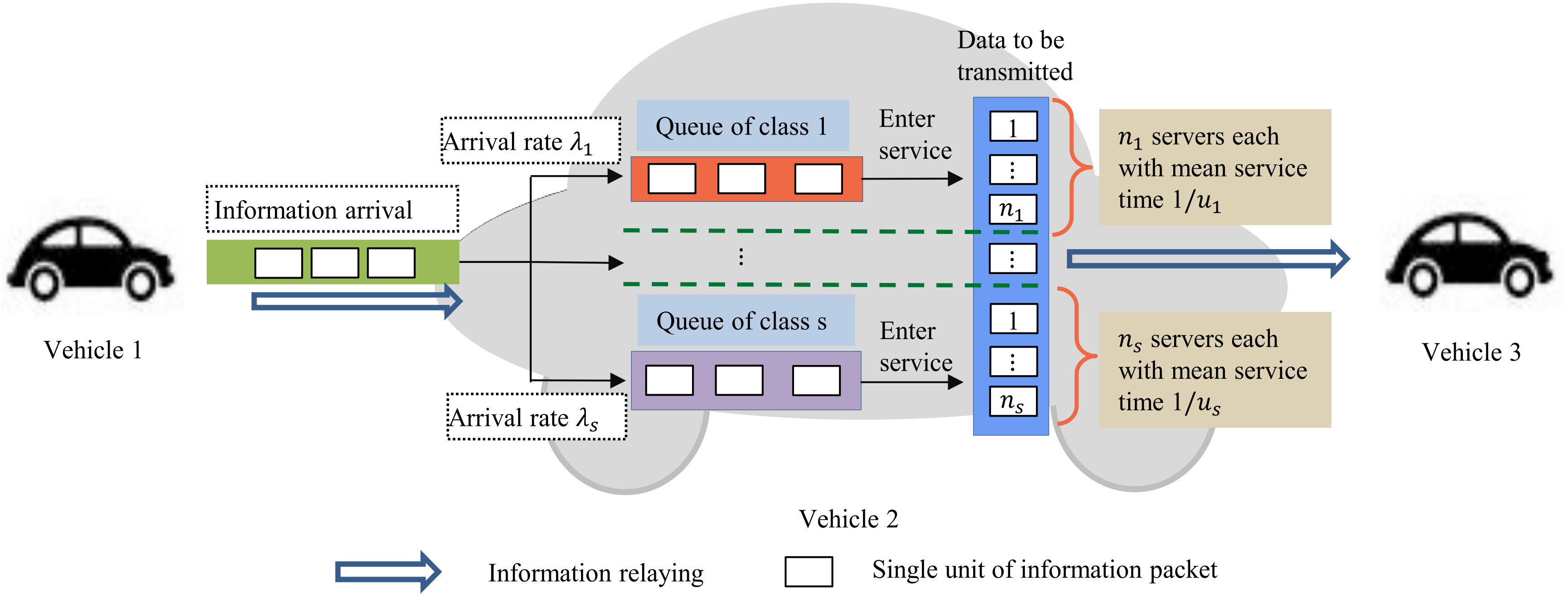
IFPW with Information Classes

- Categories of information delivered through V2V communication
  - Safety-related information (e.g., beacon information)
  - Event-driven information (e.g., congestion, travel time)

Information	Time delay	Vehicular reception ratio
Urgent information	Low	High
Congestion	Medium	Medium/High
Routing	Medium	Medium

Queuing System for Multiclass Information Propagation

- Queuing system for sending received information
  - Packets in different information class will form different queues
  - Number of servers will be assigned to send packets in different information classes to control waiting time
  - Mean service rate will be determined for each information class to control the waiting time and duration of information transmission



Model Formulation for IFPW

- **Information dissemination flow model in the upper layer**

For information packets with priority class j, we have

$$
\begin{cases}
\dfrac{\partial S_j(x,t)}{\partial t} = -\beta S_j(x,t) \displaystyle\int_{\Omega} R_j(y,t) \cdot K(x,y)dy \\
\dfrac{\partial H_j(x,t)}{\partial t} = \beta \cdot \xi_j \cdot S_j(x,t) \displaystyle\int_{\Omega} R_j(y,t) \cdot K(x,y)dy - \left(n_j u_j - \lambda_j\right) \cdot H_j(x,t) \\
\dfrac{\partial R_j(x,t)}{\partial t} = \left(1 - \xi_j\right) \cdot \beta S_j(x,t) \displaystyle\int_{\Omega} R_j(y,t) \cdot K(x,y)dy + \left(n_j u_j - \lambda_j\right) \cdot H_j(y,t) - u_j \cdot R_j(x,t) \\
\dfrac{\partial E_j(x,t)}{\partial t} = u_j \cdot R_j(x,t)
\end{cases}
$$

Rate of change in density

Information-holding vehicles

$H_j(x,t)$	Density of information-holding vehicles at location x and time t for information class j
n_j	Number of communication servers for information class j
u_j	Communication service rate for information class j

- **Traffic flow in the lower layer (LWR model)**

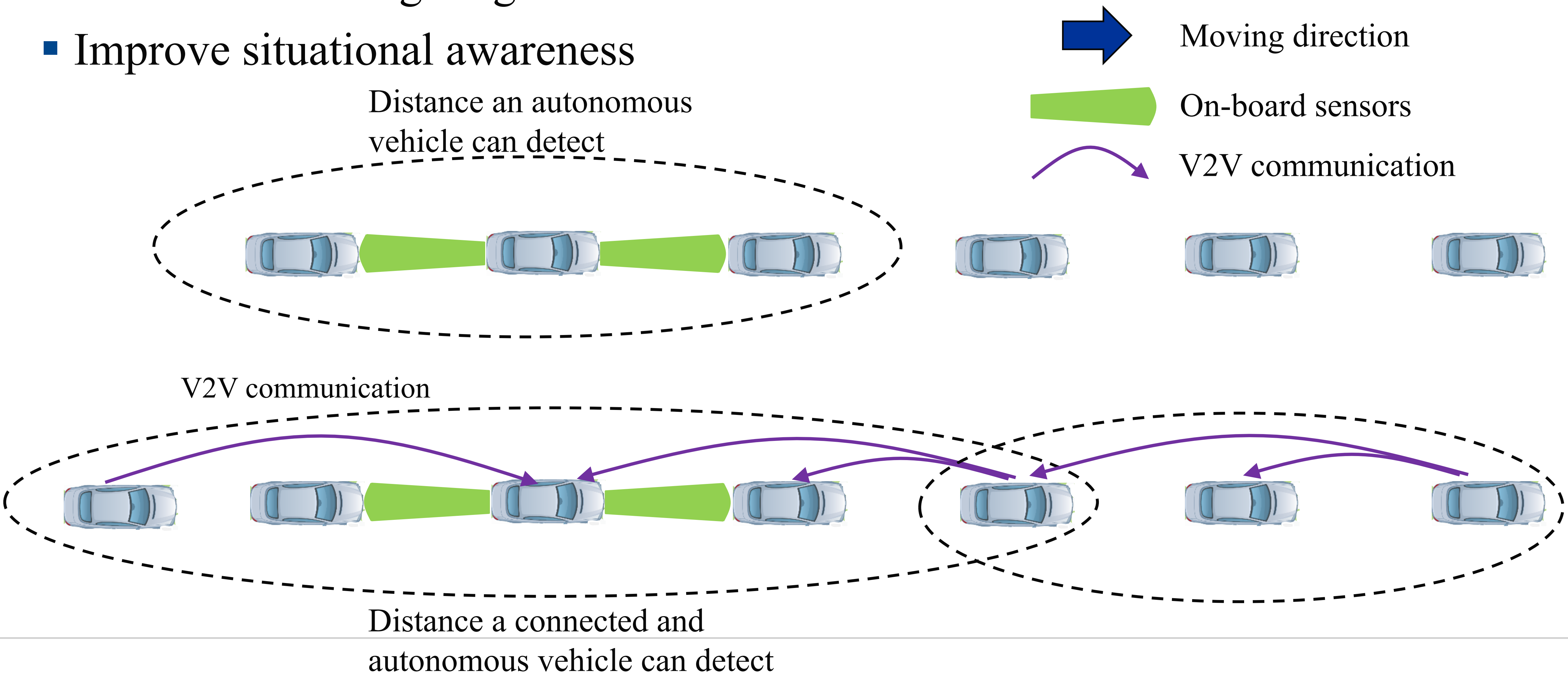
$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0$$

Information Flow Topologies for Platoon Control

- Wang, C., Gong, S., Zhou, A., Li, T. and Peeta, S. (2019). "Cooperative Adaptive Cruise Control for Connected Autonomous Vehicles by Factoring Communication-Related Constraints," ***Transportation Research, Part C: Emerging Technologies***, Vol. 38, pp. 242-262.
- Gong, S., Zhou, A. and Peeta, S. (2019). "Cooperative Adaptive Cruise Control for a Platoon of Connected and Autonomous Vehicles Considering Dynamic Information Flow Topology," ***Transportation Research Record: Journal of the Transportation Research Board***; doi.org/10.1177/0361198119847473.
- Li, Y., Chen, W., Peeta, S. and Wang, Y. (2019). "Platoon Control of Connected Multi-Vehicle Systems under V2X Communications: Design and Experiments," ***IEEE Transactions on Intelligent Transportation Systems***; doi: 10.1109/TITS.2019.2905039.
- Li, Y., Tang, C., Peeta, S. and Wang, Y. (2019). "Integral-Sliding-Mode Braking Control for Connected Vehicle Platoon: Theory and Application," ***IEEE Transactions on Industrial Electronics***, Vol. 66, No. 6, pp. 4618-4628.

V2V Communications and Autonomous Vehicles

- Extend the sensing range of an autonomous vehicle
- Improve situational awareness



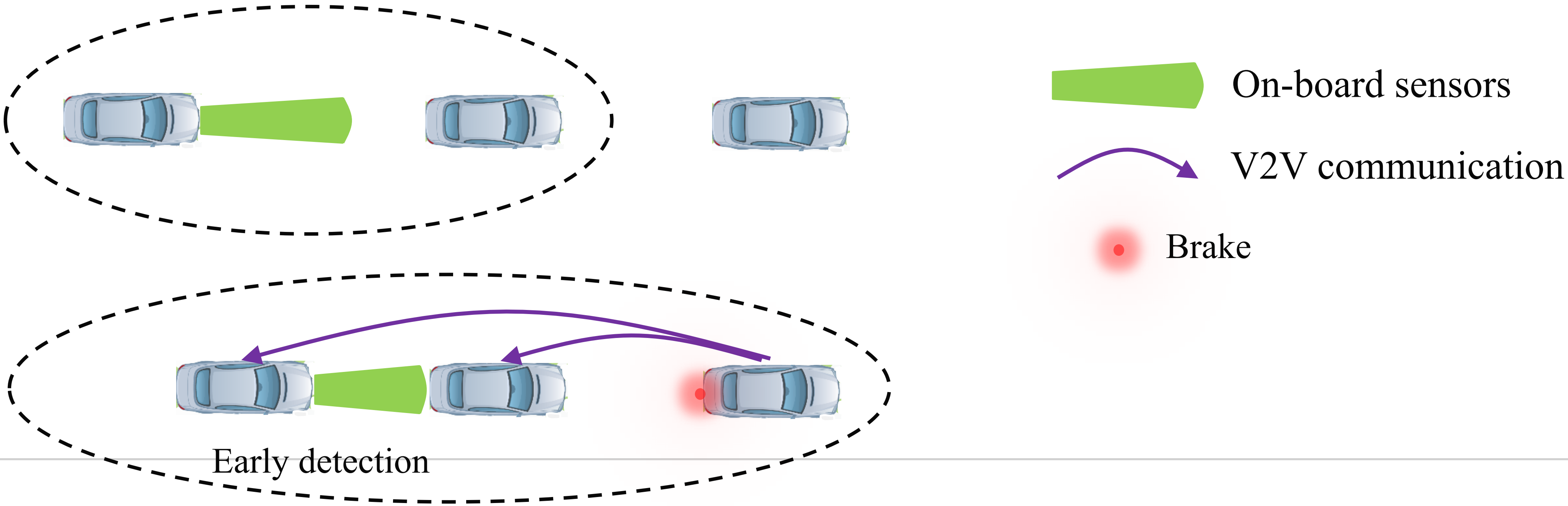
Platoon of Connected and Autonomous Vehicles (CAVs)

- Platoon of CAVs: a stream of vehicles that drive together

- Benefits of CAV platoon
  - Increase link capacity
  - Save energy
  - Reduce greenhouse gas emissions
  - Reduce traffic delays

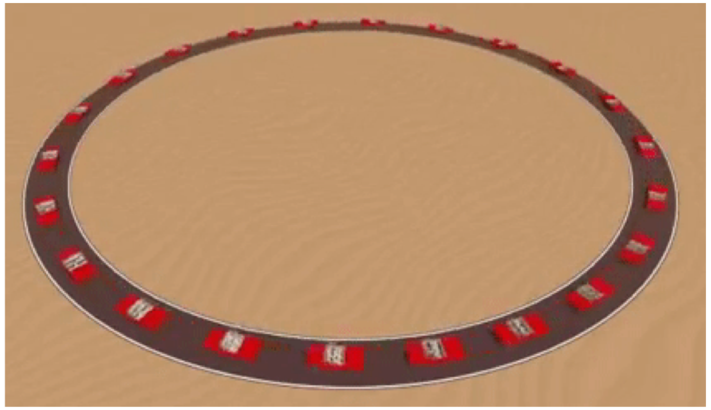
Impacts of V2V Communications on CAV Platoon

- Enable vehicles to form a platoon
- Enhance platoon stability
- Multi-anticipative capability to follow predecessor closer

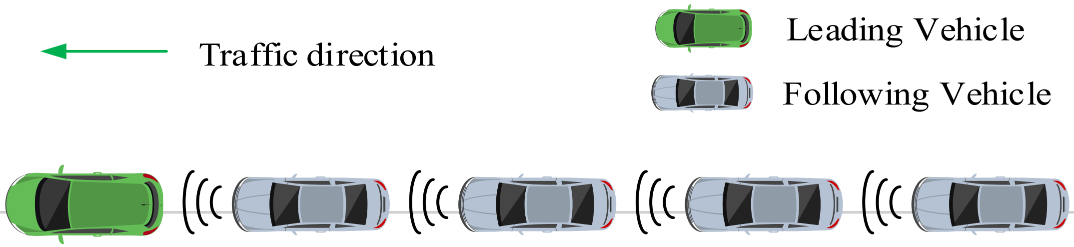


Traffic Congestion and Platoon Control

- **Traffic congestion and traffic oscillations**
  - Traffic oscillation: “stop-and-go” or “slow-and-fast” traffic propagation in traffic flow
  - Caused by improper traffic control, such as driving behavior and signal control
  - Leads to traffic congestion

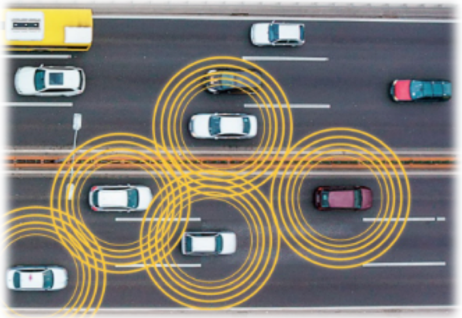


- **Platoon and Adaptive cruise control (ACC)**
  - Maintain stable and safet distance/time headway
  - Obtain real-time information from onboard sensor

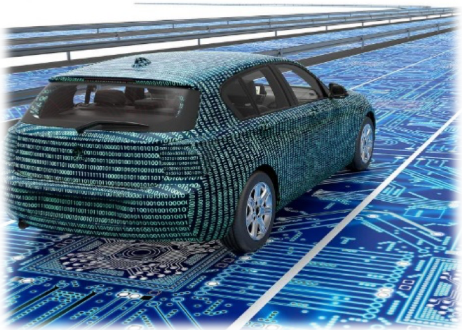


CACC

- **CAV system**
  - On-board computation enables autonomous drive
  - V2V enables information exchange
  - Obtain more information on surrounding traffic environment via V2V communications



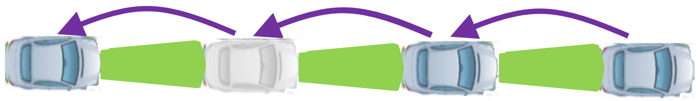
- **Cooperative adaptive cruise control (CACC)**
  - Automatically and <u>cooperatively</u> adjust CAVs' speeds
  - Maintain a stable and safety distance/time headway
  - <u>Damp traffic oscillations</u>
  - Detect real-time traffic condition:
    - On-board sensors
    - <u>Communication facilities</u>



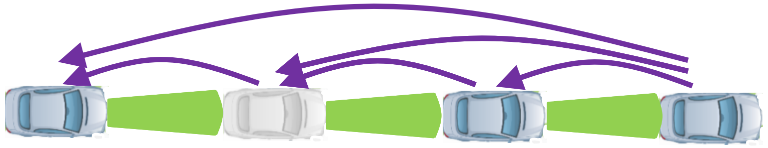
Information Flow Topology (IFT)

- **Information flow topology (IFT)**
  - IFT for CACC: the configuration of V2V communication links among CAVs
  - Typical IFTs for CACC:

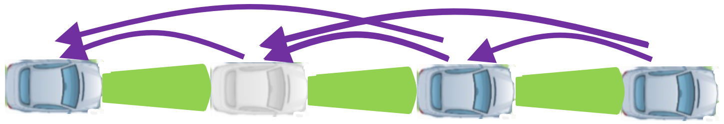
✓ Predecessor-following



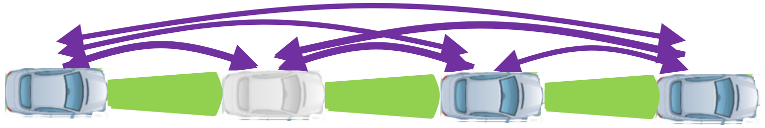
✓ Predecessor-following leader



✓ Two predecessor-following



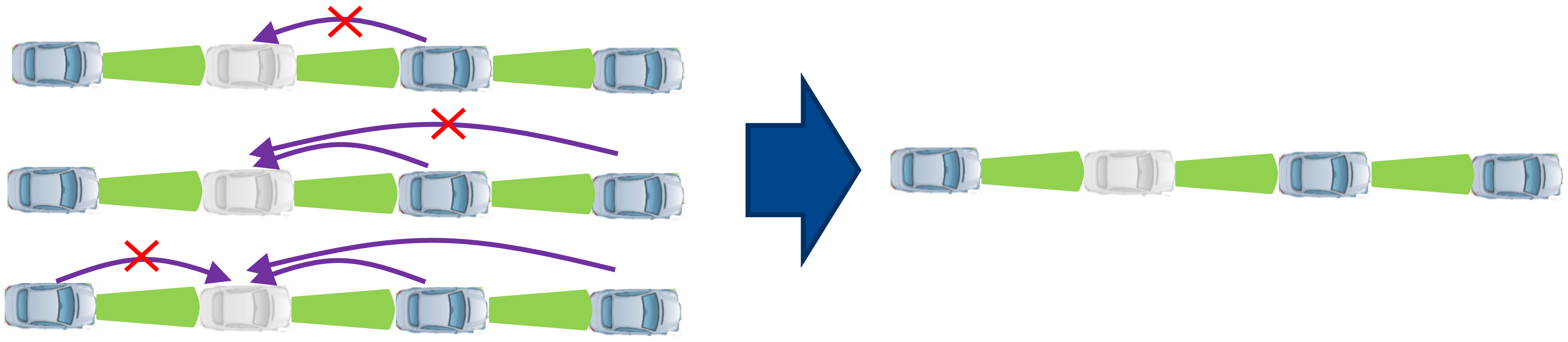
✓ Global communication



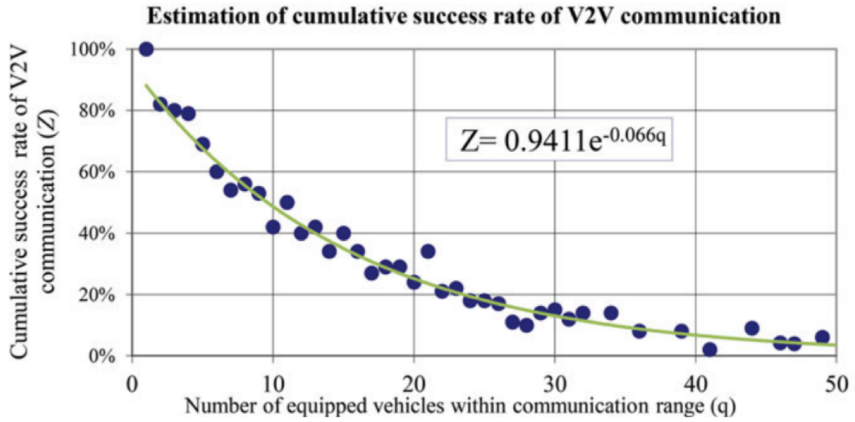
Most studies in CACC design assume a fixed and predetermined IFT

V2V Communication Failures

- Fixed and predetermined IFT ignores the fact that IFT can change dynamically due to communication failures



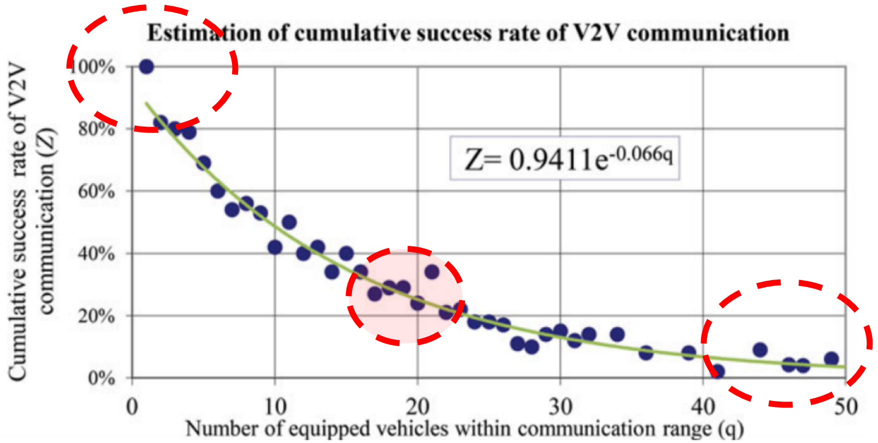
- Failure of V2V communications due to many factors
  - CAV traffic density
  - Number of ongoing V2V communications occurring within communication range (Kim et al., 2017)

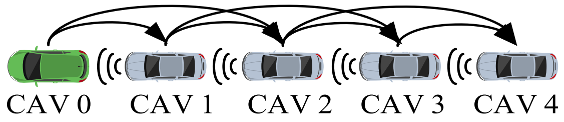


Communication success rate can increase under high CAV density if some communication devices are <u>deactivated</u>

Optimal IFT

Trade-off





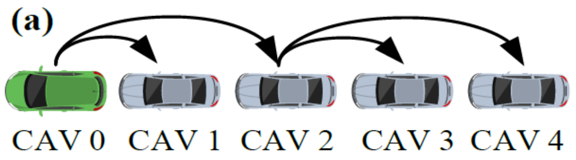
IFT robustness	**Good**	**Bad**
Theoretical performance (without communication failure)	**Bad**	**Good**

An **optimal IFT** which achieves **trade-off** between **IFT robustness** and **theoretical performance** to enhance CACC performance in practice

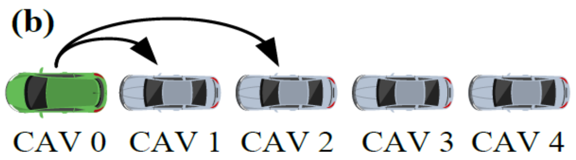
Find optimal IFT

IFT Degeneration Scenarios

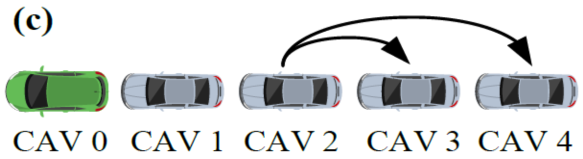
- **IFT degeneration**
  - For an optimal IFT, communication failure can occur and degenerate the IFT
    - Sender failure is considered. (Receiver-related failure: the distance between some senders is too large (Jeong et al., 2010; Whitehouse et al., 2005))
  - For example, optimal IFT in (a) has four degeneration scenarios



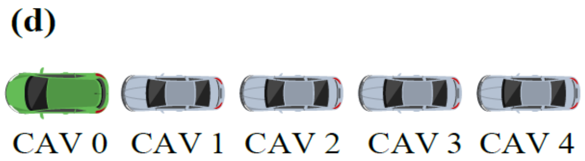
An example IFT with "send" functionalities of CAVs 1, 3 and 4 deactivated



Degeneration scenario of (b) with CAV 2 failing to send message



Degeneration scenario of (b) with CAV 0 failing to send message



Degeneration scenario of (b) with both CAVs 0 and 2 failing to send messages

New CACC controller to deal with dynamic IFT; focus on speed oscillation energy and string stability

Acknowledgments: My students and post-docs, NSF, USDOT

Questions and Comments

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