Transportation System Analysis Methods

TRANSPORTATION SYSTEMS MANAGEMENT AND OPERATIONS (TSMO)

TSMO refers to multimodal transportation strategies to maximize the efficiency, safety, and utility of existing and planned transportation infrastructure. Strategies including but not limited to:

- Traffic incident management.
- Traffic signal coordination.
- Transit signal priority.
- Freight management.
- Work zone management.
- Special event management.
- Road weather management.
- Congestion pricing.
- Managed lanes.
- Ridesharing programs.
- Parking management.

Active

Adaptive

Intelligent

Smart

How?
Rely on modern detection, communication, and control technologies and algorithms to allow agencies to improve the performance of the transportation system.

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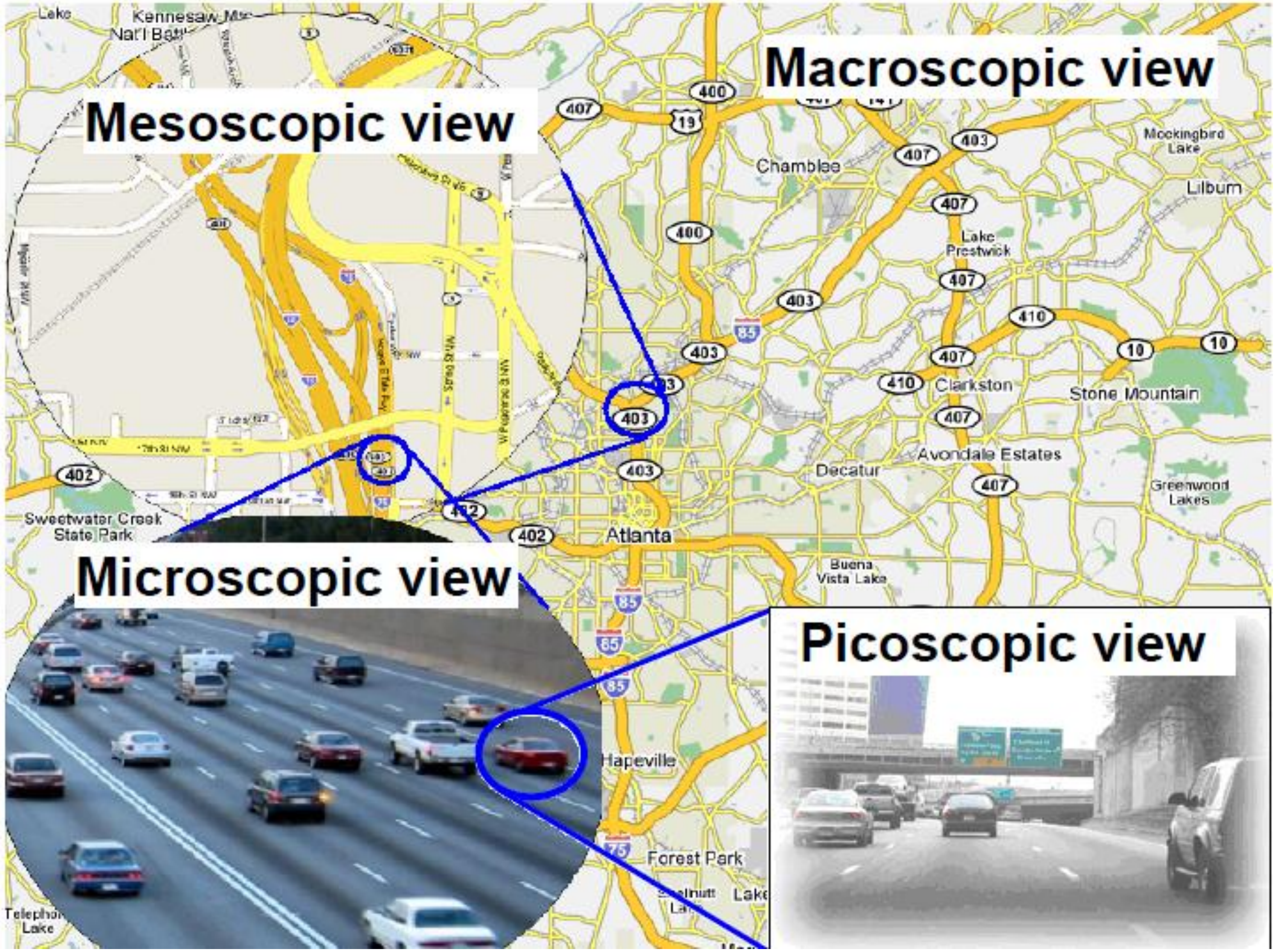

30,000 ft

10,000ft

1,000ft

Landed!!

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Source: Traffic Flow Theory: Characteristics, Experimental Methods, and Numerical Techniques (1st Edition) by Daiheng Ni

WHAT YOU HAVE SEEN…

- Viewing traffic at 30,000ft high, it appears to be a compressible fluid and its states (speed, flow and density) propagate like waves
- Viewing traffic at 10,000ft high, the sense of waves recedes and replaced by a scene of particles, or a chain of vehicles.
- Viewing traffic at 1,000ft high, the scene is more vivid and dominated by moving vehicles that interact with each other in order to maintain safe distance in traffic stream.
- Finally, viewing traffic from your windshield, you interact with the driving environment (e.g. roadways, traffic controls, and other cars, etc.) and constantly make decisions.

Traffic Flow Representation by Scale

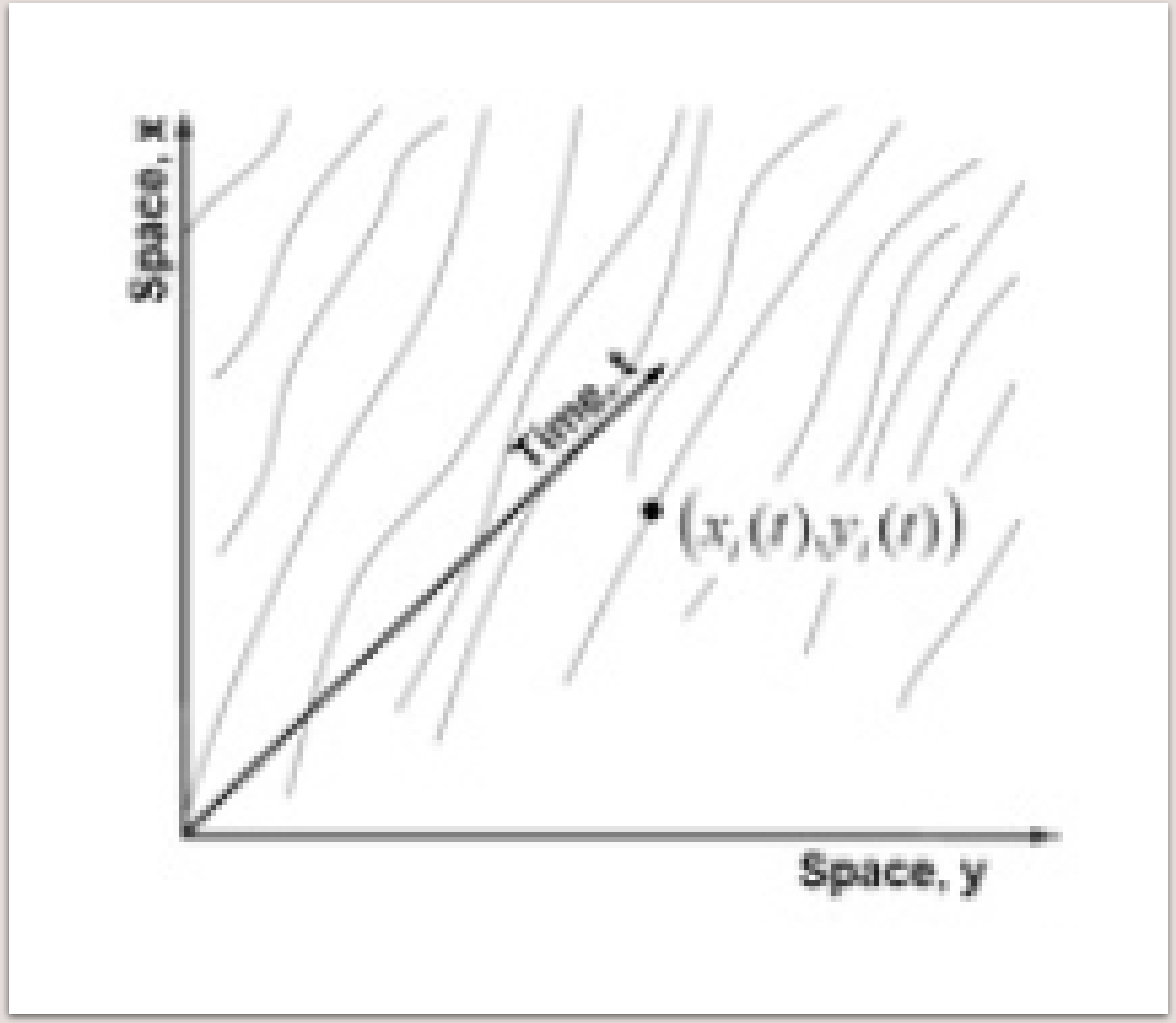
- Traffic flow representation can be translated between different scales.
- From high-resolution, low level to low-resolution, high level, or vice versa.
- Why do we want to model traffic flow at different scales?
- How do we model traffic flow at different scales?
- Do the models at different scales perform consistently or share the same theoretical foundation?

The Picoscopic Scale

- Picoscopic modeling represents traffic flow by the **trajectory of each vehicle** using state variables($x_i(t)$; $y_i(t)$) where i $\in$(1,2,3..) denotes vehicles that can be tracked both longitudinally (x) and laterally (y) over time.
- Once the vehicle trajectory is known, the state and dynamics of the traffic system can be determined (Think about in-vehicle GPS!)
- Applications: automotive engineering
  - Driver models (vehicle handling and stability)
  - (vehicle) control theories
  - Fuzzy logic and ANN

Traffic State Diagram at Picoscopic Scale

- The state diagram is in a three-dimensional domain (x, y, t)

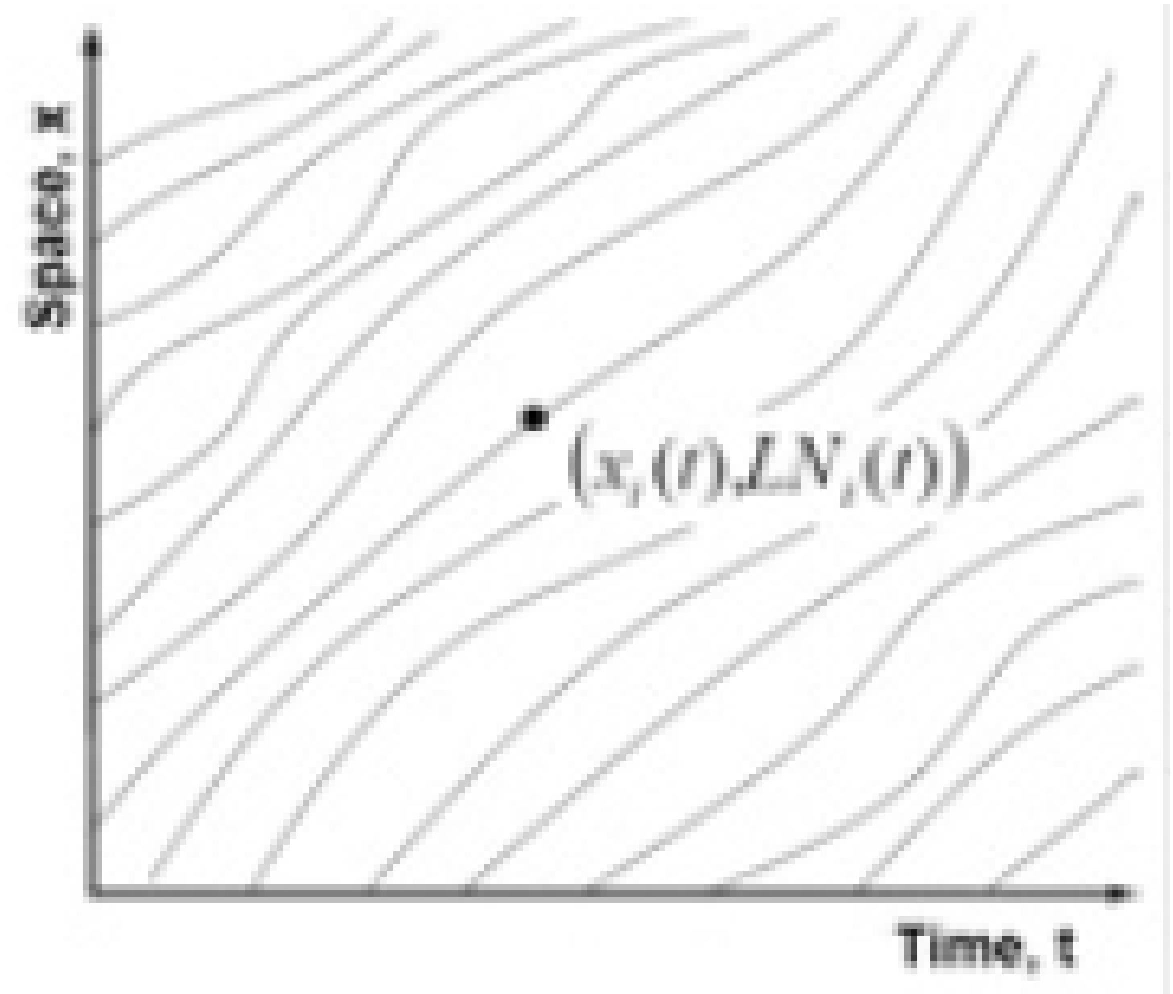


The Microscopic Scale

- Individual vehicles with detailed behavior
- Microscopic modeling also represents traffic flow by the trajectory of each vehicle but only in **the longitudinal direction** $x_i(t)$ with the lateral direction being discretized by lanes $LN_i(t)$ where $LN \in (1,2,3,..)$.
- Microscopic models treat driver-vehicle units as massless particles with personalities.

Traffic State Diagram at Microscopic Scale

- State variables ($x_i(t)$, $LN_i(t)$) governs the state and dynamics of traffic flow and the corresponding state diagram is a two-dimensional domain (x,t).



The Microscopic Scale (cont.)

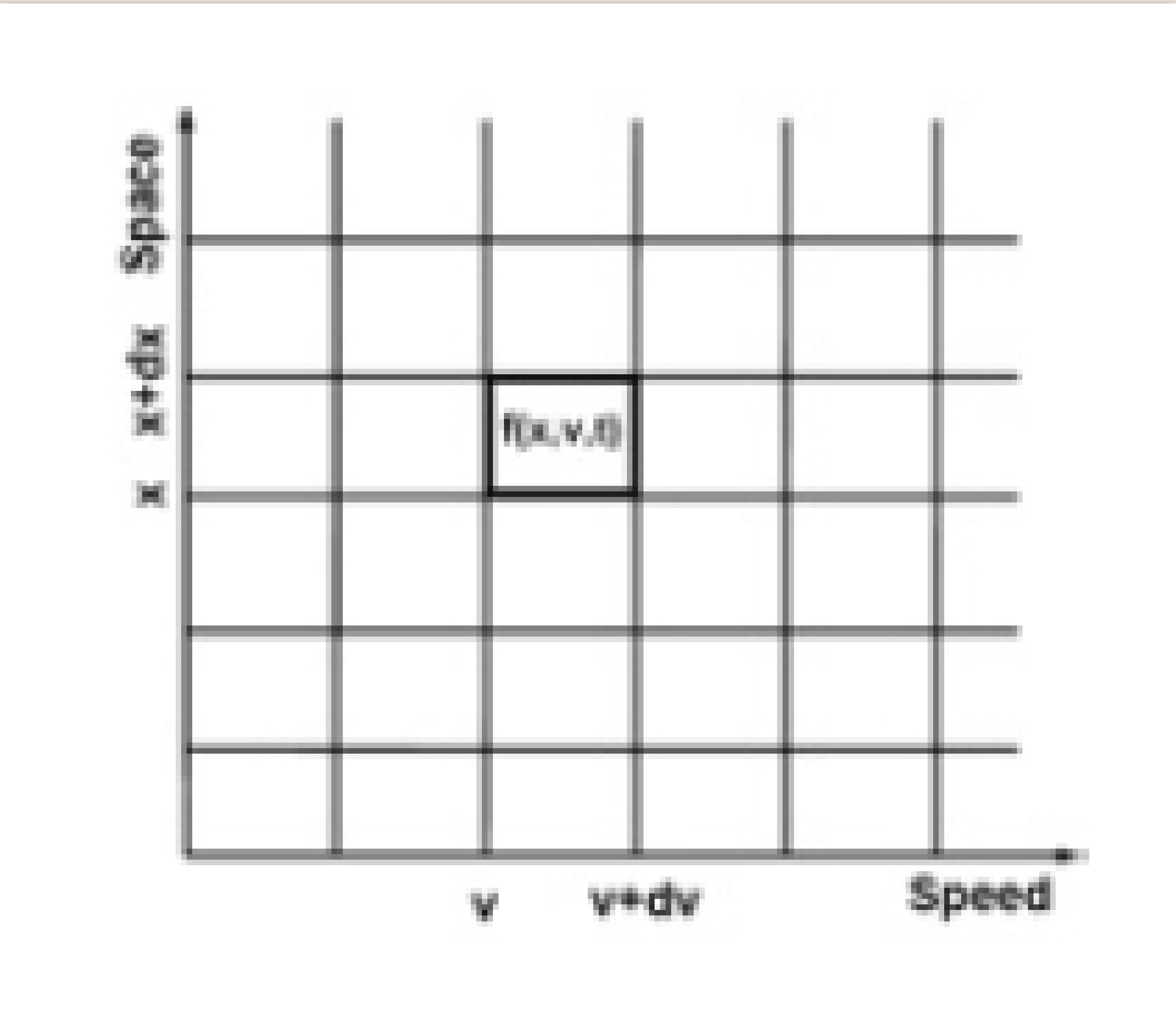
- The behavior of these particles are determined by car-following models in the longitudinal direction and discrete choice (e.g., lane-changing, gap-acceptance) models in the lateral direction, also called behavior models.
  - Car-following models describe how a following vehicle is reacting to the lead vehicle based on different theories (e.g. stimulus-response model, psycho-physical models, safe distance, and rule-based models).
  - Lane-changing and gap-acceptance models describe the type of lane change decision (e.g., mandatory and discretionary lane-changing (MLC/DLC)) and how the driver executes such a decision (e.g., deterministic, probabilistic models, and neuro-fuzzy hybrid models), respectively.

The Mesoscopic Scale

- Mesoscopic modeling represents traffic flow so that the probability of the presence of a vehicle at a longitudinal location x with speed v at time t is tracked.
- The state variable is a distribution function $f(x; v; t)$ such that $f(x; v; t)dxdv$ denotes the probability of having a vehicle within space range $(x; x + dx)$ and speed range $(v; v + dv)$ at time t. Knowing the distribution function $f(x; v; t)$, the dynamics of the system can be determined statistically.

Traffic State at Mesoscopic Scale

- The state diagram is two-dimensional domain (x,v) at time t.



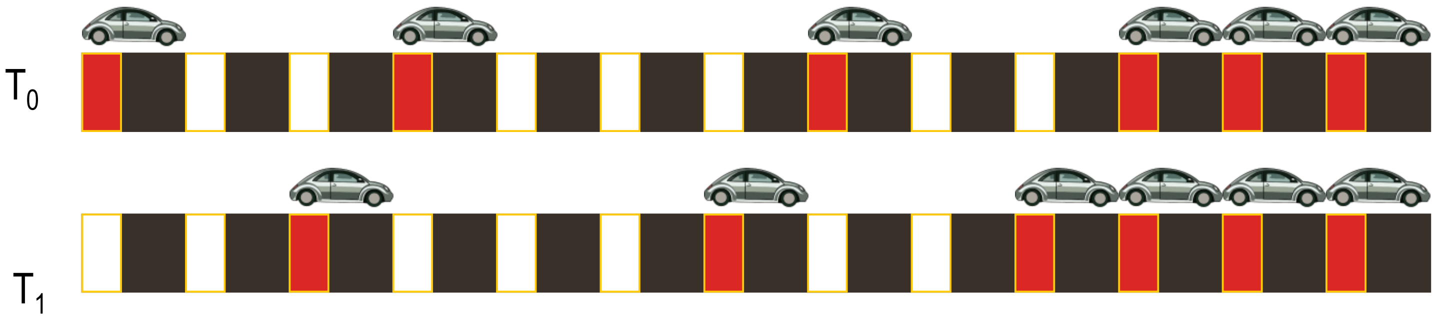
THE MESOSCOPIC SCALE (CONT.)

Cellular Automata: cell-hopping vehicles

1. Acceleration of free vehicles: IF ($v < v_{max}$) THEN $v = v + 1$

2. Deceleration due to other cars: IF ($v > gap$) THEN $v = gap$

3. Stochastic driver behavior: IF ($v > 0$) AND ($rand < p_{noise}$) THEN $v = v - 1$

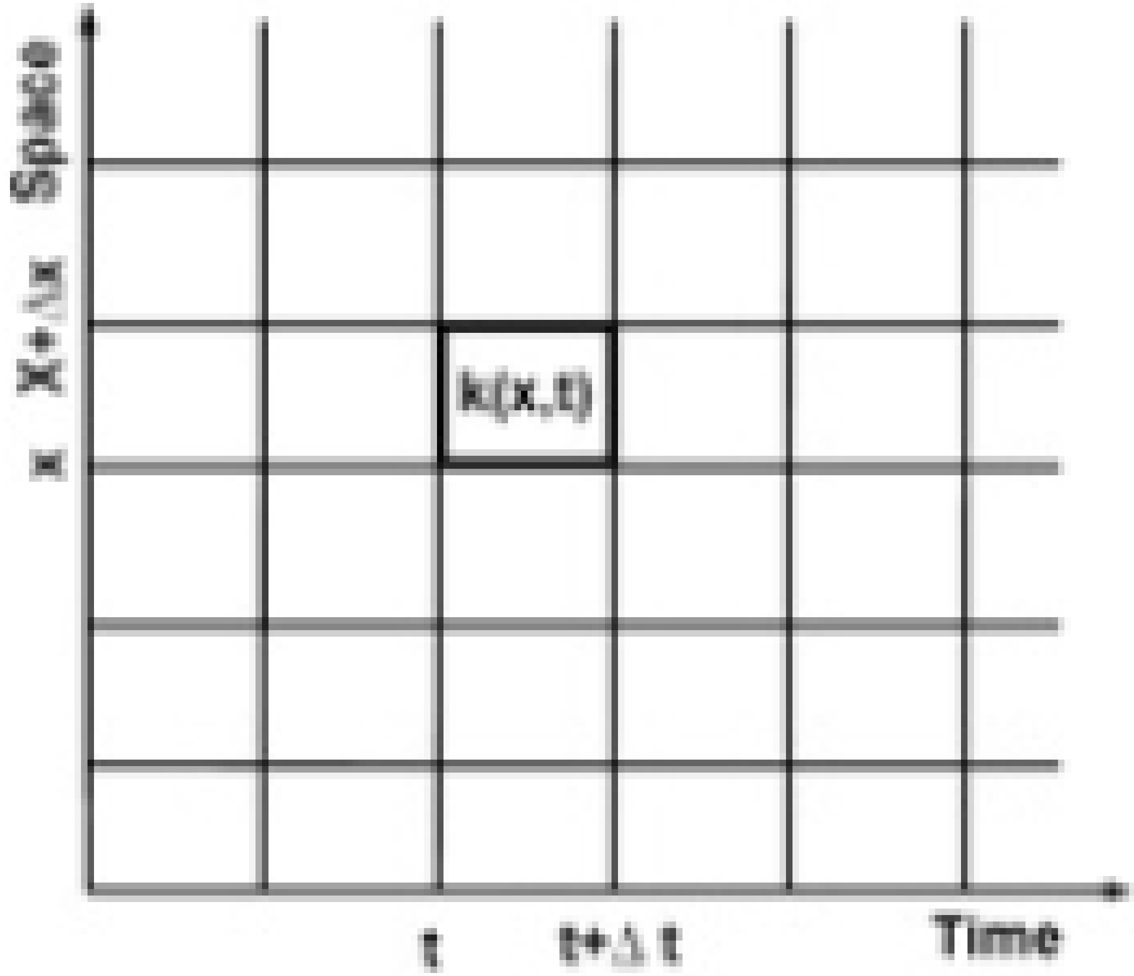


The Macroscopic Scale

- Like water flowing through a pipe
- Macroscopic modeling represents traffic flow so that the local aggregation of traffic flow (e.g. density k, speed u, and flow rate q) over space (longitudinal) x and time t is tracked.

Traffic State Diagram at Macroscopic Scale

- The state diagram typically involves a two dimensional domain (x; t). Knowing k(x; t), the dynamics of the system can be determined macroscopically.



THE MACROSCOPIC SCALE (CONT.)

- The Lighthill, Whitham and Richards (LWR) model uses the analogy between traffic flows and the fluid flows.
- Theoretical foundation is the **Law of Conservation** of vehicles in traffic: No cars can vanish, nor appear out of the blue.

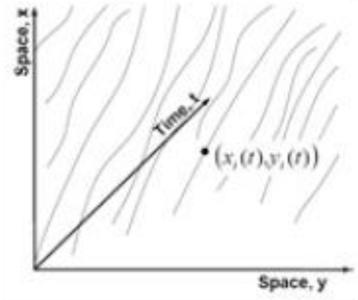
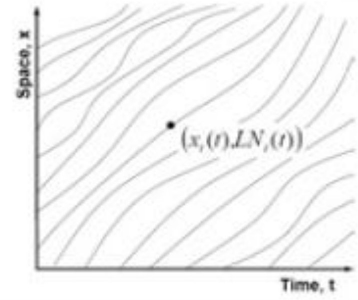
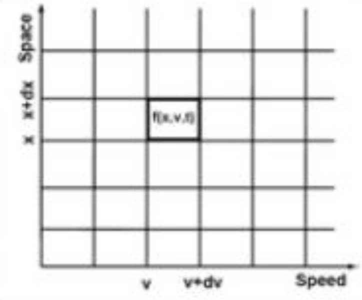
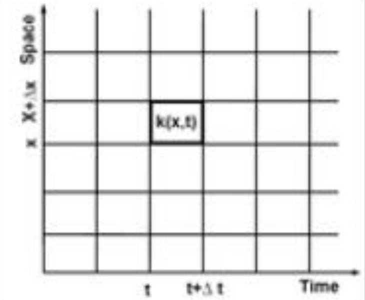
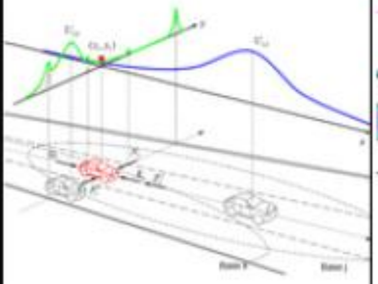
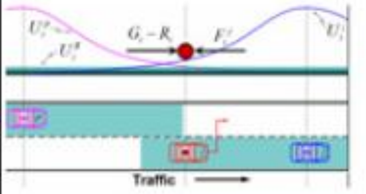
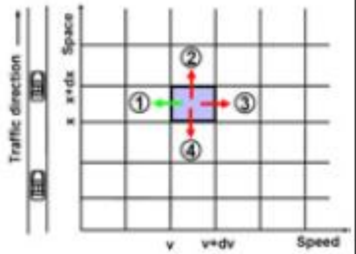
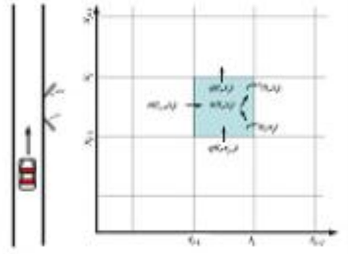
$$\boxed{\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(k(x,t))}{\partial x} = 0}$$

- Applying fluid behavior traffic (i.e., continuum models) implies greater concern in the overall traffic stream than in the interactions between particles.

Applications of Macroscopic Flow Models

- The traffic system consists of the network topology and the traffic control system
- Travel demand
  - The number of trips between origin and destination points, along with the desirable arrival, departure time, comprise the travel demand.
- Highway capacity: physical capacity and operational capacity
- Traffic system performance: The response of that system given travel demand levels.
- Performance measures
  - level of service: throughout volume, flow rate, travel time, delay, etc.

The Spectrum of Modeling Scales

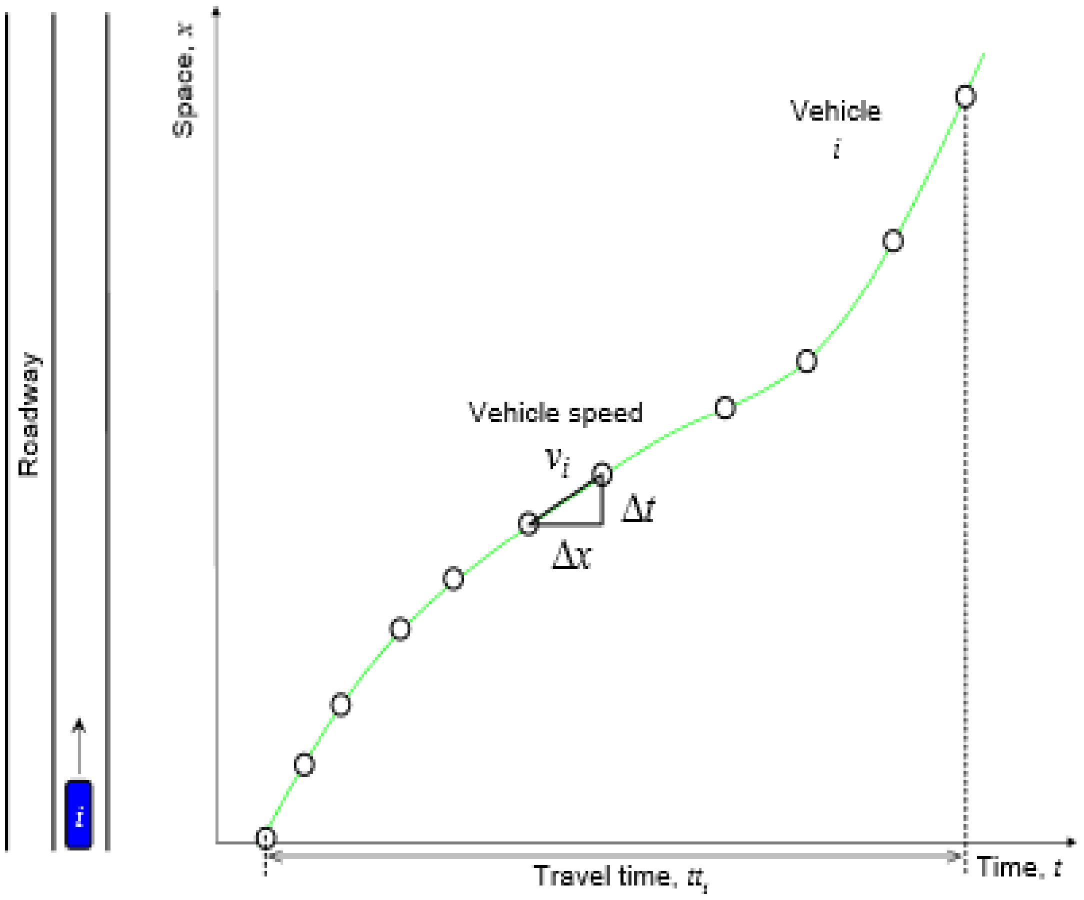
Scale	Picoscopic	Microscopic	Mesoscopic	Macroscopic
State variable	$\left(x_i(t), y_i(t)\right)$ $i = 1,2,3,\ldots \quad 0 < t < \infty$	$\left(x_i(t), LN_i(t)\right)$ $LN \in \{1,2,\ldots,n\}$	$f(x,v,t)$	$k(x,t)$
Variable description	Vehicle trajectory in longitudinal x and lateral y directions	Vehicle trajectory in x direction and lane # LN in y direction	Distribution of a vehicle at location x and time t with speed v	Concentration of vehicles at location x and time t
State diagram				
Underlying principle	Control theory System dynamics Field theory	Field theory	Statistical mechanics	Fluid dynamics
Modeling approach				

Source: Traffic Flow Theory: Characteristics, Experimental Methods, and Numerical Techniques (1st Edition) by Daiheng Ni

Measuring Traffic

- Control and optimization of traffic operations rely on an accurate understanding of traffic flow conditions which in turn comes from **field data collection**.
- As defined in the handbook, "*A traffic flow sensor is a device that indicates the presence or passage of vehicles and provides data or information that supports traffic management applications such as signal control, freeway mainline and ramp control, incident detection, and gathering of vehicle volume and classification data to meet State and Federal reporting requirements*.“ (Traffic Detector Handbook)
  - Mobile sensors
  - Point sensors (speed monitoring, freeway traffic management (ramp metering, priority treatment, surveillance, incident management, advanced traveler information),signal control for city streets,
    - Aggregated
    - Pair-match
  - Space sensors

CHARACTERISTICS AND MOBILE SENSORS



Time	X (ft)	Y (ft)
9:00:00	0	0
9:00:01	3	0
9:00:02	5	0
9:00:03	7	0
9:00:04	10	1
9:00:05	15	4
9:00:06	18	9
9:00:07	21	12
9:00:08	23	12
9:00:09	27	12
9:00:10	30	12

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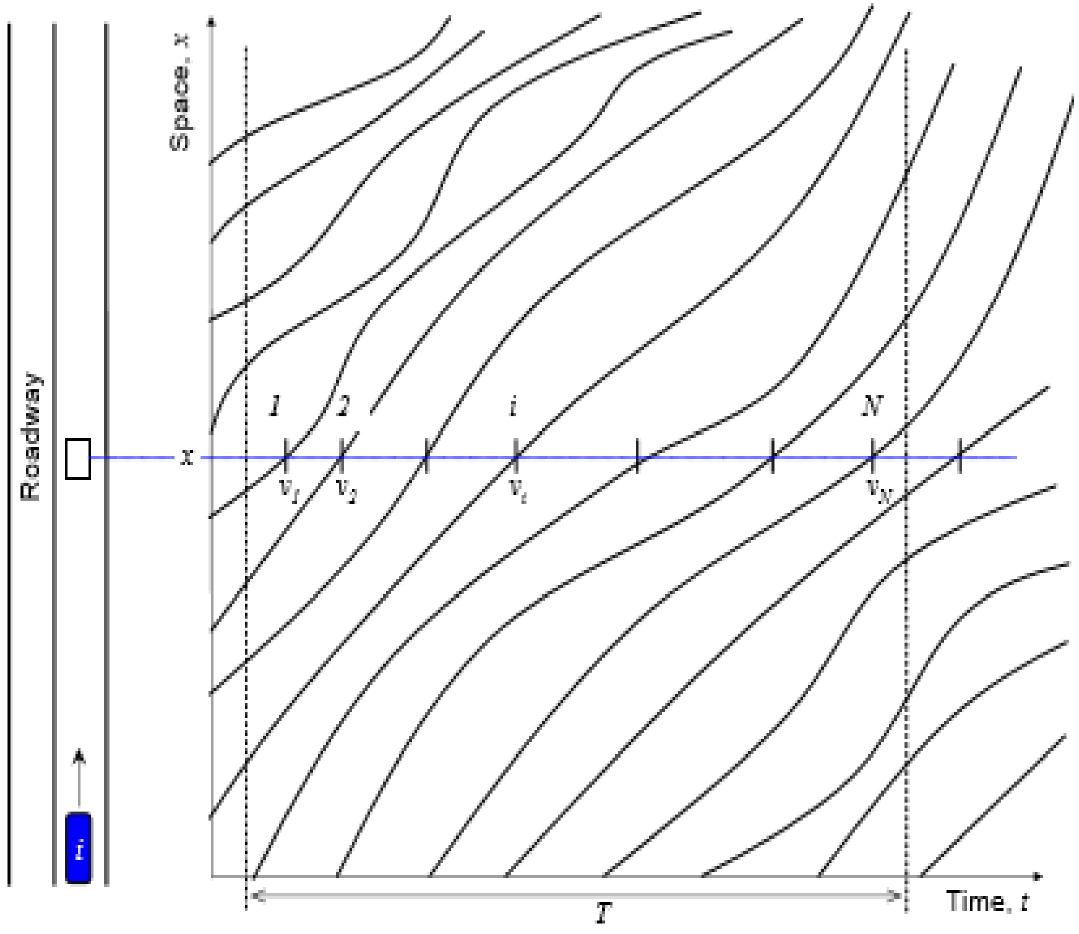
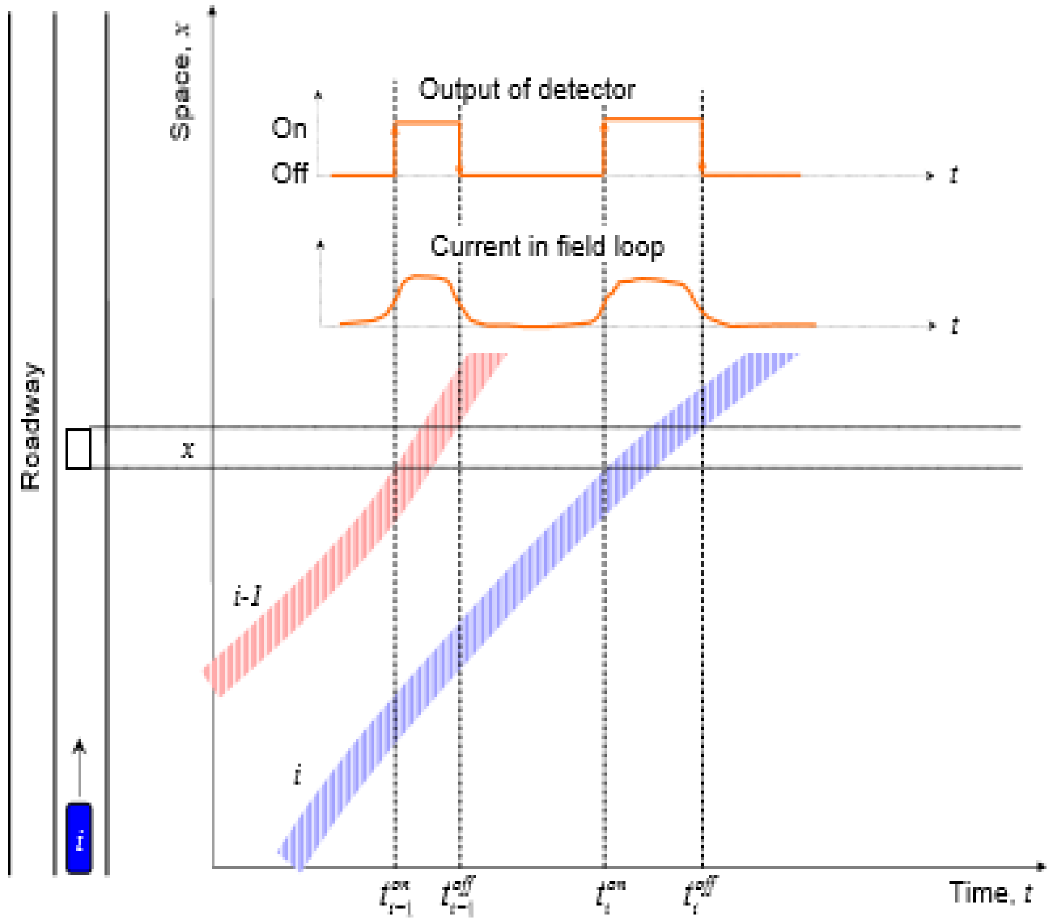
CHARACTERISTICS AND POINT SENSORS





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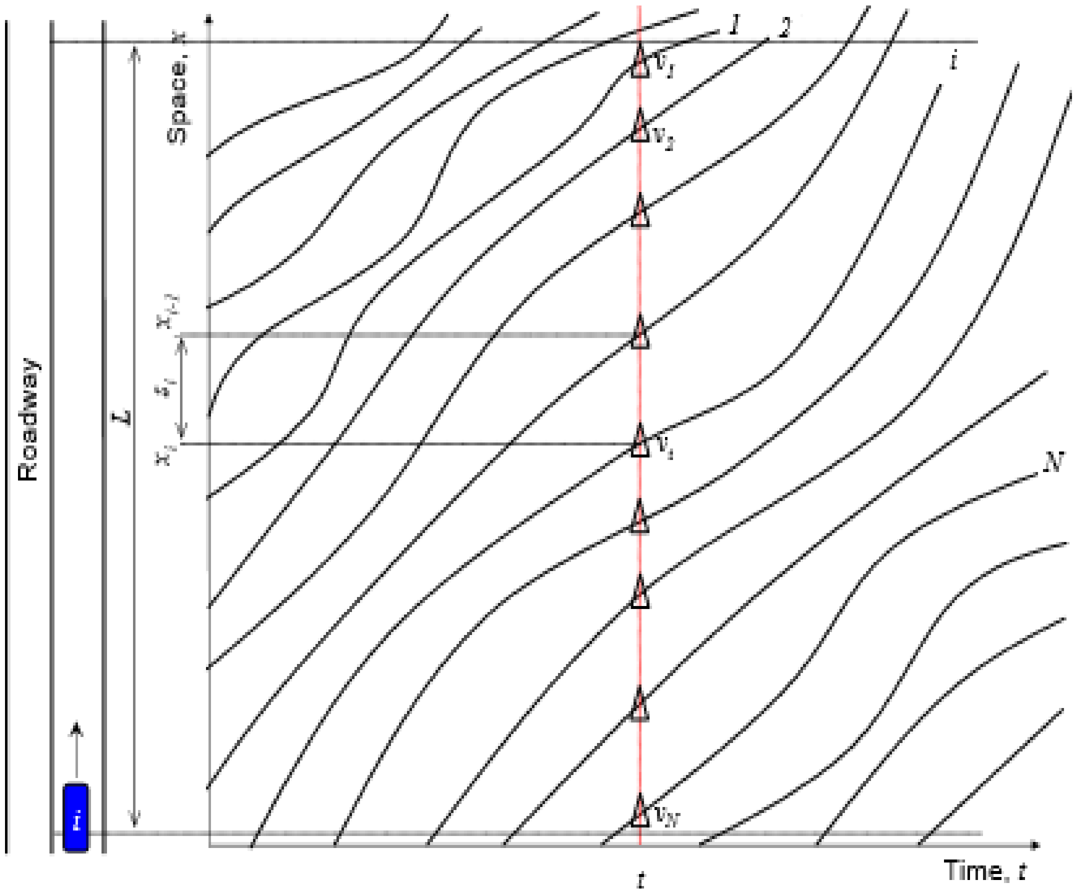
Characteristics and space sensors



If one takes aerial photos of a roadway from a helicopter, one is able to locate vehicles in each of these snapshots.

Source: Traffic Flow Theory: Characteristics, Experimental Methods, and Numerical Techniques (1st Edition) by Daiheng Ni

TRAFFIC CHARACTERISTICS

- Traffic count *N*

For vehicle i:

- Headway
- ON time
- Vehicle speed
- Occupancy
- Time mean speed

Time

- Spacing
- Density
- Vehicle speed: measured with two snapshots
- Space mean speed:

Space

Time Mean Space and Space Mean Speed

Below is an example that illustrates the difference between the two mean traffic speeds. Consider two lanes of traffic which is perfectly controlled so that there are only two streams of traffic: fast vehicles all travel at 60 miles per hour (mph) in the inner lane and slow vehicles all move at 30 mph in the outer lane. traffic flow in each lane is 1200 vph and lane change is prohibited. What is the time-mean speed and space-mean speed?

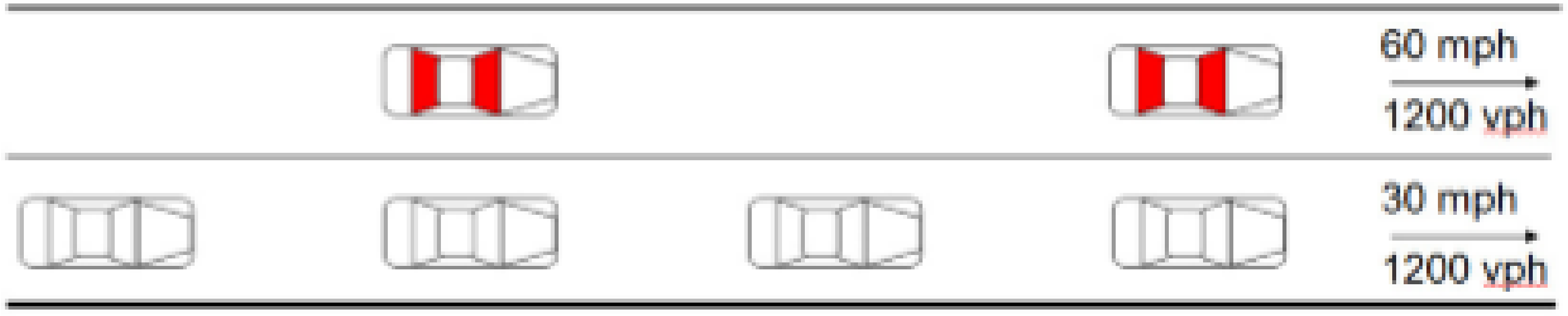


Figure 3.3: Time-mean speed vs. space-mean speed

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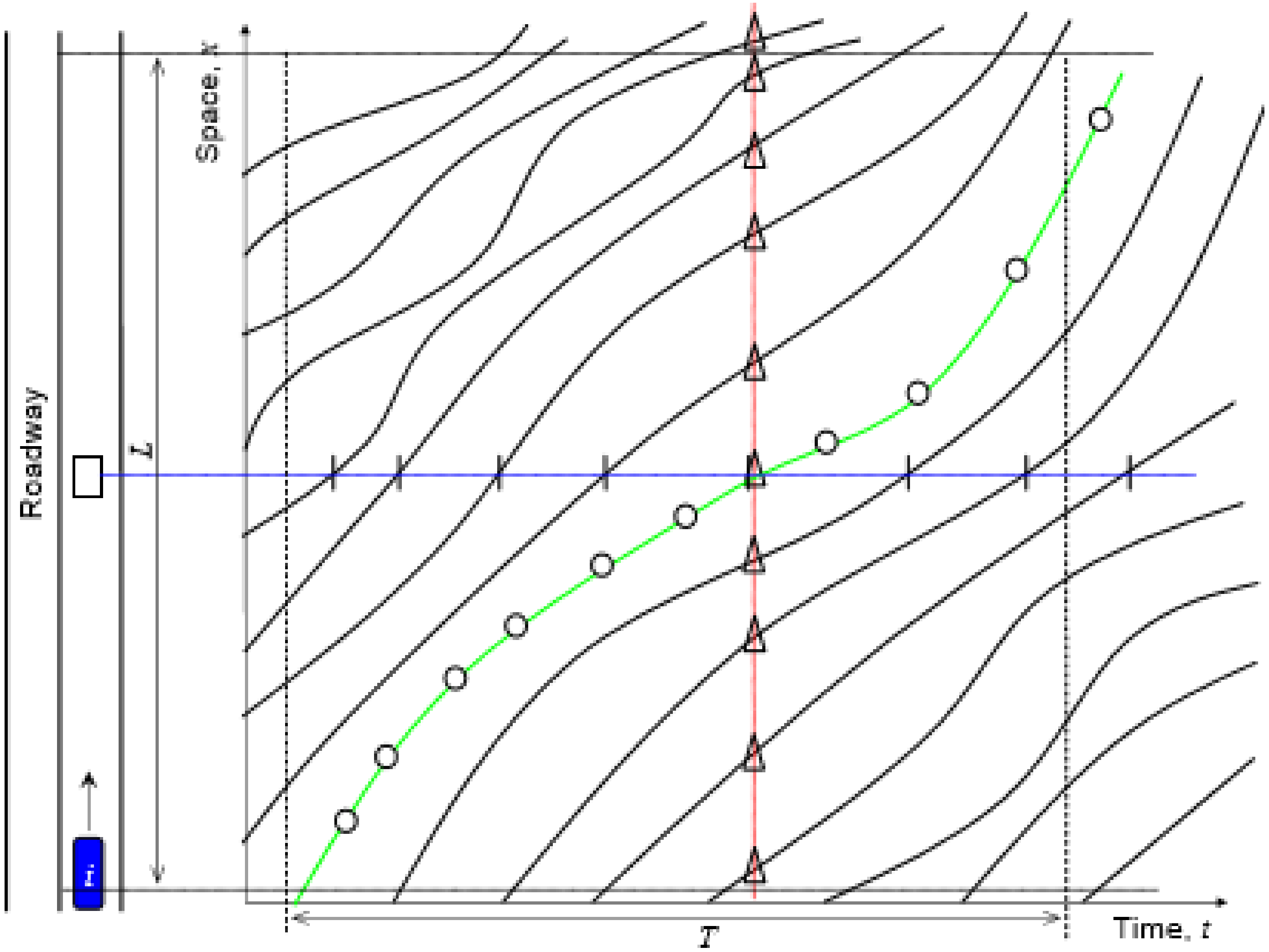
DETERMINING SPACE-MEAN SPEED FROM POINT SENSOR DATA

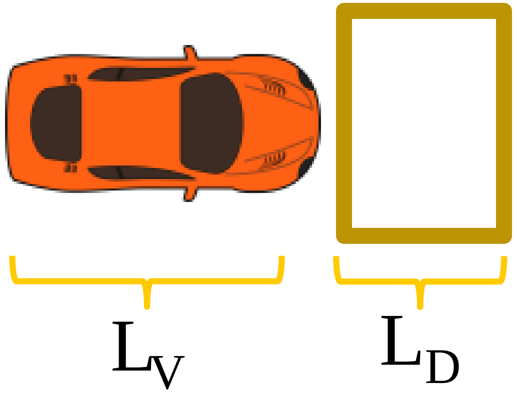


$$v_s = \frac{1}{\frac{1}{N}\sum_i t_i} = \frac{1}{\frac{1}{N}\sum_i (\frac{1}{\dot{x}_i})}$$

where $\dot{x}_i$ *is spot speed*

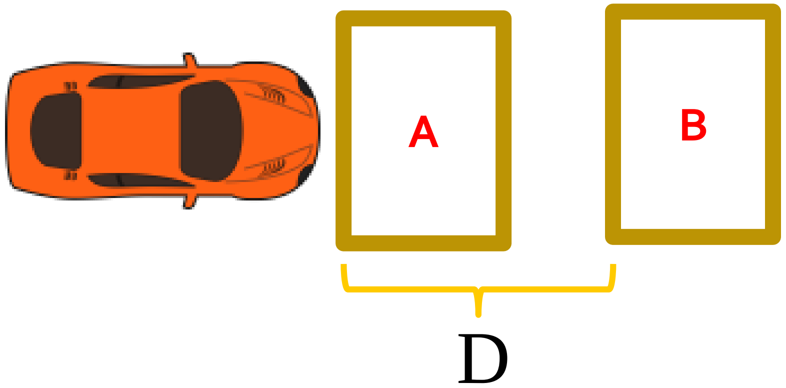
$$v_t = v_s + \frac{\sigma^2}{v_s}$$

Measure density using loop detector



%OCC: % of time the detector is occupied during time interval T.

Measure speed using dual-loop detector



μ: vehicle speed

$$\mu = \frac{D}{t_{B\ on} - t_{A\ on}}$$

L: vehicle length

$$\mu = \frac{D}{t_{B\ on} - t_{A\ on}}$$

Occupancy and Density

$$\%OCC = \frac{\sum t_i}{T}100\% = \frac{\sum\left(\frac{L_{V_i}+L_D}{5280\mu_i}\right)}{T}100\% \approx \frac{\sum\left(\frac{\overline{L_V}+L_D}{52.80\mu_i}\right)}{T} = \frac{(\overline{L_V}+L_D)}{52.8}\frac{\sum\left(\frac{1}{\mu_i}\right)}{T} = \frac{(\overline{L_V}+L_D)}{52.8}\frac{n}{\mu_{sms}T} = \frac{(\overline{L_V}+L_D)}{52.8}\frac{q}{\mu_s} = \frac{(\overline{L_V}+L_D)}{52.8}\mathrm{k}$$

$$k = {}^{5280}\!/_{d}$$

$$k = \frac{52.8}{\overline{L_V} + L_D}\%OCC$$

SENSORS AND TRAFFIC FLOW CHARACTERISTICS

Category	Sensors	Micro Character	Macro Character
Flux	Mobile	-	-
	Point	h_i	N, q
	Space	-	-
Speed	Mobile	$\dot{x}_i$	-
	Point	$\dot{x}_i$	v_t
	Space	$\dot{x}_i$	v_s
Concentration	Mobile	-	-
	Point	τ_i	o
	Space	s_i	k

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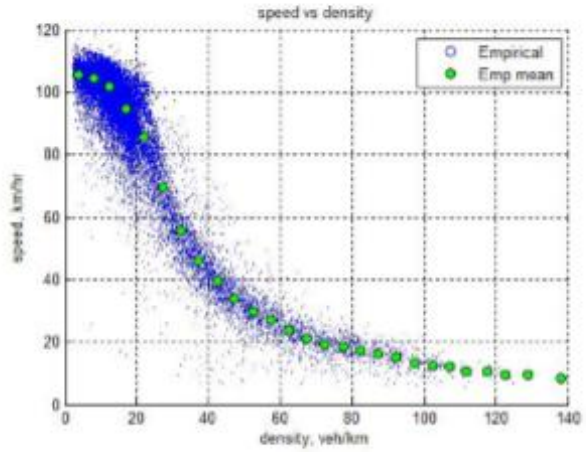
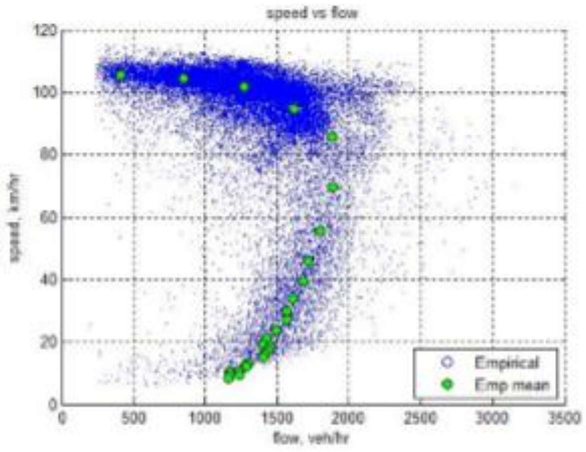
Observed q-k-v Relationships

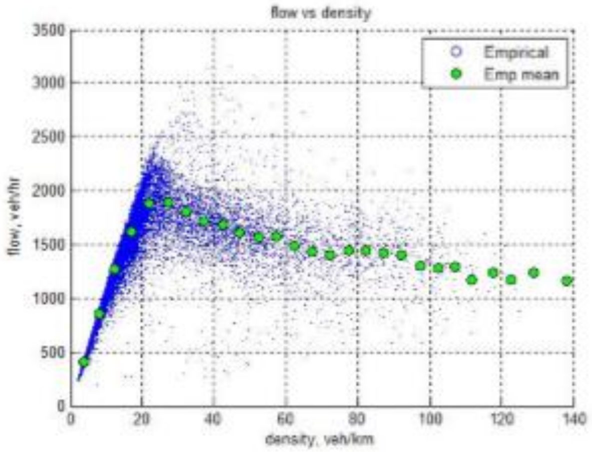
Speed vs. Density

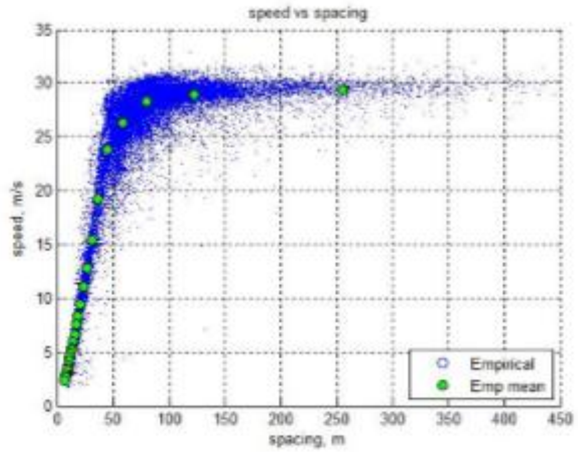




Speed vs. Flow

Flow vs. Density





Speed vs. Spacing

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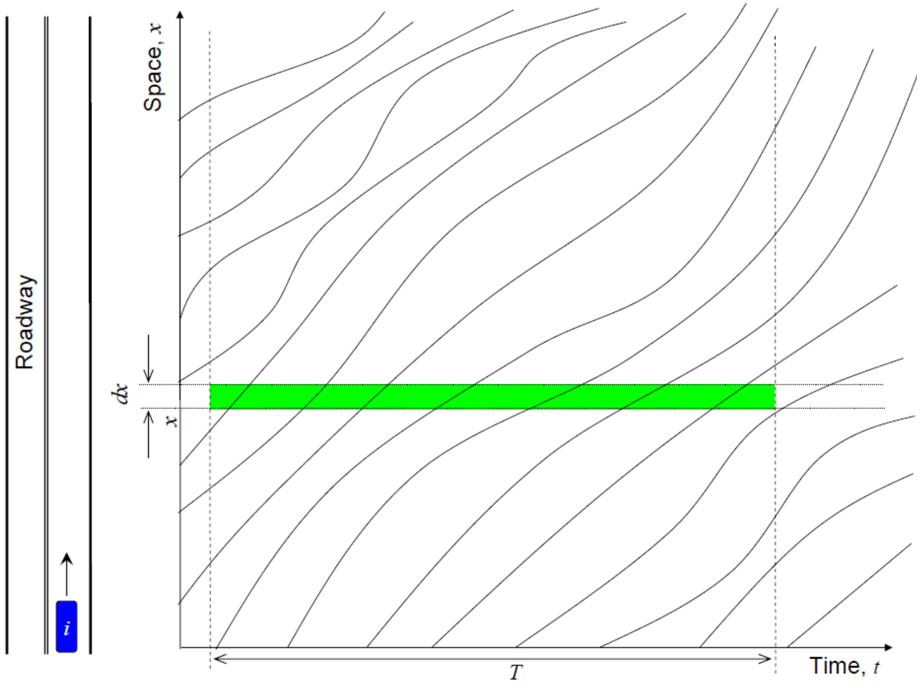
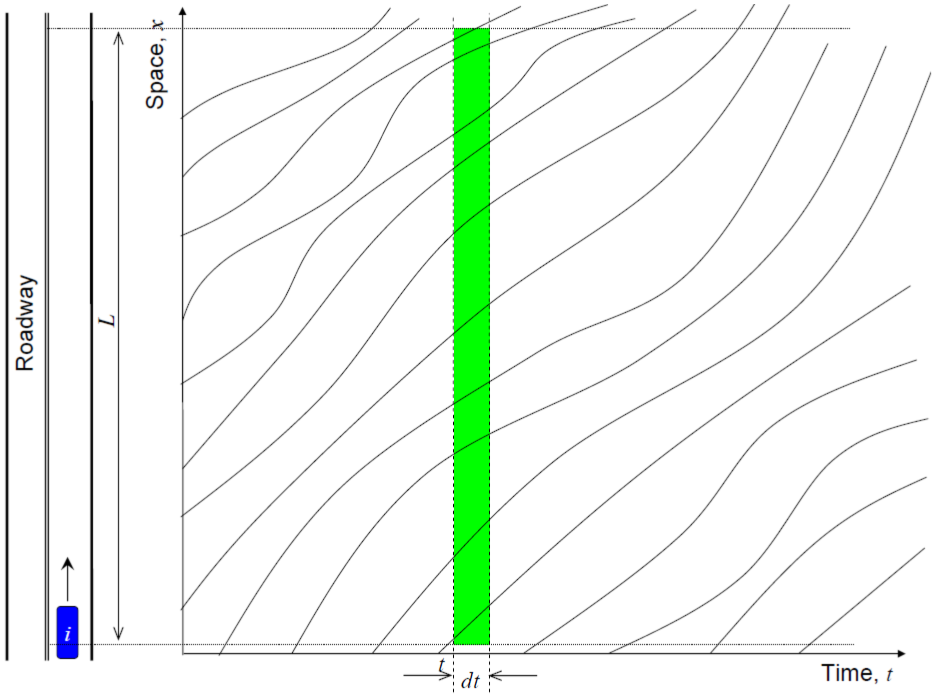
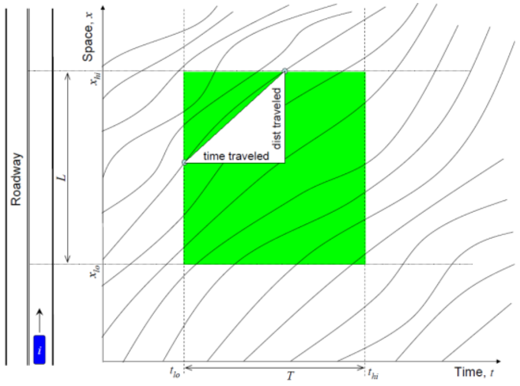
*Q=U*K?*

Generalized definition: $q = u \cdot k$

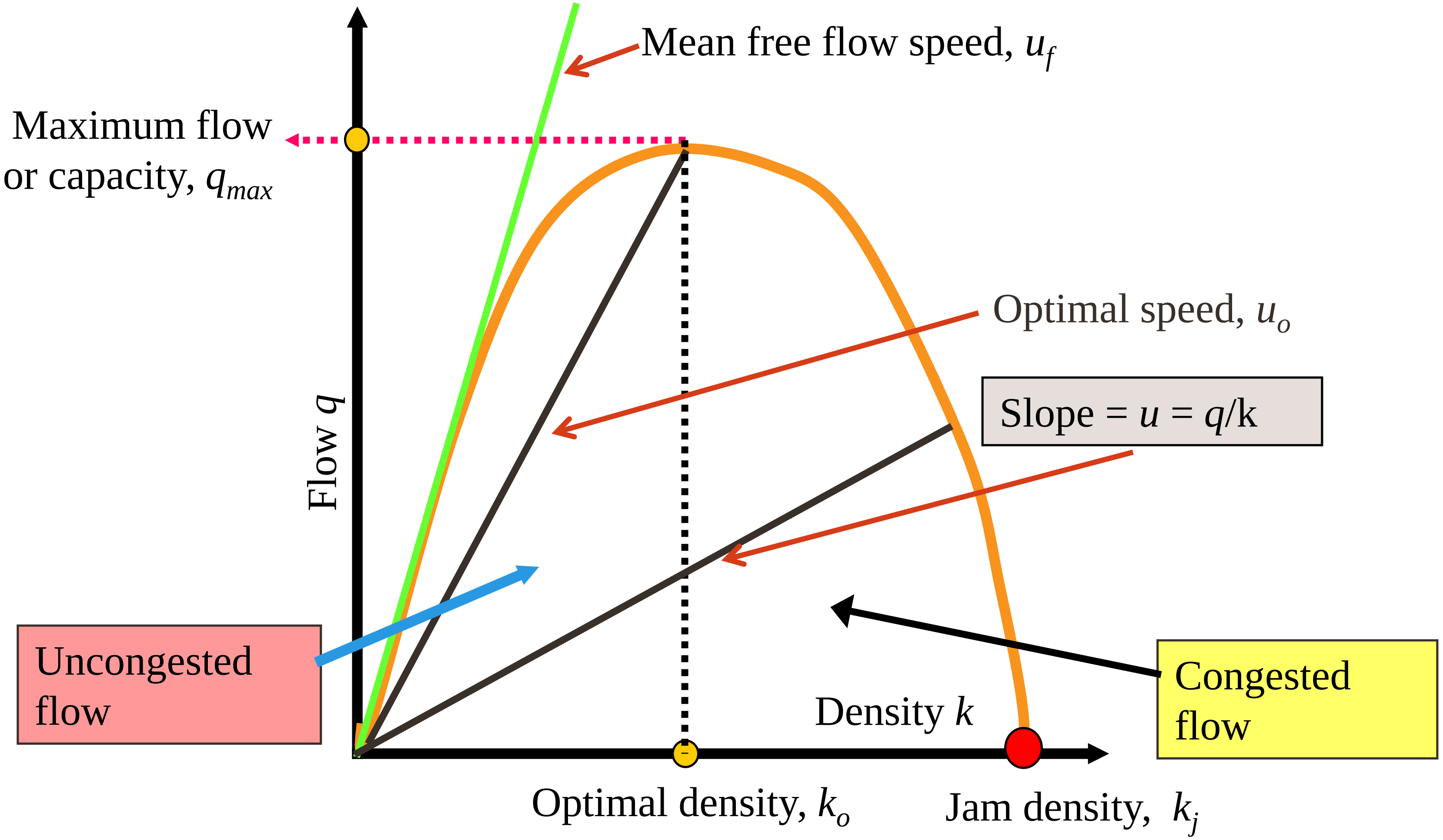
L. C. Edie. Discussion on traffic stream measurements and definitions. In Proceedings of the 2nd Int. Symp. Theory Traffic Flow, Paris, France, page 139-154, 1963.







MACROSCOPIC FUNDAMENTAL DIAGRAM (MFD)



Flow-Speed-Density

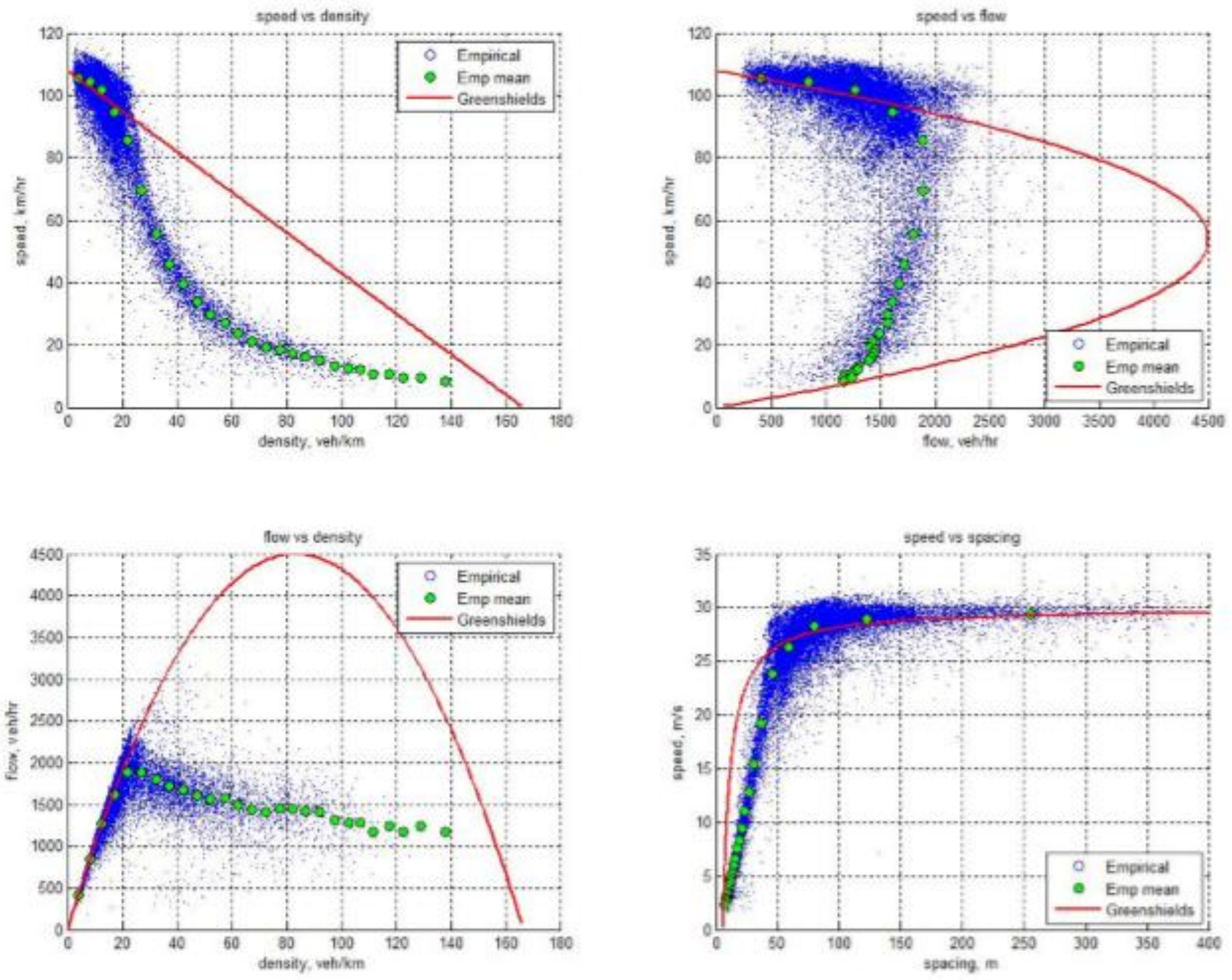


Figure 5.5: Fundamental implied by Greenshields model

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GREENSHIELDS MODEL (1934)

$$\mu = \mu_f \left(1 - \frac{k}{k_j} \right)$$

- Limitations
  - Jam density is difficult to obtain in the test fields
  - Observed optimum density is not half of the theoretical jam density (185~250 vehicles)

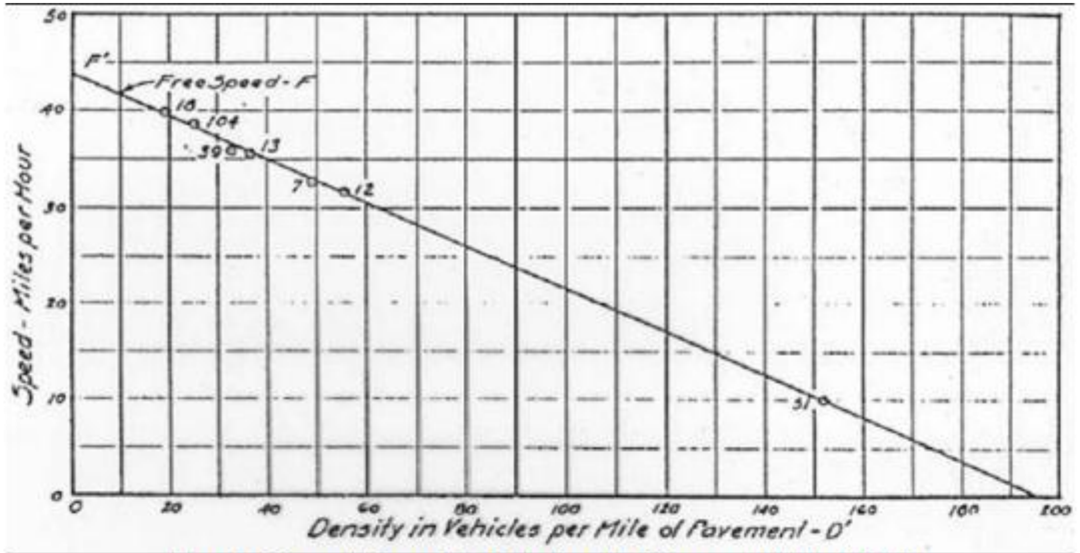
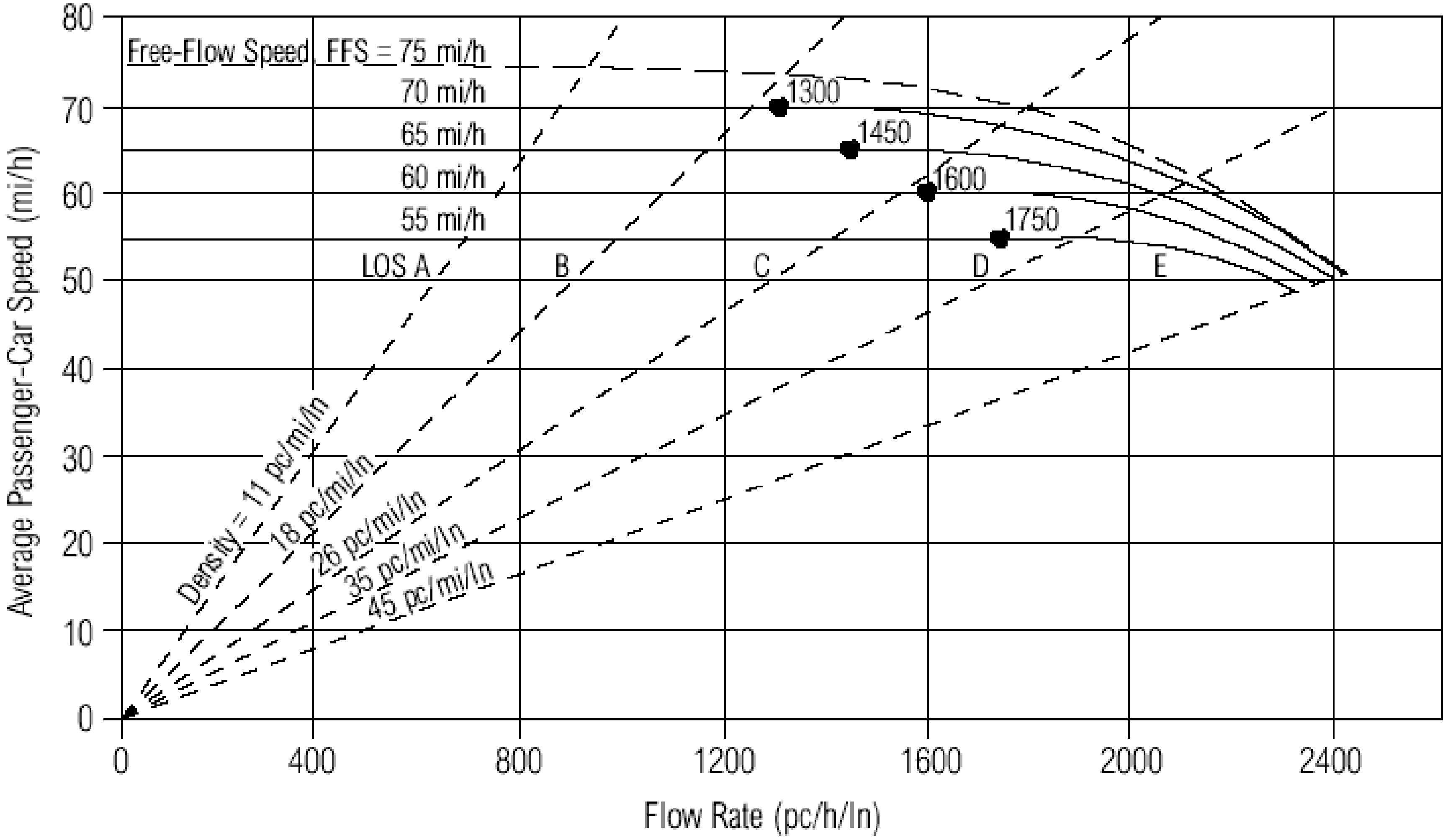


Fig. 5: Speed Density Relation V (Greenshield 1934)

BASIC FREEWAY SEGMENT SPEED-FLOW CURVES AND LEVEL OF SERVICE



Source: Highway Capacity Manual

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SINGLE REGIME MODELS

Author	Model	Parameters
Greenshields [50]	$v = v_f(1 - \frac{k}{k_j})$	$v_f,\ k_j$
Greenberg [49]	$v = v_m \ln(\frac{k_j}{k})$	$v_m,\ k_j$
Underwood [146]	$v = v_f e^{-\frac{k}{k_m}}$	$v_f,\ k_m$
Northwestern [29]	$v = v_f e^{-\frac{1}{2}(\frac{k}{k_m})^2}$	$v_f,\ k_m$
Drew [31]	$v = v_f[1 - (\frac{k}{k_j})^{n+\frac{1}{2}}]$	$v_f,\ k_j,\ n$
Pipes-Munjal [120, 97]	$v = v_f[1 - (\frac{k}{k_j})^n]$	$v_f,\ k_j,\ n$

Source: Traffic Flow Theory: Characteristics, Experimental Methods, and Numerical Techniques (1st Edition) by Daiheng Ni

Model Limitations and Applications

Models	Greenfields	Greenberg	Underwood
Format	$\mu = \mu_f \left(1 - \frac{k}{k_j}\right)$	$\mu = \mu_0 \ln\left(\frac{k_j}{k}\right)$	$\mu = \mu_f e^{\frac{-k}{k_0}}$
Pros	1. Simple	1. non-linear	1. non-linear
	2. free-flow speed is easy to observe		2. free-flow speed is easy to observe
Cons	1. Less accurate	1. free-flow speed goes to infinity	1. Speed never reaches zero
	2. Jam density is difficult to obtain	2. Jam density is difficult to obtain	2. Jam density is infinity
	3. Optimal density is not half of the jam density according to field observation	3. Requires knowledge of optimal density	3. Requires knowledge of optimal density
Application	Both regimes	Congested regime	Free-flow regime

Multi-regime Models

Regimes / Models	Free-flow	Transitional	Congested
Edie model	$v = 54.9e^{-k/163.9}$ $k \leq 50$	- -	$v = 26.8\ln(162.5/k)$ $k > 50$
2-regime model	$v = 60.9 - 0.515k$ $k \leq 65$	- -	$40 - 0.265k$ $k > 65$
Modi. Greenberg	$v = 48$ $k \leq 35$	- -	$v = 32\ln(145.5/k)$ $k > 35$
3-regime model	$v = 50 - 0.098k$ $k \leq 40$	$v = 81.4 - 0.913k$ $40 < k \leq 65$	$v = 40 - 0.265k$ $k > 65$

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A DETERMINISTIC OR A STOCHASTIC RELATIONSHIP?

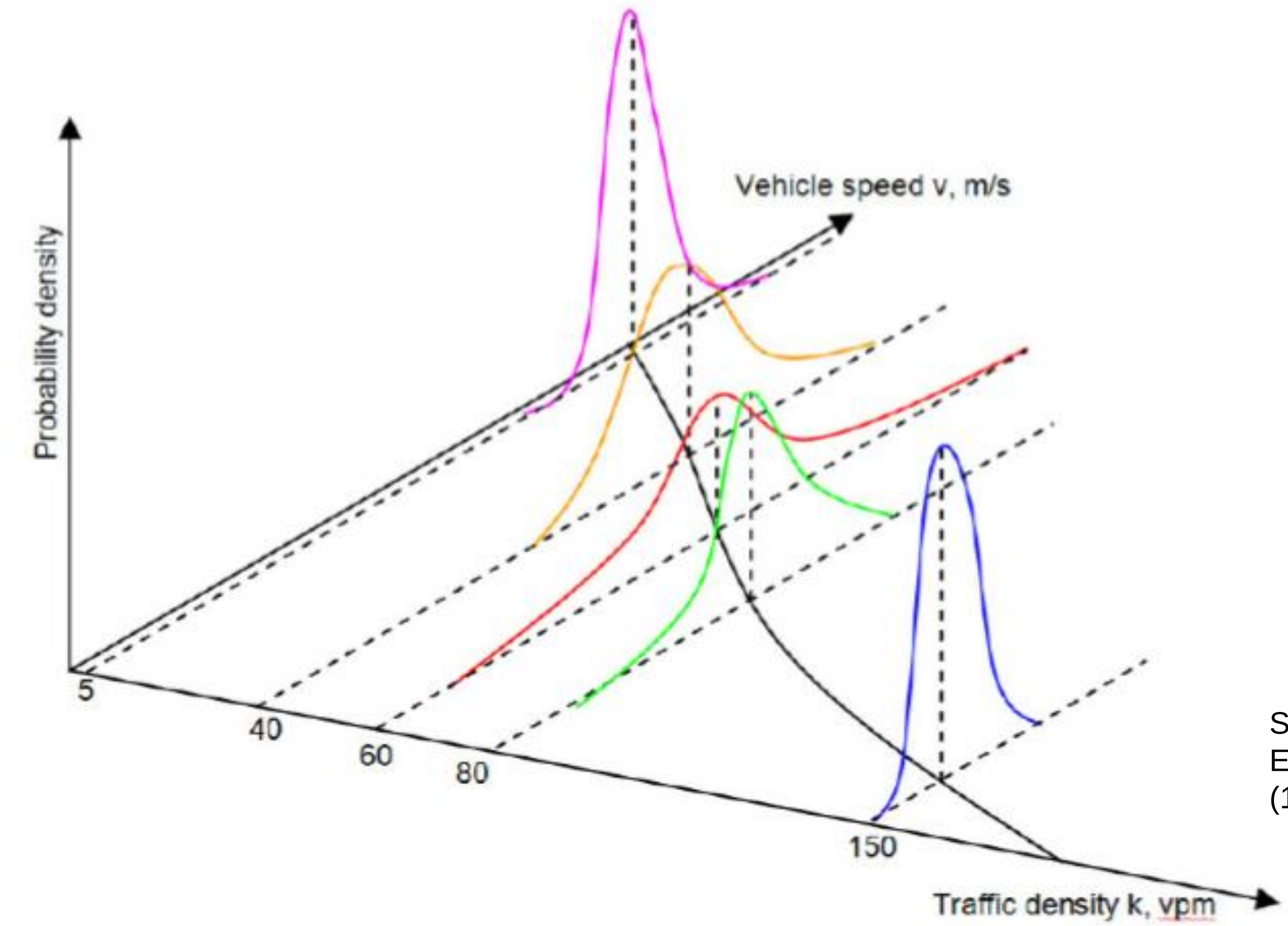

Figure 5.8: 3D representation of speed-density relationship

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