CIVL6415

TRAFFIC ANALYSIS AND SIMULATION

MODULE 1

Traffic flow fundamentals

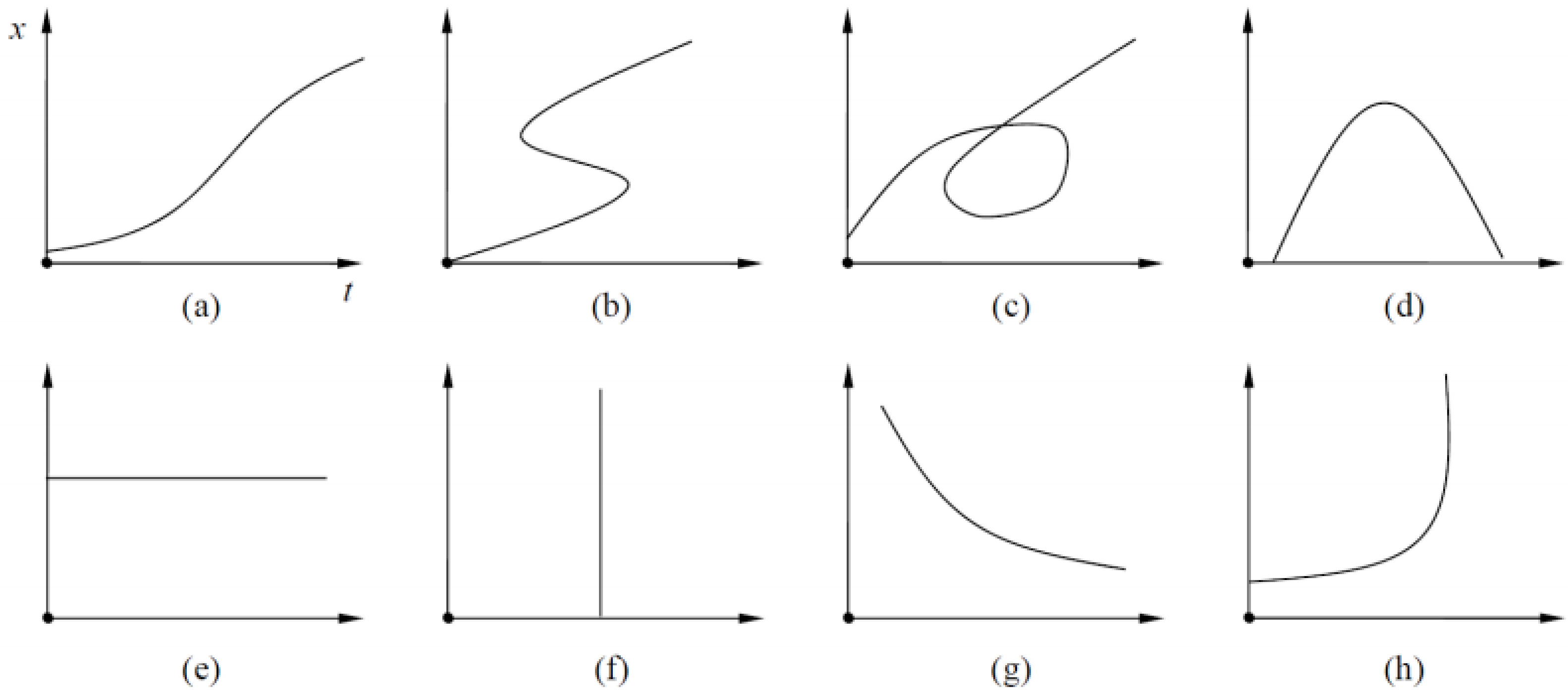
Dr. Mehmet Yildirimoglu
School of Civil Engineering
The University of Queensland

Outline

- **Basic Descriptors of Traffic Flow**
  - Flow, Density (Occupancy), Speed
  - Headway, Spacing
- **Relationships between Traffic Flow Parameters**
  - Flow, Density, and Speed
  - Flow vs. Headway
  - Density vs. Spacing
  - Space mean speed vs. Time mean speed
- **Graphical Relationships for Uninterrupted Flow**
  - Speed vs. Density
  - Flow vs. Density
  - Speed vs. Flow
- **Generalized Definitions of Flow, Density and Speed**

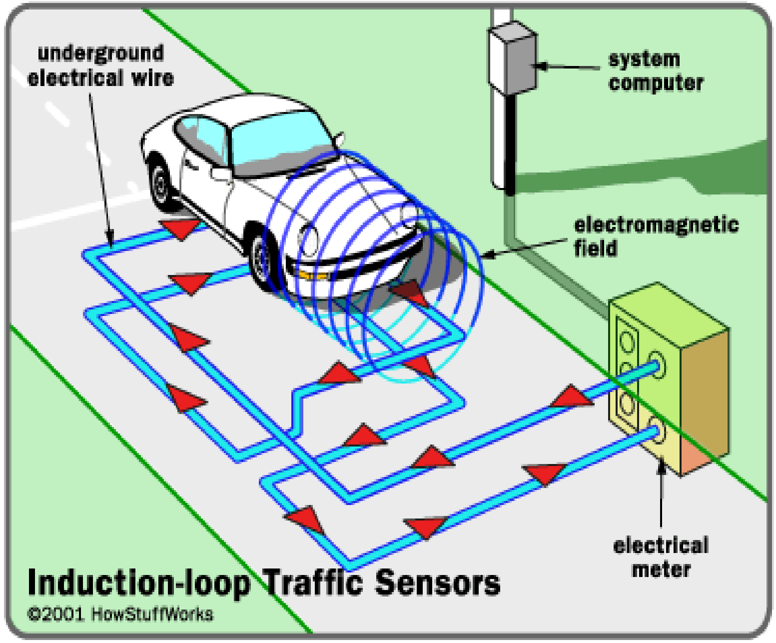
Space-time diagram

THE UNIVERSITY OF QUEENSLAND AUSTRALIA



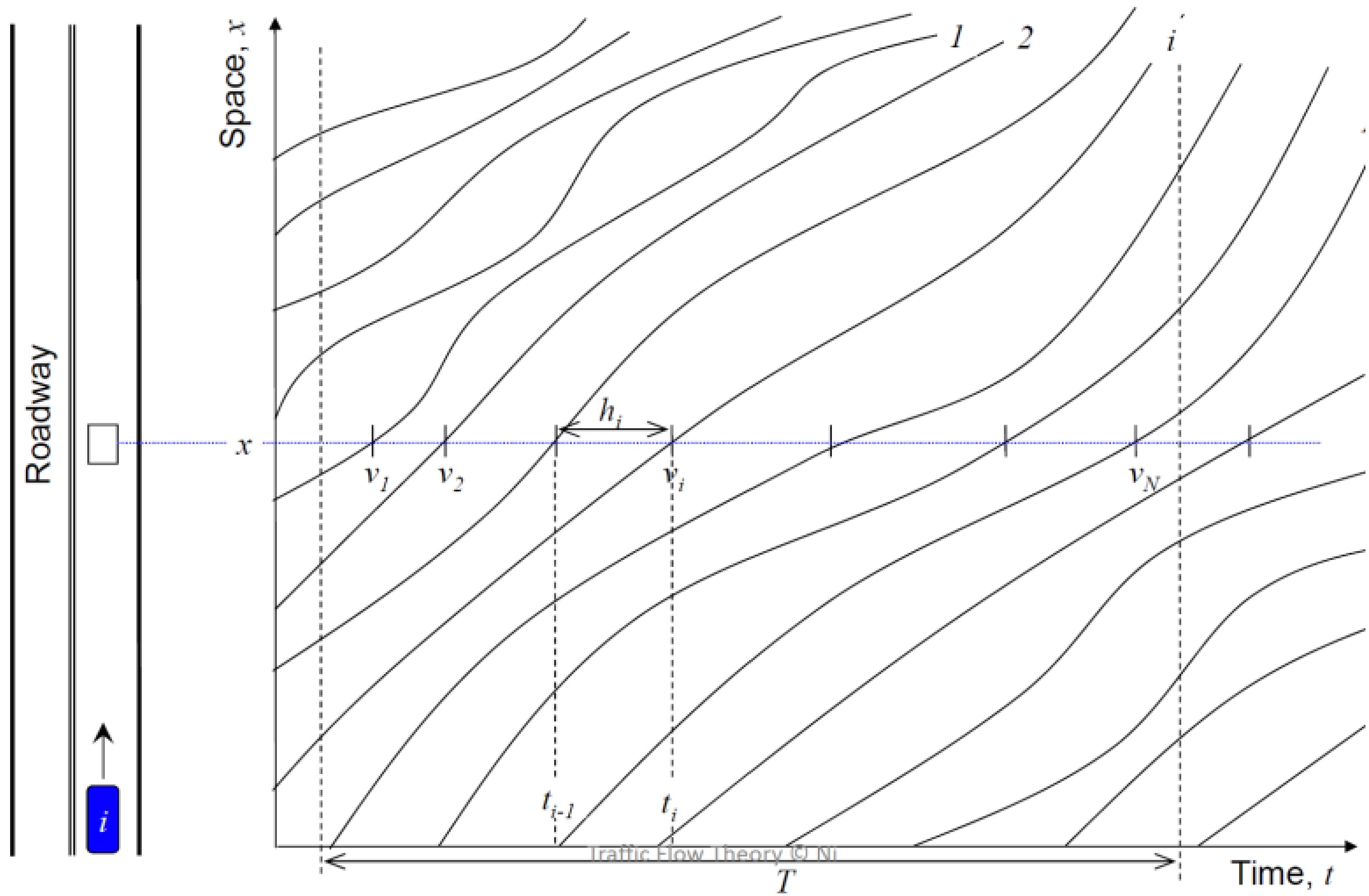
Point sensors

- Inductive loops
  - Coil of wire in pavement
  - Energised by AC
  - Detector senses the ‘presence’ of vehicle
  - Single loop: volume & occupancy
  - Dual loops: vol, occ & speed
  - typically spaced at 500 m on motorways
  - actuated signals
  - dominant technology (low cost)

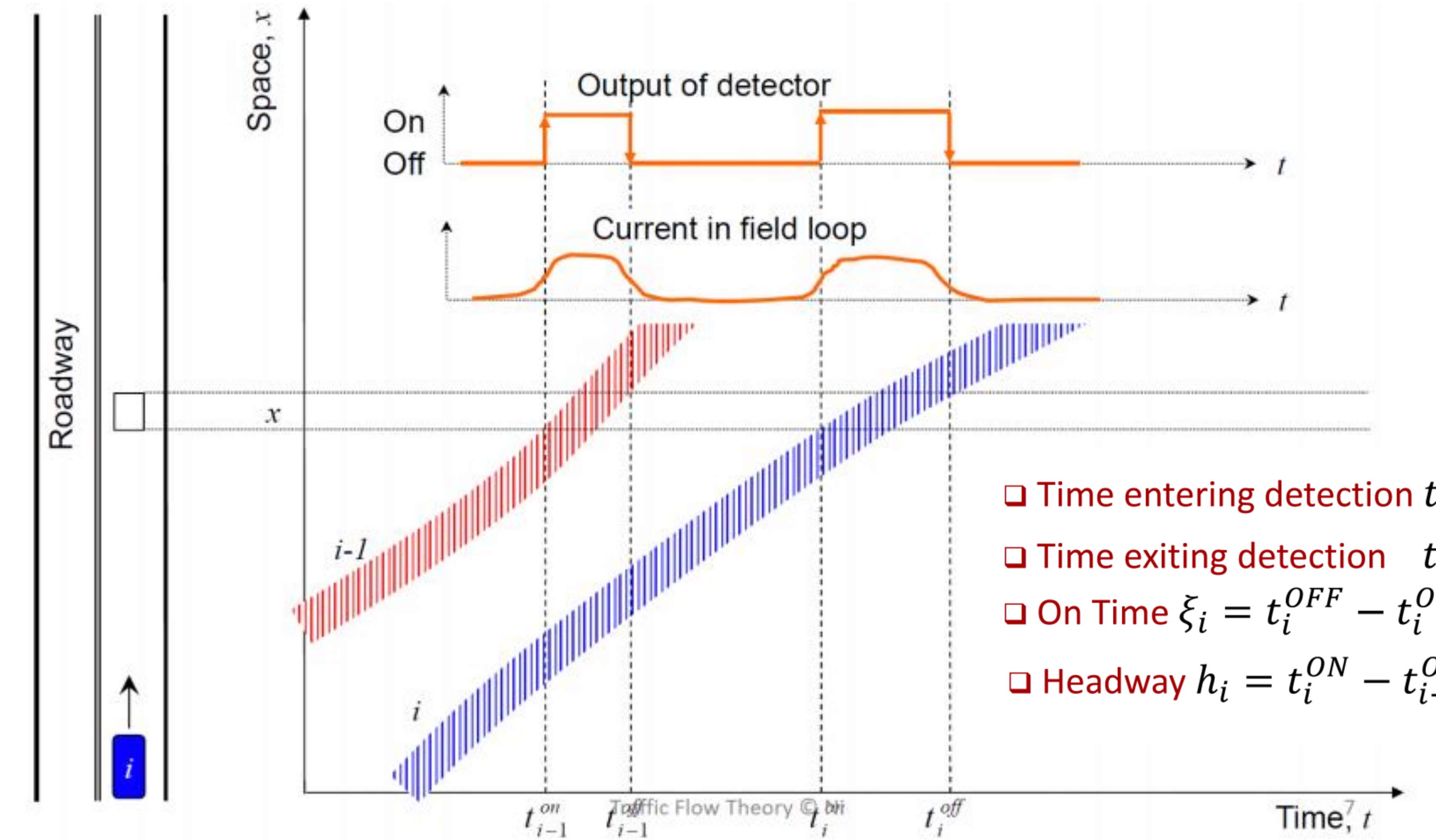


- CCTV cameras

Point sensor data



Point sensor data



- Time entering detection t_i^{ON}
- Time exiting detection t_i^{OFF}
- On Time $\xi_i = t_i^{OFF} - t_i^{ON}$
- Headway $h_i = t_i^{ON} - t_{i-1}^{ON}$

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Basic Descriptors of Traffic Flow

Basic Traffic Flow Parameters

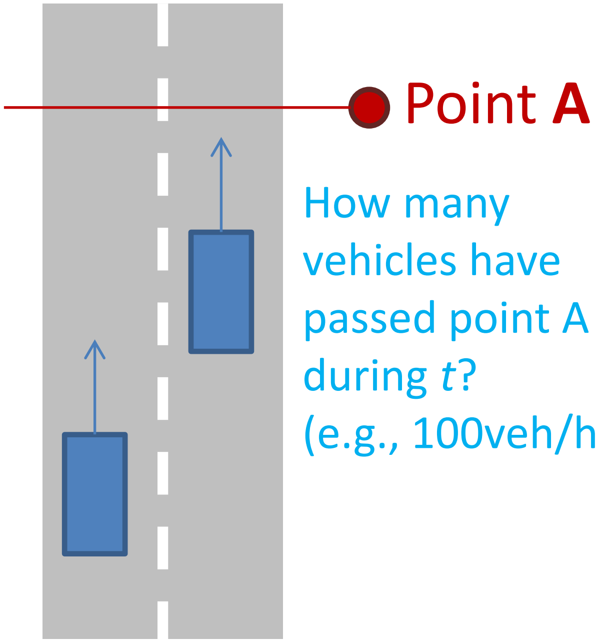
- **Three Principal Traffic Flow Descriptors**

  - Volume (q)
  - Density (k) + Occupancy (Occ)
  - Speed (v)
  - Headway (h)
  - Spacing (s)

Volume or Flow

- **Flow (q)** (also called 'Volume' or 'Flow rate')
  - Number of vehicles per unit time passing a given point on a road
  - *vehicles per second* (veh/s), *vehicles per hour* (veh/h), or *vehicles per day* (veh/d).

Flow $$q = \frac{N}{T}$$



How many vehicles have passed point A during *t*? (e.g., 100veh/h)

where:

- *N = number of vehicles passing some designated roadway point during time t, and*
- *T = duration of time interval.*

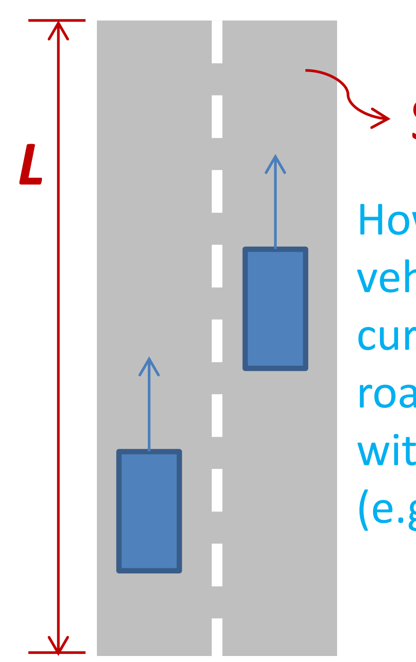
Density

- **Density (k)** (also known as 'Concentration')
  - Number of vehicles present within a unit length of lane or road at a given instant of time
  - *vehicles per kilometre* (veh/km) or *vehicles per metre* (veh/m)

Density $$k = \frac{N}{L}$$

where:

- *N = number of vehicles occupying some length of roadway at some specified time, and*
- *L = length of roadway.*

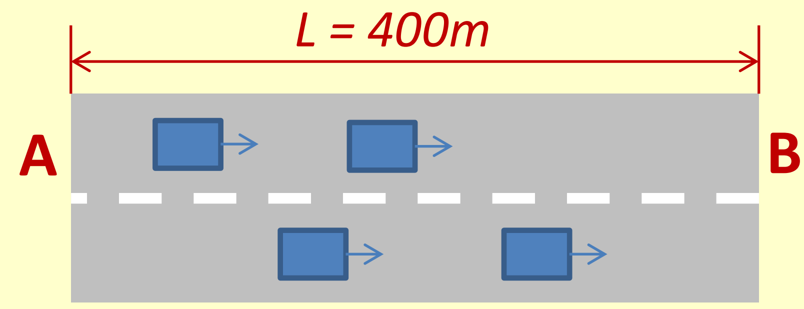


How many vehicles are currently on the road section B with length *L*? (e.g., 50veh/km)

Question 1

Flow and Density

- An observer located at point A observes four vehicles passing point A during 30 sec. The figure shows their positions at an instant of time by photography. Calculate flow (veh/h) and density (veh/km).



A. q = 0.13 veh/h, k = 0.01 veh/km

B. q = 8 veh/h, k = 1 veh/km

C. q = 240 veh/h, k = 10 veh/km

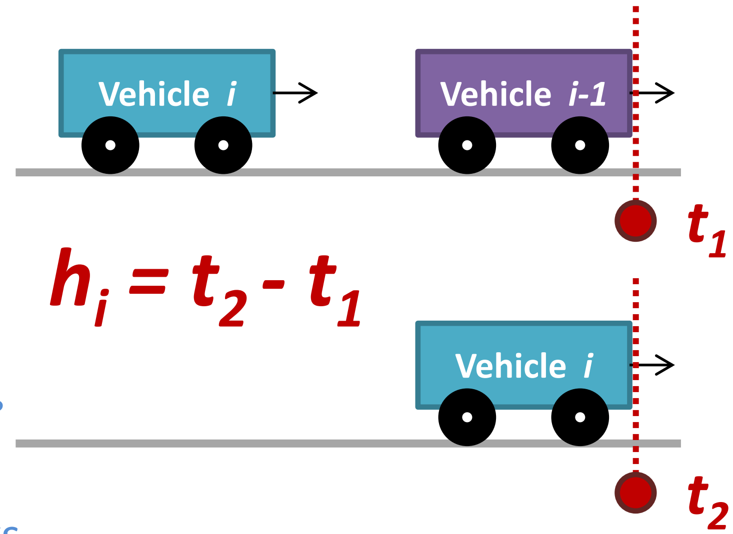
D. q = 480 veh/h, k = 10 veh/km

E. None of the above

Headway

- **Headway (h)**
  - Time interval separating the passing of a fixed point by two consecutive vehicles in a traffic stream, expressed as *seconds per vehicle* (s/veh)
  - The average headway (h) of the stream over a given time interval is the arithmetic mean of the series of headways occurring over that interval

Average headway $$h = \frac{1}{N}\sum_{i=1}^{N} h_i$$



where:

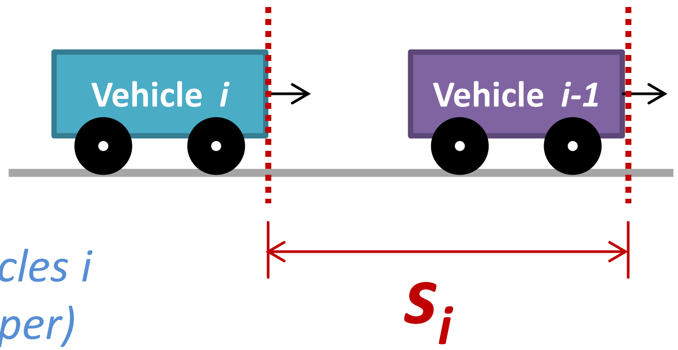
- h_i = *time headway of vehicle i (the elapsed time between the arrivals of vehicles i and i-1)*
- N = *number of measured vehicle time headways*

Spacing

- **Spacing (s)**
  - Distance between the fronts of two consecutive vehicles in a traffic stream at a given instant of time, expressed as *metres per vehicle* (m/veh)
  - The average spacing (s) of the stream over a given length of lane or carriageway is the arithmetic mean of the individual spacings occurring over that length at that instant of time

Average spacing

$$s = \frac{1}{N}\sum_{i=1}^{N} s_i$$



where:

- *s_i = spacing of vehicle i (the distance between vehicles i and i-1, measured from front bumper to front bumper)*
- *N = number of measured vehicle spacings*

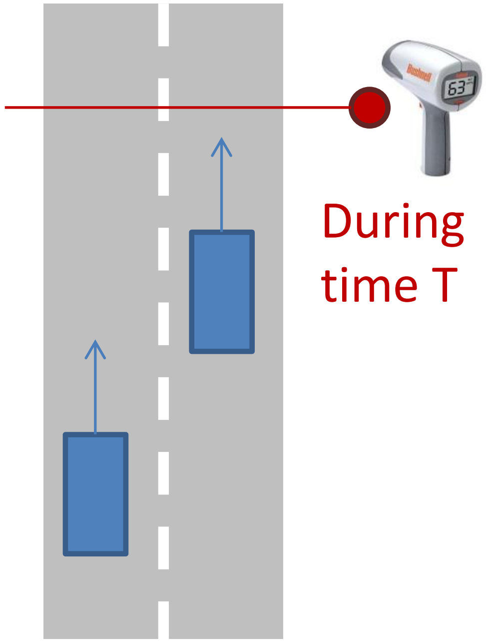
Speed

- **Speed (v)**
  - Distance travelled by a vehicle during a unit of time
  - Travel distance / travel time
  - *metres per second* (m/s) or *kilometres per hour* (km/h or kph)
- **Two Ways in which average speeds can be obtained:**
  - Time Mean Speed (v_t):
    - The average speed for vehicles that travel an equal amount of time
    - Average speed over time = Average travel distance / Fixed time
  - Space Mean Speed (v_s):
    - The average speed for vehicles that travel an equal amount of distance
    - Average speed over space = Fixed distance / Average travel time

Speed

- **Time Mean Speed (v_t)**
  - Arithmetic mean of the measured speeds of all vehicles passing a given point during a given time interval
  - Measured by taking a reference point on the roadway over a fixed period of time T
  - Average travel distance / Fixed time T:

Time mean speed
$$v_t = \frac{\frac{1}{N}\sum_{i=1}^{N} d_i}{T} = \frac{\frac{1}{N}\sum_{i=1}^{N} T v_i}{T} = \frac{1}{N}\sum_{i=1}^{N} v_i$$



where

- d_i = *travel distance of vehicle i during T*
- v_i = *individual speed (or 'spot speed') of vehicle i*
- N = *number of vehicles during T*

Speed

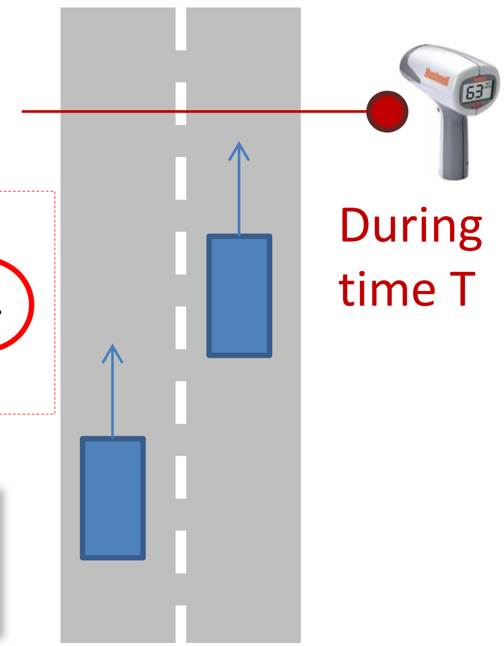
- **Time Mean Speed (v_t)**
  - Arithmetic mean of the measured speeds of all vehicles passing a given point during a given time interval
  - Measured by taking a reference point on the roadway over a fixed period of time T
  - Average travel distance / Fixed time T:

Time mean speed
$$v_t = \frac{\frac{1}{N}\sum_{i=1}^{N} d_i}{T} = \frac{\frac{1}{N}\sum_{i=1}^{N} Tv_i}{T} = \frac{1}{N}\sum_{i=1}^{N} v_i$$

where

- d_i = *travel distance*
- v_i = *individual spee*
- N = *number of vehicles during T*

Arithmetic mean of spot speeds



Speed

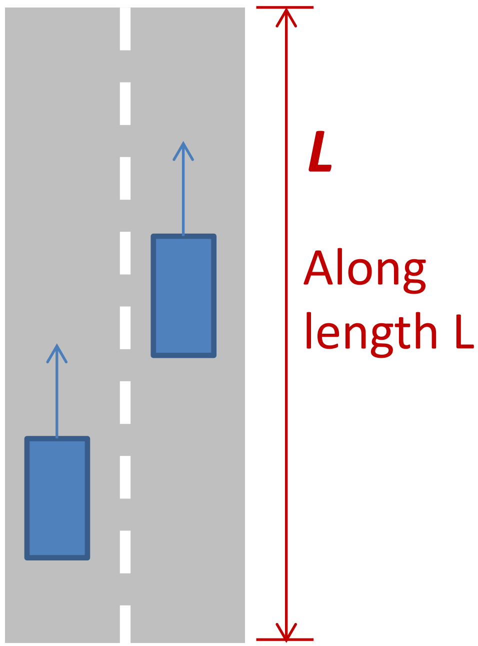
- **Space Mean Speed (v_s)**
  - Arithmetic mean of the measured speeds of all vehicles within a given length of lane or carriageway, at a given instant of time
  - Measured by taking the whole roadway segment into account
  - Fixed length L / Average travel time:

Space mean speed

$$v_s = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} t_i} = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} \frac{L}{v_i}} = \frac{1}{\frac{1}{N}\sum_{i=1}^{N} \frac{1}{v_i}}$$

where:

- *t_i = travel time of vehicle i to traverse length L*
- *v_i = individual speed (or 'spot speed') of vehicle i*
- *N = number of vehicles along L at a given time*

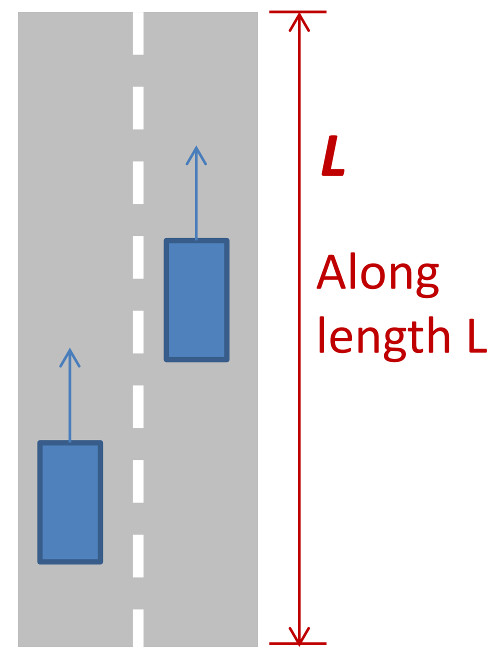


Speed

The University Of Queensland
AUSTRALIA

- **Space Mean Speed (v_s)**
  - Arithmetic mean of the measured speeds of all vehicles within a given length of lane or carriageway, at a given instant of time
  - Measured by taking the whole roadway segment into account
  - Fixed length L / Average travel time:

Space mean speed $$v_s = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} t_i} = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} \frac{L}{v_i}} = \frac{1}{\frac{1}{N}\sum_{i=1}^{N} \frac{1}{v_i}}$$



where:

- *t_i = travel time of vehicle i to traverse length L*
- *v_i = individual spee*
- *N = number of vehi*

Harmonic mean of spot speeds

Question 2

Speed

- Three vehicles traverse a 1 km segment of freeway in 1.2, 1.5, and 1.0 minutes respectively. What are the time-mean and space-mean speeds (km/h) ? (Assume that the speeds are constant along the segment).

A. v_t = 41.8 km/h, v_s = 40.9 km/h

B. v_t = 40.9 km/h, v_s = 41.8 km/h

C. v_t = 50.0 km/h, v_s = 48.7 km/h

D. v_t = 48.7 km/h, v_s = 50.0 km/h

E. None of the above

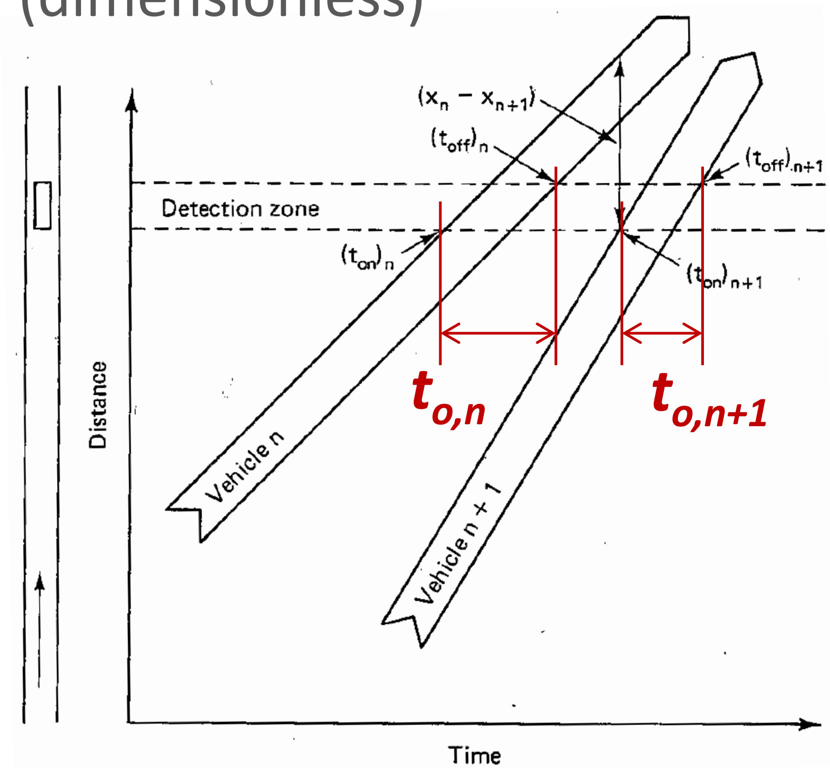
Lane Occupancy

- **Occupancy (Occ)**
  - – The proportion of time for which a detector is "occupied" or covered by a vehicle at a given location over a defined period of time T, expressed as a proportion (dimensionless)

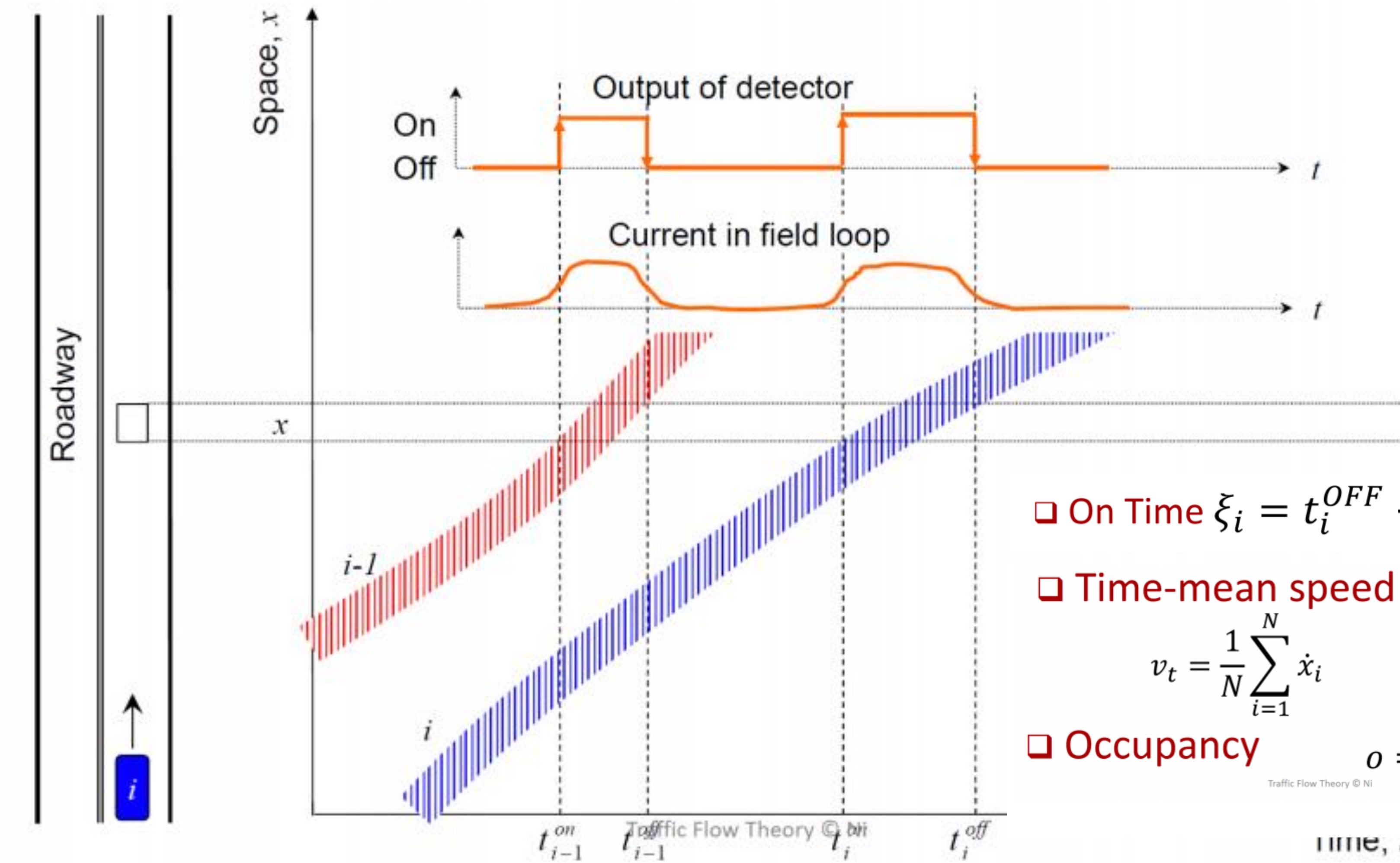
Occupancy $$Occ = \frac{\sum_{i=1}^{N} t_{o,i}}{T}$$

where:

- *$t_{o,i}$ = duration of the period when the detection zone is occupied by vehicle i*
- *N = number of vehicles detected during time period T*
- *T = observation time period*



Point sensor data



- On Time $\xi_i = t_i^{OFF} - t_i^{ON}$
- Time-mean speed

$$v_t = \frac{1}{N}\sum_{i=1}^{N} \dot{x}_i$$

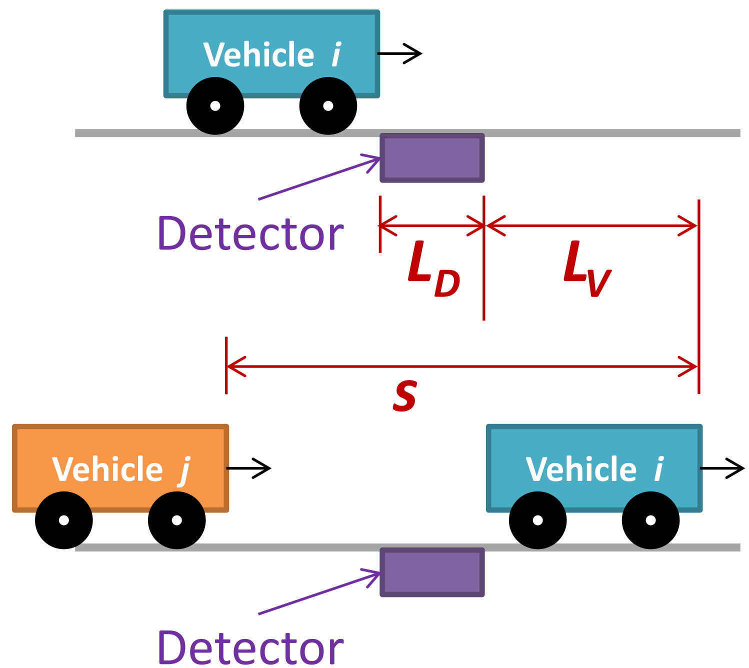
- Occupancy

$$o = \frac{\sum_{i=1}^{N} \xi_i}{T}$$

Lane Occupancy

- **Occupancy (Occ)**
  - Related to the average spacing (s) as follows:

Occupancy $$Occ = \frac{\sum_{i=1}^{N} t_{o,i}}{T} = \frac{L_V + L_D}{s}$$



where:

- $t_{o,i}$ = *duration of the period when the detection zone is occupied by vehicle i*
- L_V = *average length of a vehicle (m)*
- L_D = *effective length of detector (m)*
- *s = average spacing of vehicles (m/veh)*

Lane Occupancy

- **Density and Occupancy**
  - Occupancy is often used as a 'surrogate' for density (k) because density is difficult to measure directly (e.g., need aerial photography)
  - Obtain Density from Occupancy:

$$Occ = \frac{L_V + L_D}{s} \qquad \leftarrow s[\mathrm{m/veh}] = \frac{1000}{k[\mathrm{veh/km}]}$$

$$k = \frac{1000}{s} = \frac{1000 \cdot Occ}{L_V + L_D} = \frac{10 \cdot (\%Occ)}{L_V + L_D}$$

where:

- *%Occ = occupancy expressed as a percentage*
- *L_V, L_D = vehicle length and detector length, respectively (m)*

Question 3

Density and Occupancy

- A detector records a %occupancy of 20% for a 15-minute analysis period. If the average vehicle length is 9m and the detector is 1m long, what is the density?

A. 0.2 veh/km

B. 4 veh/km

C. 10 veh/km

D. 20 veh/km

E. None of the above

$$Occ = \frac{\sum_{i=1}^{N} t_{o,i}}{T}$$

$$k = \frac{1000 \cdot Occ}{L_V + L_D} = \frac{10 \cdot (\%Occ)}{L_V + L_D}$$

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Relationships between Traffic Flow Parameters

Macroscopic vs. Microscopic

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

- **Macroscopic Parameters**
  - Describing the entire traffic stream

- **Microscopic Parameters**
  - Describing individual vehicles

Macroscopic	Microscopic
Flow (q)	Headway (h_i)
Density (k)	Spacing (s_i)
Speed (v_s, v_t)	Speed (v_i)

Fundamental Relationships

- **Flow is the product of Density and (Space Mean) Speed**

$$\boxed{q = k \times v_s} \qquad \left[\frac{\text{veh}}{\text{h}}\right] = \left[\frac{\text{veh}}{\text{km}}\right] \times \left[\frac{\text{km}}{\text{h}}\right]$$

- **Flow is the inverse of Average Headway**

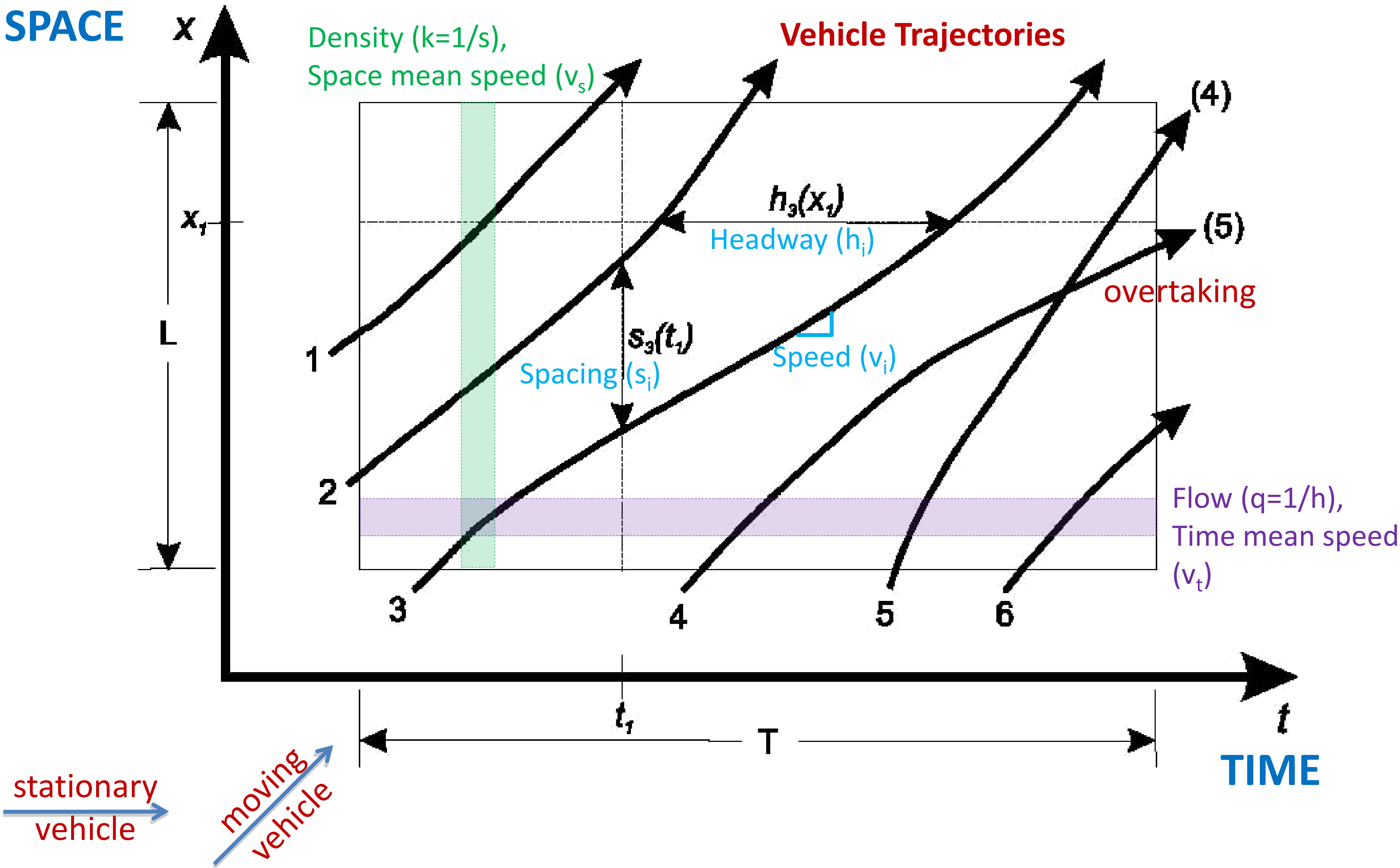
$$q = 1/h \qquad q = \frac{3600}{h} \quad \left[\frac{\text{veh}}{\text{h}}\right] = 1 \Big/ \left[\frac{\text{s}}{\text{veh}} \times \frac{1\text{h}}{3600\text{s}}\right]$$

- **Density is the inverse of Average Spacing**

$$k = 1/s \qquad k = \frac{1000}{s} \quad \left[\frac{\text{veh}}{\text{km}}\right] = 1 \Big/ \left[\frac{\text{m}}{\text{veh}} \times \frac{1\text{km}}{1000\text{m}}\right]$$

- **Other derived relations:** $h = s/v \qquad s = h \cdot v$

Space-Time Diagram



Question 4

Headway and Flow

- Traffic flow on a one lane ramp is 360 veh/h, what is the average headway (seconds)?

A. 0.1 s

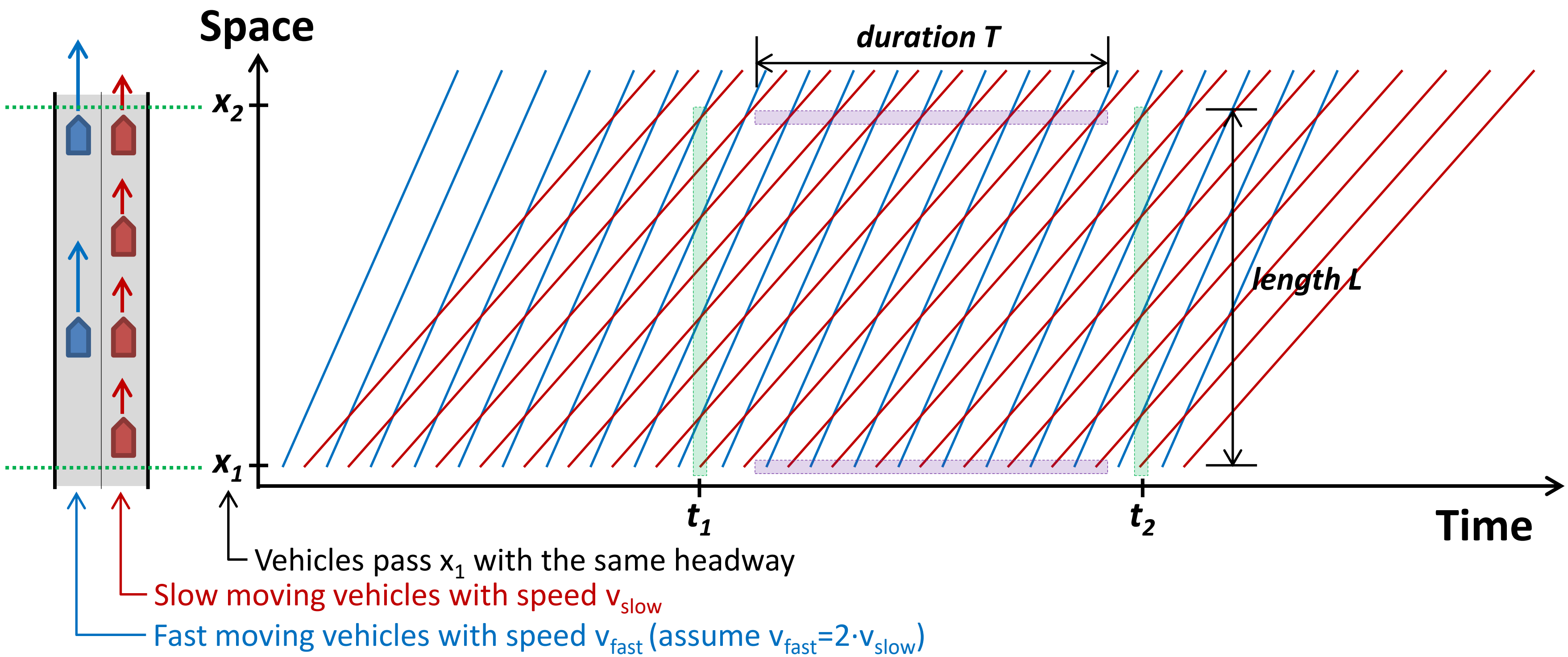
B. 10 s

C. 36 s

D. 60 s

E. None of the above

Why $V_s \leq V_t$??



Slower vehicles occupy any given segment of road for a longer period of time than faster vehicles, and therefore receive a greater weighting in the calculation of space mean speed than they do in the calculation of time mean speed.

[Time Mean Speed] During ***T*** at any given location ***x***, the sample contains an equal number of slow and fast vehicles

$\rightarrow v_t = \frac{1}{2} v_{slow} + \frac{1}{2} v_{fast}$

[Space Mean Speed] Over ***L*** at any given time ***t***, the sample contains twice as many slow vehicles as fast vehicles

$\rightarrow v_s = \frac{2}{3} v_{slow} + \frac{1}{3} v_{fast}$

Relationships between V_t and V_s

- **The Approximate Relationship between Time Mean Speed and Space Mean Speed**

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

σ_s^2 = the variance of space mean speed,

i.e., $\sigma_s^2 = \frac{\sum_{i=1}^{N}(v_i - v_s)^2}{N-1}$

- **Space mean speed is always less than or equal to time mean speed ($V_s \leq V_t$)**

  When all vehicles have exactly the same speed, the two mean speeds are equal ($V_s = V_t$).

Graphical Relationships for Uninterrupted Flow

Types of Traffic Flow

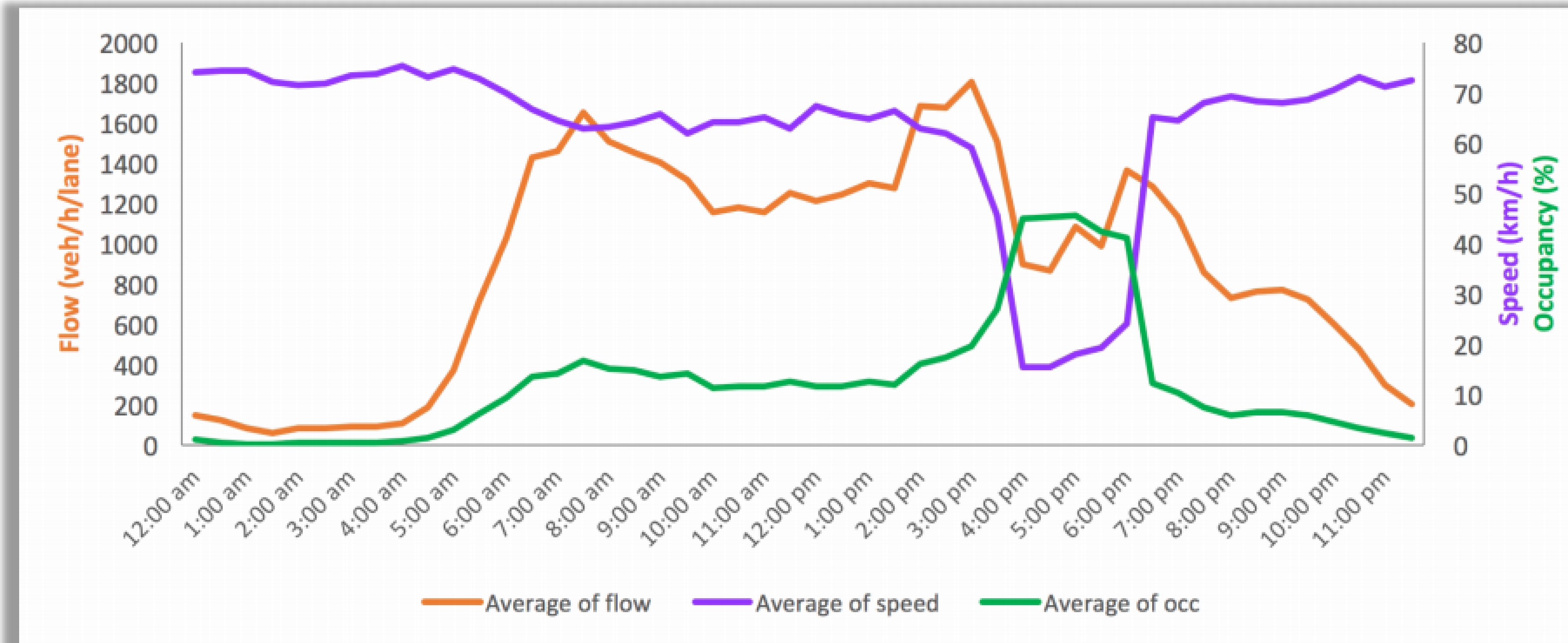
- **Uninterrupted Flow** Vs. **Interrupted Flow**
  - Uninterrupted flow occurs in a traffic stream that is not delayed or interfered with by factors external to the traffic stream itself
  - Uninterrupted flow facilities
    - No intersections at grade, traffic signals, STOP or GIVE WAY signs, direct property access (e.g., controlled-access roads such as motorways)
    - The characteristics of the traffic stream are based solely on the interactions among vehicles and with the roadway and the general environment.

Types of Traffic Flow

- **Uninterrupted Flow** Vs. **Interrupted Flow**
  - Interrupted flow occurs when external factors have significant effects on the traffic flow.
  - Interrupted flow facilities
    - Incorporate fixed external interruptions into their design and operation: traffic signal, STOP or GIVE WAY signs, unsignalized at-grade intersections, land access operations (e.g., arterials and other urban streets)
    - The characteristics of the traffic stream are primarily based on external interruptions (e.g., "red" signals stop traffic periodically and create a platoons of vehicles); vehicle-vehicle interactions and vehicle-roadway interactions play a secondary role in defining the traffic flow.

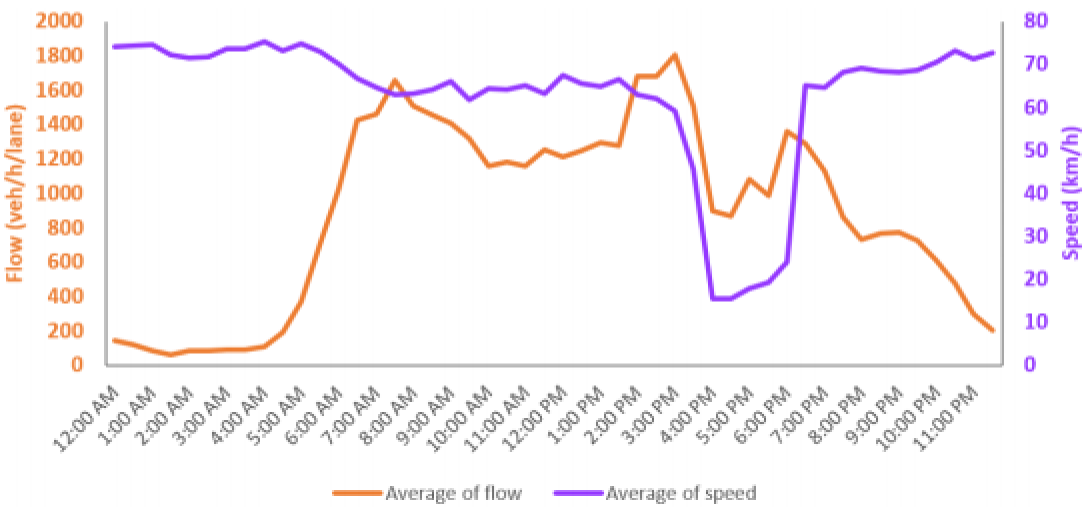
Traffic Characteristics

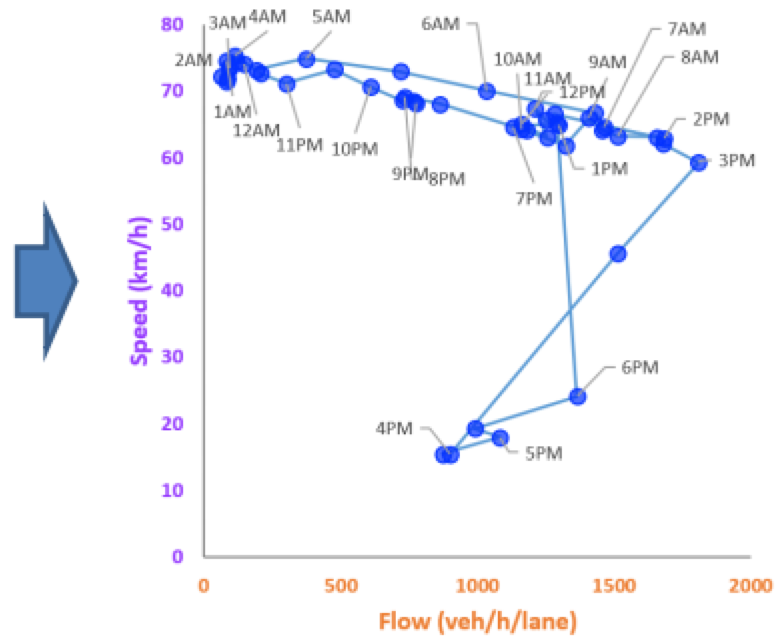
- **Flow, Density, and Speed Relationship**



Traffic Characteristics

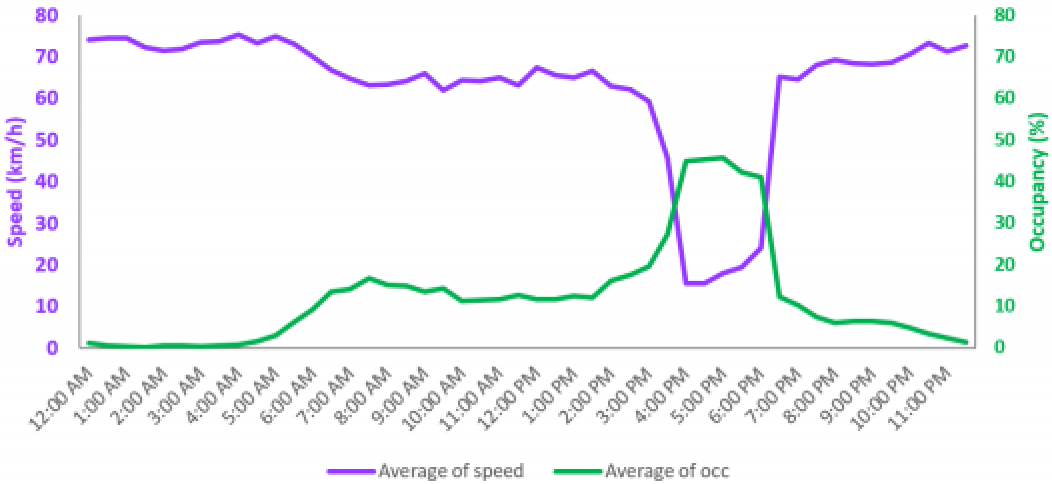
- **Speed (v) – Flow (q) Plot**

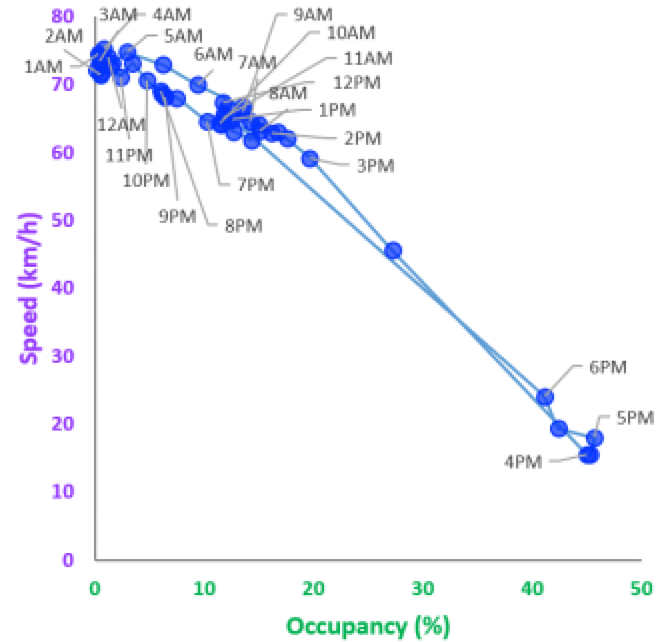




Traffic Characteristics

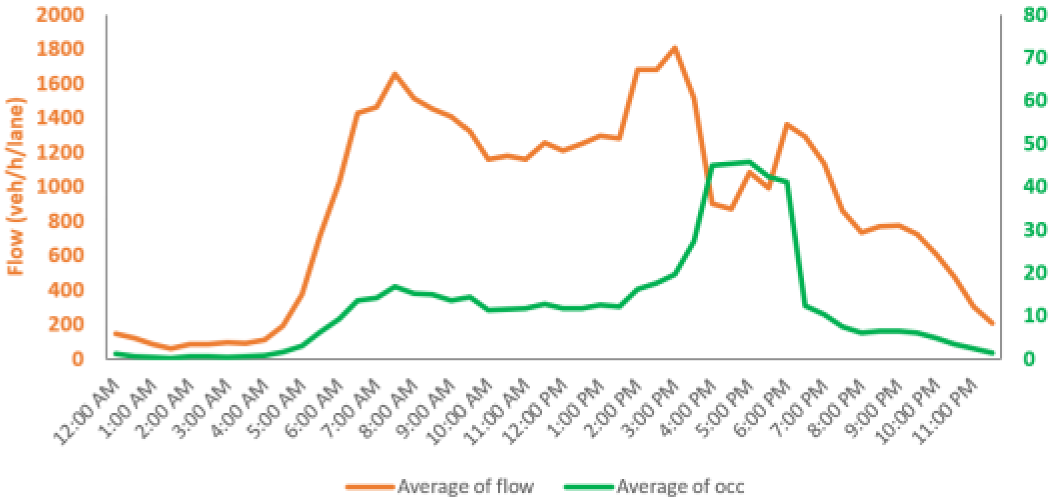
- ## Speed (v) – Density (k) Plot

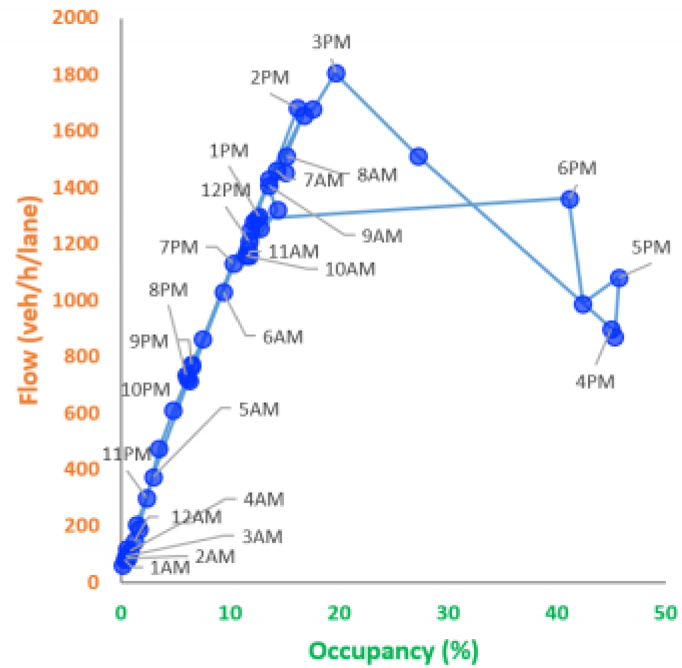




Traffic Characteristics

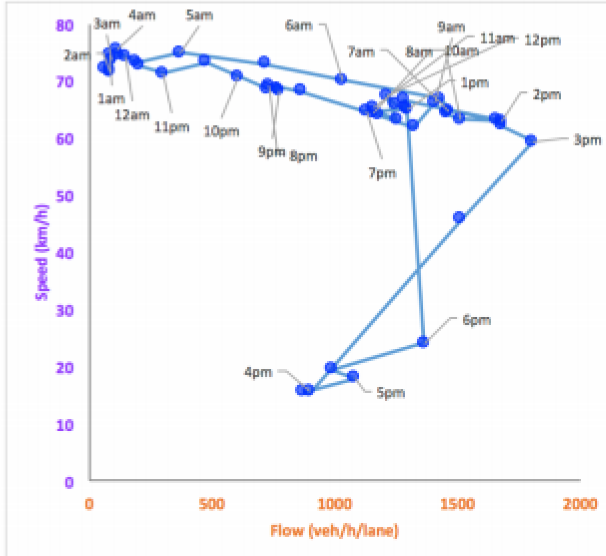
- **Flow (q) – Density (k) Plot**

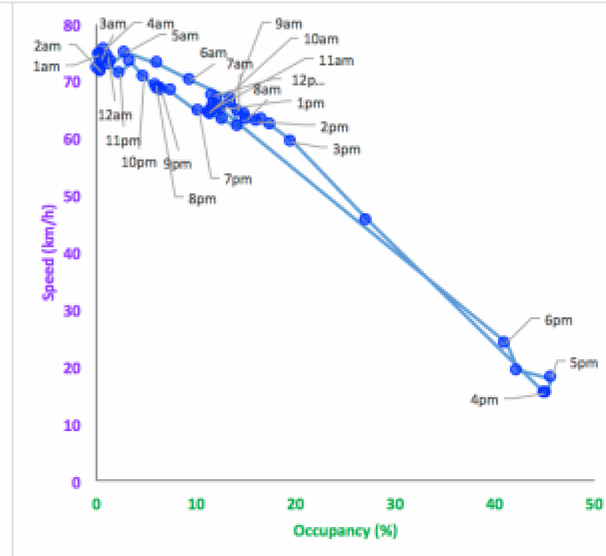


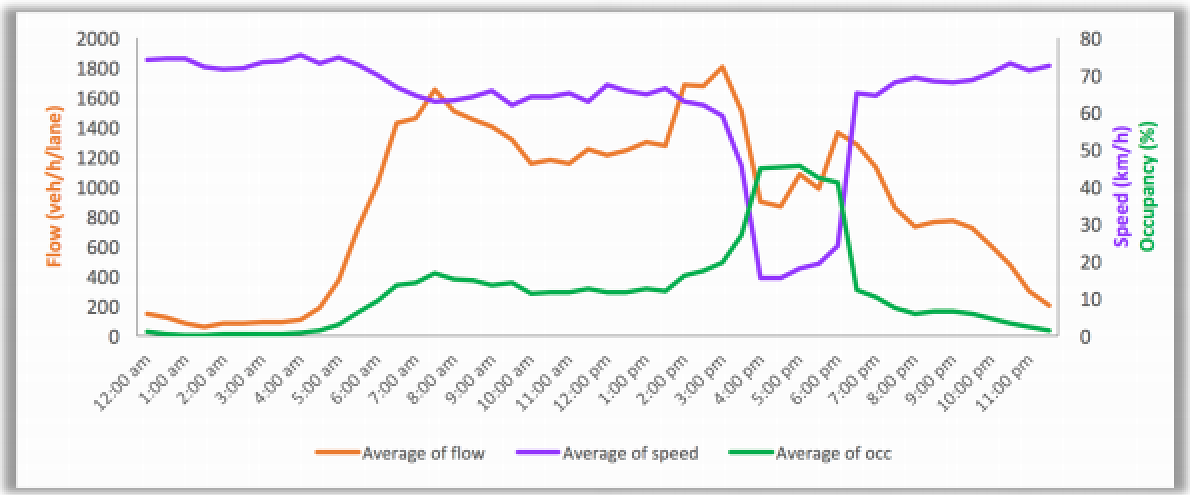


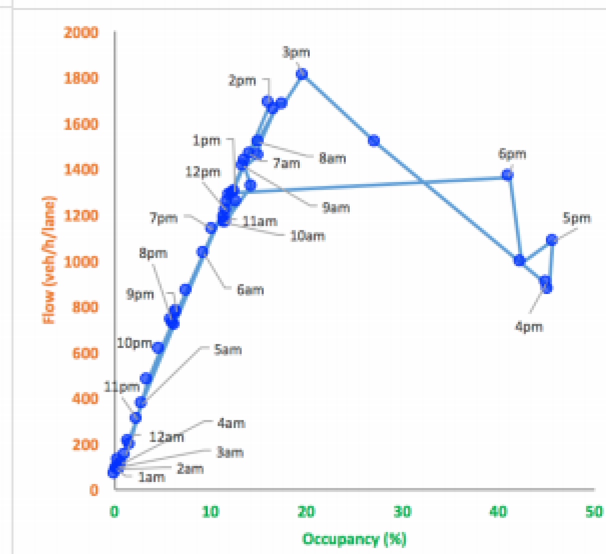
Traffic Characteristics

- **Fundamental relationships of '*uninterrupted*' traffic flow**

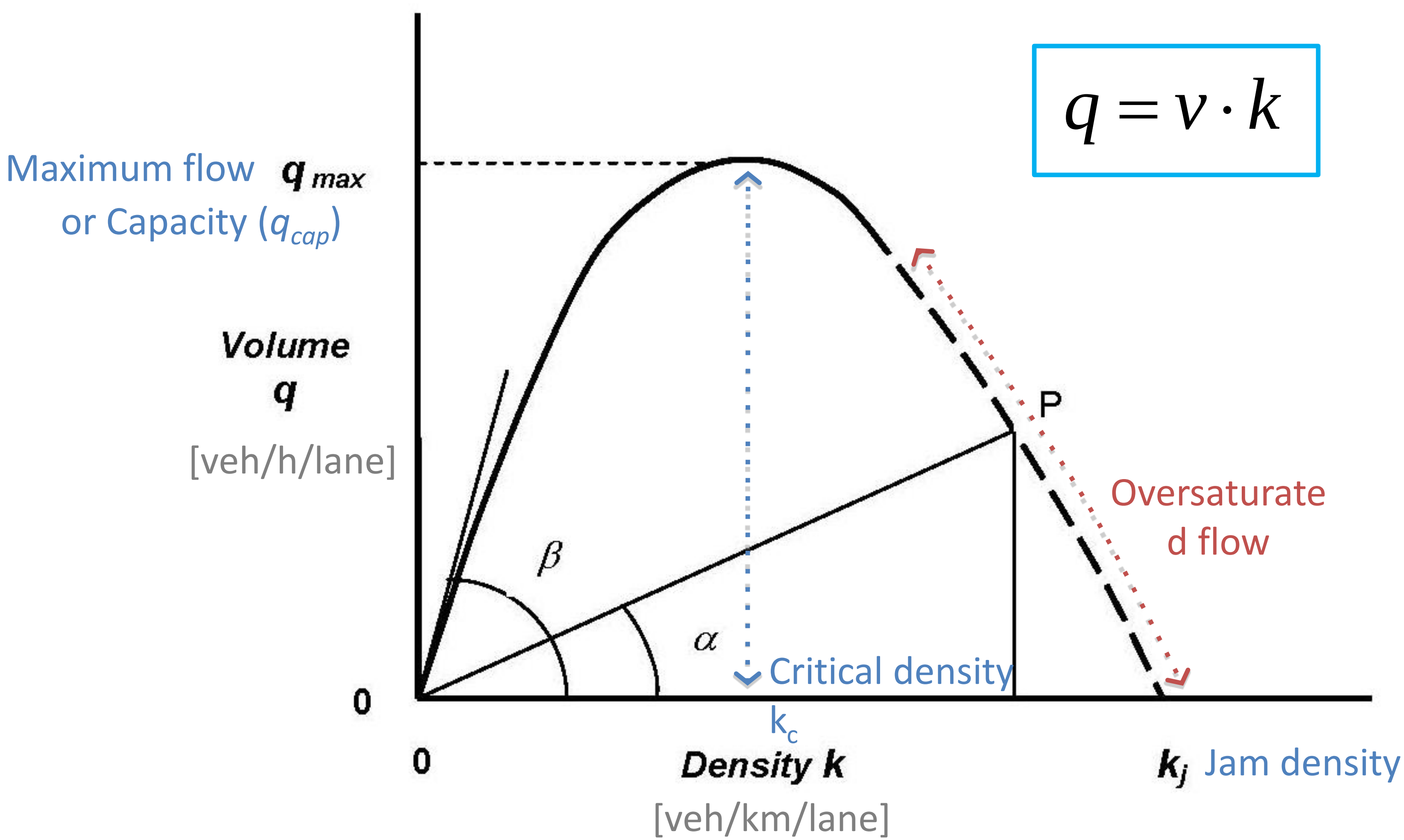




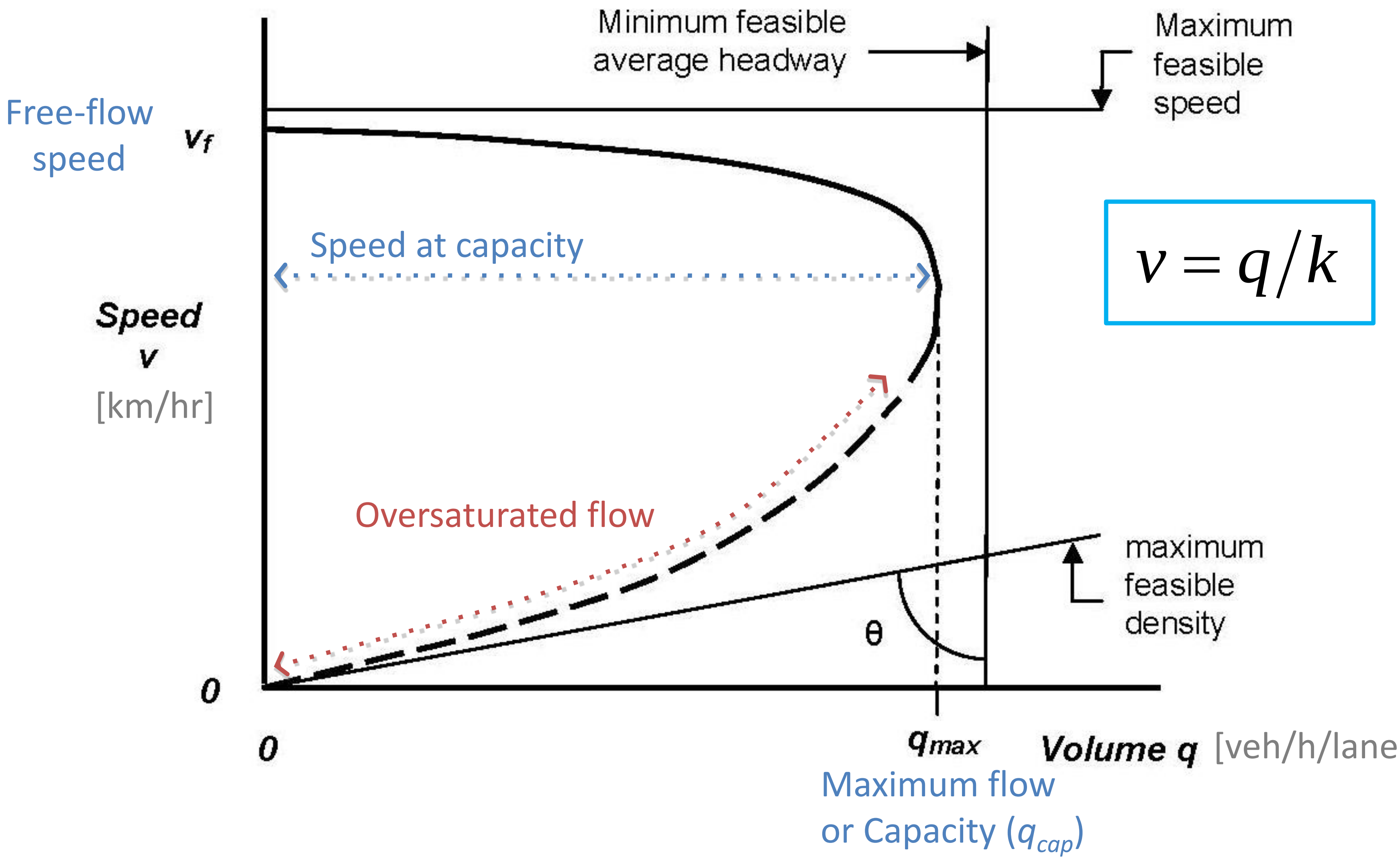




Flow-Density Relationship



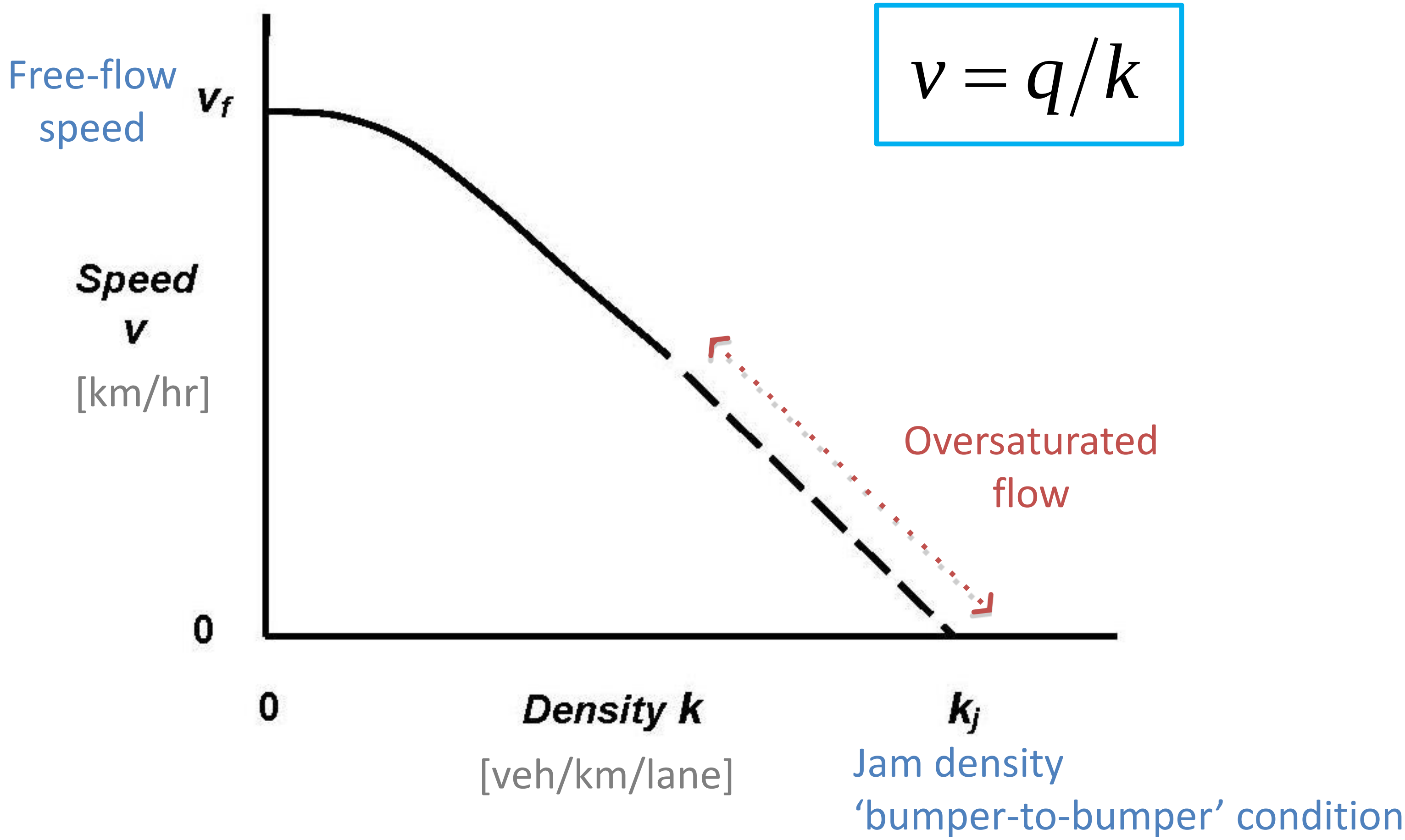
Speed-Flow Relationship



$$\boxed{v = q/k}$$

Speed-Density Relationship

$$v = q/k$$



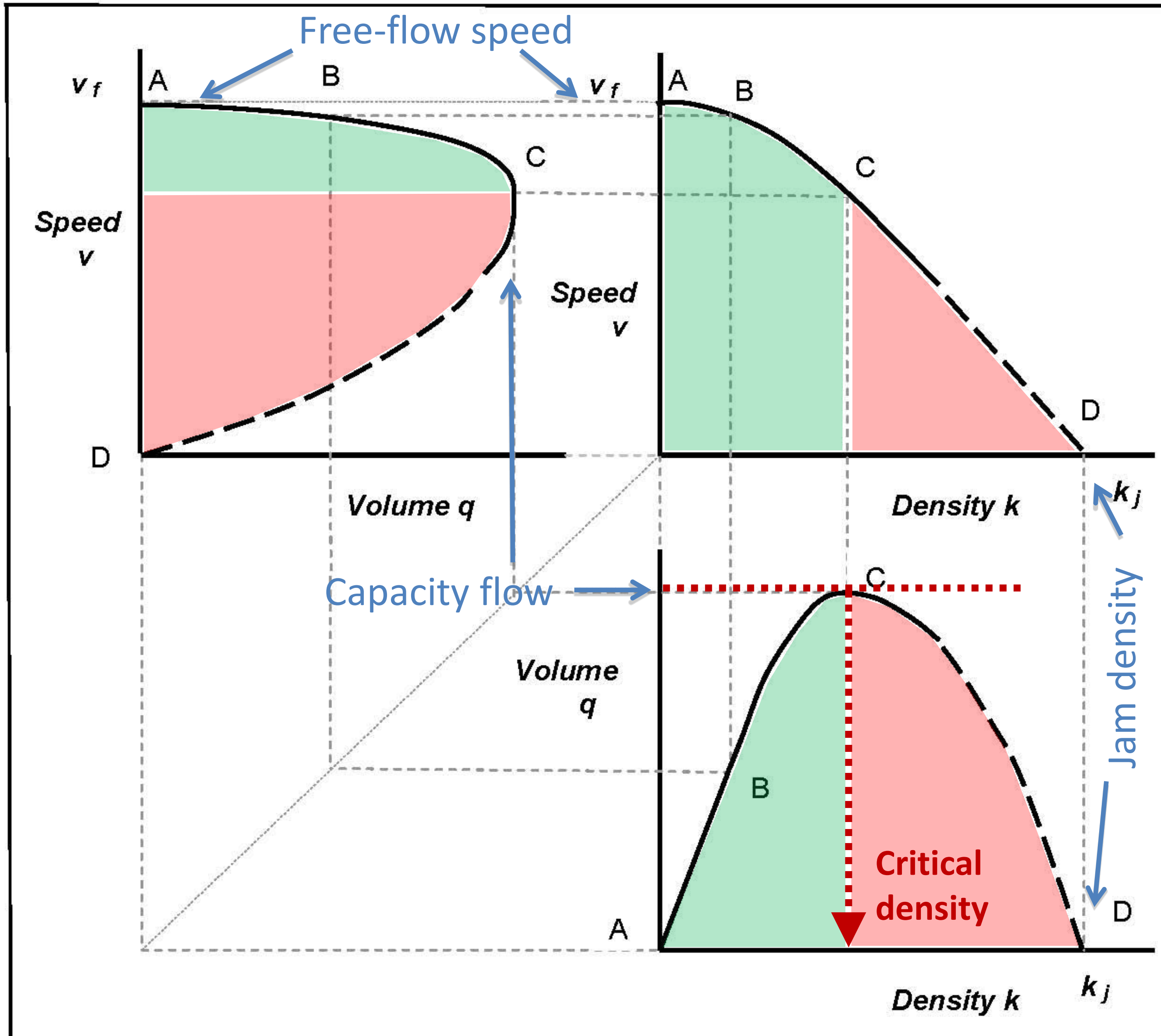
Flow-Density-Speed Relationships

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Fundamental Diagrams (FD)

'Fundamental relationships' of 'uninterrupted' traffic flow

At **A**, no interaction
A-**B**, free flow
B-**C**, steady flow
At **C**, traffic unstable
C-**D**, forced flow
At **D**, traffic stationary

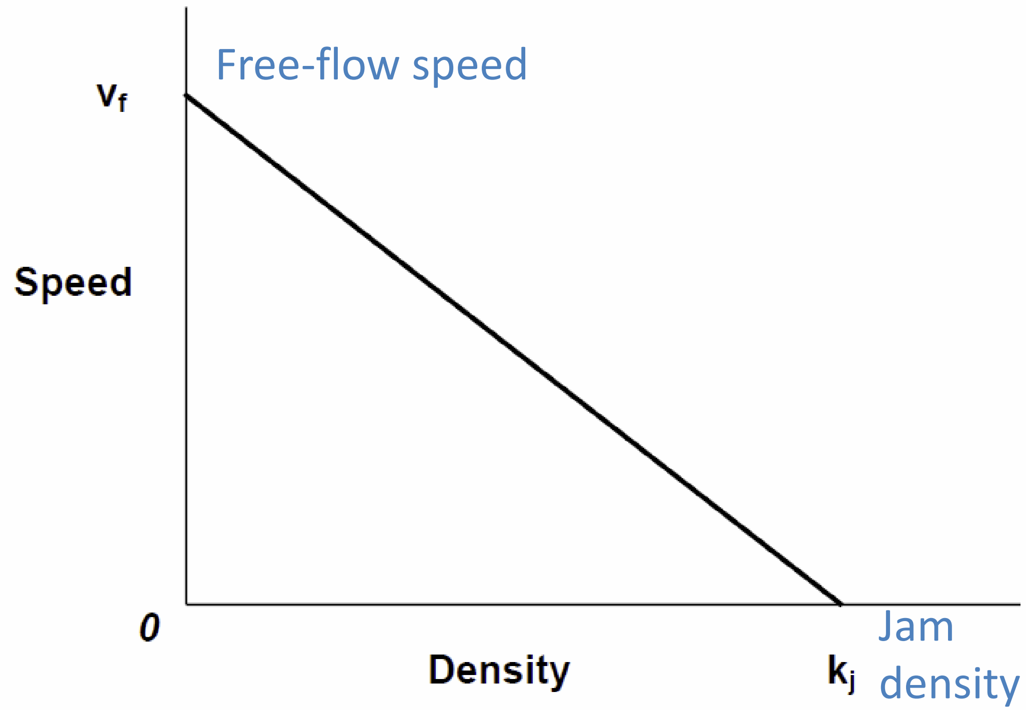


Traffic Stream Model

- *Linear* **Speed-Density Relationship**
  - The first traffic stream model, developed by Greenshields (known as 'Greenshields model')
  - Assumes that the space mean speed of the traffic would decrease linearly from the mean free speed, v_f, at zero density, to zero speed at the jam density, k_j.

$$v = v_f \left(1 - \frac{k}{k_j} \right) \quad \cdots\cdots (1)$$

where:
*v = **space-mean** speed (km/h)*
v_f = free-flow speed (km/h)
k = density (veh/km)
k_j = jam density (veh/km)

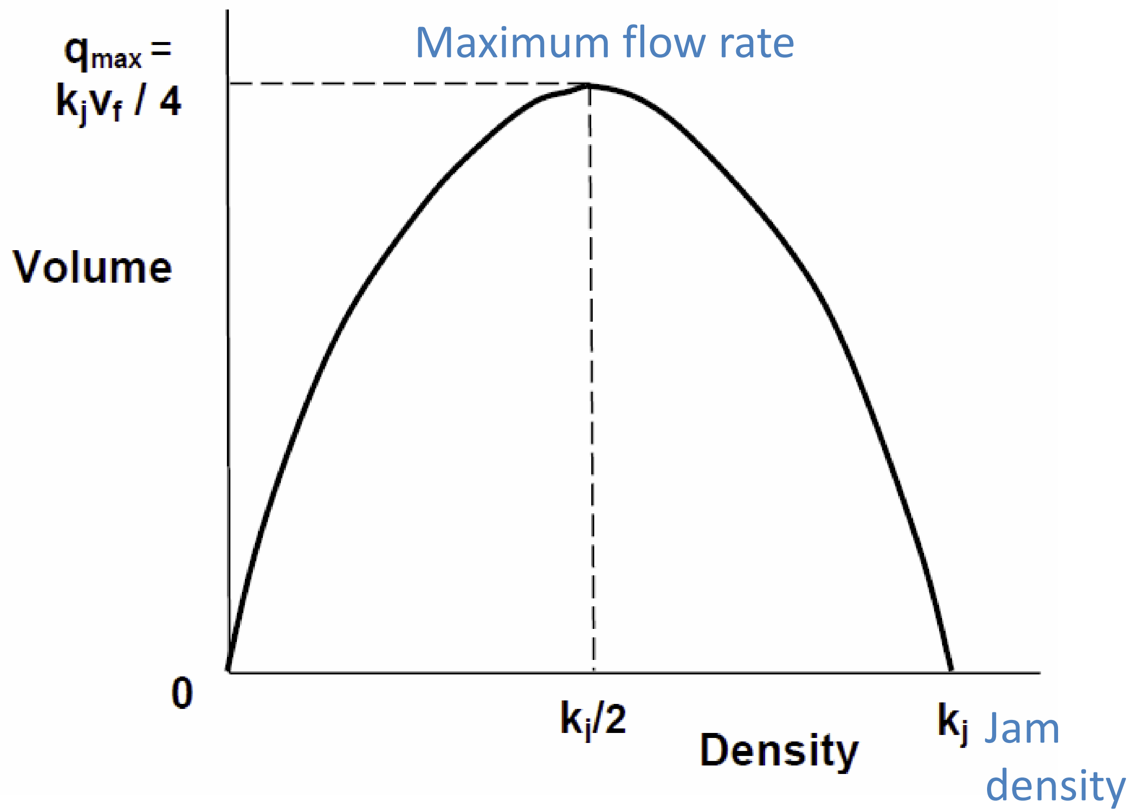


Traffic Stream Model

- *Parabolic* **Flow-Density Relationship**
  - $q = k \cdot v$ ← Eq. (1)

$$q = v_f \left(k - \frac{k^2}{k_j} \right) \quad \cdots\cdots (2)$$

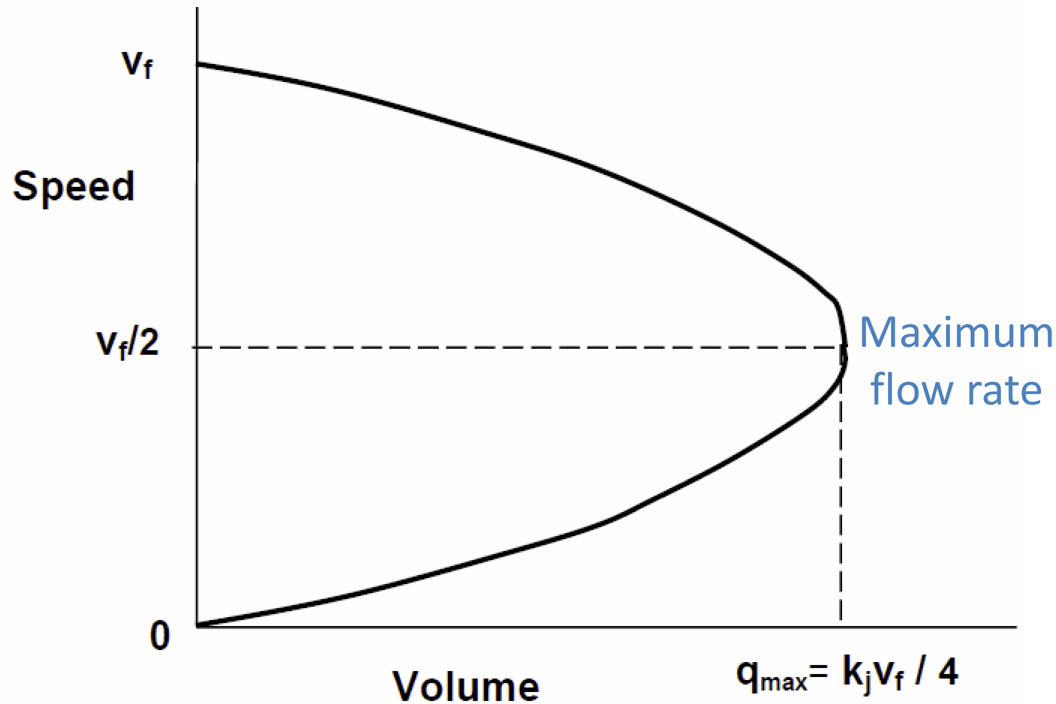
where:
q = flow rate or volume (veh/h)
v_f = free-flow speed (km/h)
k = density (veh/km)
k_j = jam density (veh/km)



Traffic Stream Model

- *Parabolic* **Speed-Flow Relationship**
  - Rearranging Eq.(1) → $k = k_j\left(1 - v/v_f\right)$
  - *q=k·v* ← *k*

$$q = k_j\left(v - \frac{v^2}{v_f}\right) \quad \cdots\cdots (3)$$



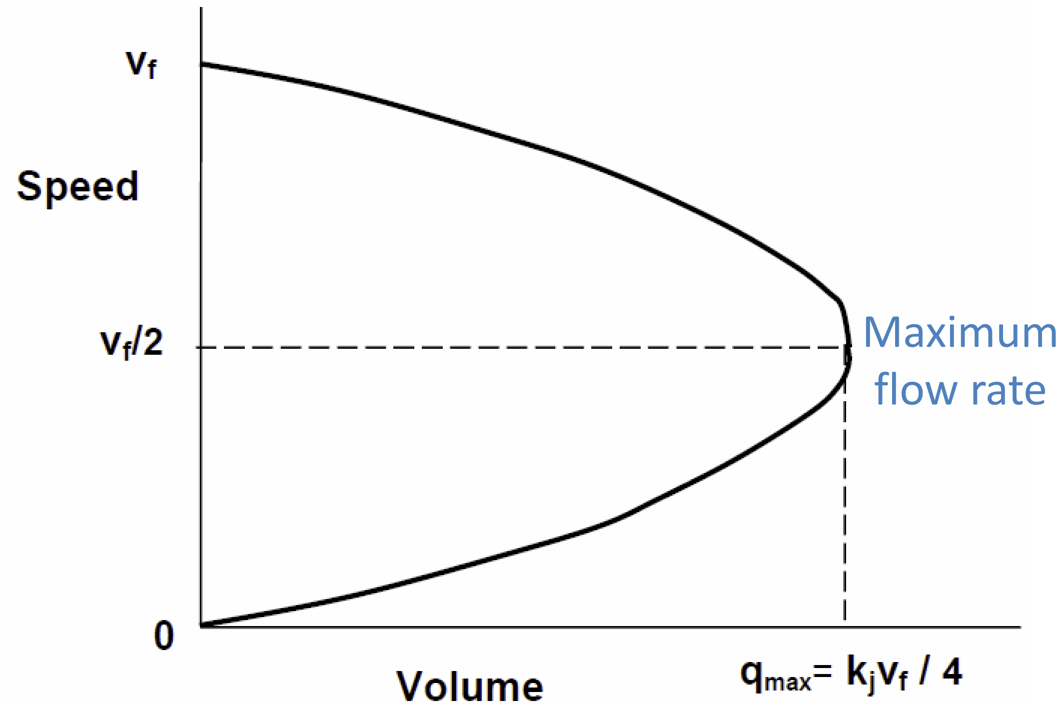
where:
q = flow rate or volume (veh/h)
*v = **space-mean** speed (km/h)*
v_f = free-flow speed (km/h)

Traffic Stream Model

- *Parabolic* **Speed-Flow Relationship**
  - Rearranging Eq.(1) → $k = k_j(1 - v/v_f)$
  - $q=k \cdot v$ ← k

$$q = k_j\left(v - \frac{v^2}{v_f}\right) \quad \text{..... (3)}$$

$$\frac{dq}{dv} = 0 \Rightarrow \boxed{v_{cap} = \frac{v_f}{2}}$$



where:

q = flow rate or volume (veh/h)

*v = **space-mean** speed (km/h)*

v_f = free-flow speed (km/h)

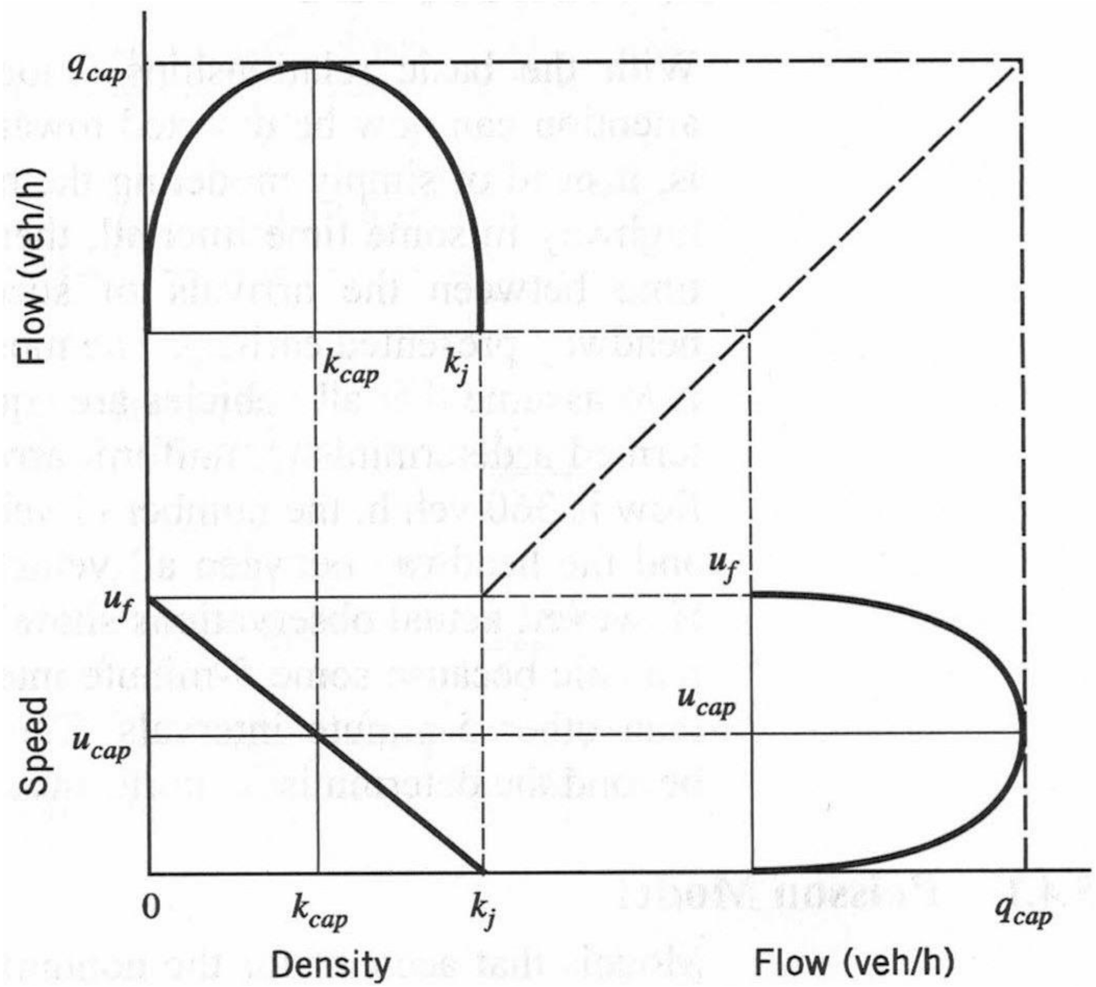
v_{cap} = speed at capacity or maximum flow

Traffic Stream Model

- **Speed-Flow-Density Relationships**

$$q = v_f\left(k - \frac{k^2}{k_j}\right)$$

..... (2)



$$v = v_f\left(1 - \frac{k}{k_j}\right)$$

..... (1)

$$q = k_j\left(v - \frac{v^2}{v_f}\right)$$

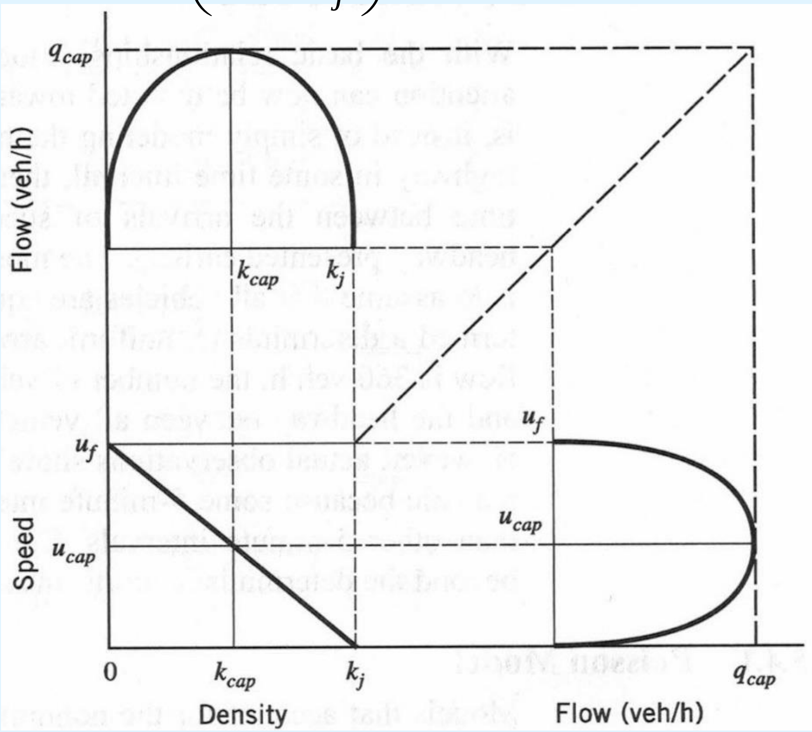
..... (3)

Exercise: Traffic Stream Model

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

- A section of highway is known to have a free-flow speed of 88 km/h and a capacity of 3300 veh/h. In a given hour, 2100 vehicles were counted at a specified point along this highway section. If the linear speed-density relationship in Eq. (1) applies, what would you estimate the space-mean speed of these 2100 vehicles to be?

$$q = v_f\left(k - \frac{k^2}{k_j}\right) \quad \cdots\cdots (2)$$



$$v = v_f\left(1 - \frac{k}{k_j}\right) \quad \cdots\cdots (1)$$

$$q = k_j\left(v - \frac{v^2}{v_f}\right) \quad \cdots\cdots (3)$$

Exercise: Traffic Stream Model

- A section of highway is known to have a free-flow speed of 88 km/h and a capacity of 3300 veh/h. In a given hour, 2100 vehicles were counted at a specified point along this highway section. If the linear speed-density relationship in Eq. (1) applies, what would you estimate the space-mean speed of these 2100 vehicles to be?

$$q_{cap} = \frac{v_f k_j}{4} \Rightarrow k_j = \frac{4q_{cap}}{v_f} = \frac{4 \times 3300}{88}$$

$$\Rightarrow k_j = 150 \text{ veh/km}$$

$$\begin{cases} q = 2100 \text{ veh/h} \\ k_j = 150 \text{ veh/km} \end{cases} \Rightarrow v = ?$$

Rearranging Eq. (3):

$$q = k_j \left(v - \frac{v^2}{v_f} \right) \Rightarrow \frac{k_j}{v_f} v^2 - k_j v + q = 0$$

$$\Rightarrow \frac{150}{88} v^2 - 150v + 2100 = 0$$

$$\Rightarrow v = 70.53 \text{ km/h or } 17.47 \text{ km/h}$$

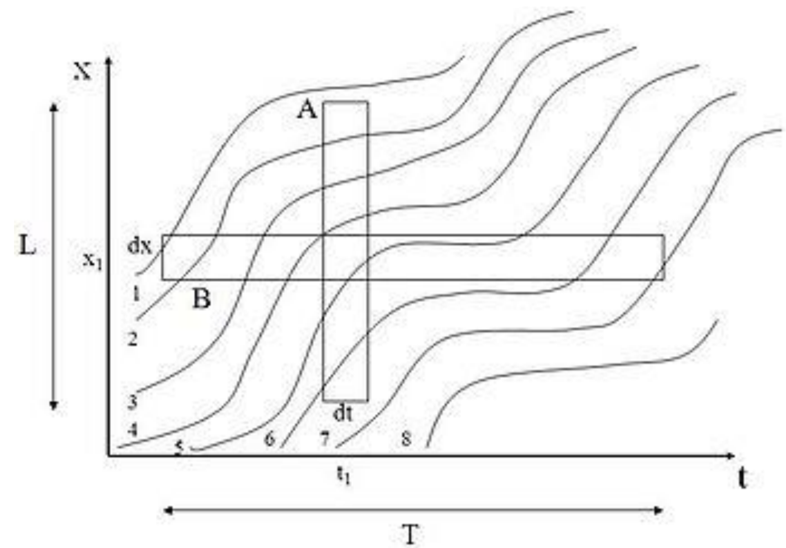
Generalized Definitions of Flow, Density, and Speed

Generalized Definition for *q* and *k*

- **A More Generalized Definition of Flow and Density:**

$$q = \frac{N}{T} = \frac{N \times dx}{T \times dx} = \frac{d(B)}{|B|}$$

dx : infinitesimal distance
d(B) : sum of distances travelled by all vehicles during T
|B| : area of time-space rectangle B bounded by T and dx
Flow (q) : total distance travelled by all vehicles within B divided by the area of B



$$k = \frac{N}{L} = \frac{N \times dt}{L \times dt} = \frac{t(A)}{|A|}$$

dt : infinitesimal duration
t(A) : sum of times spent by all vehicles within A
|A| : area of time-space rectangle A bounded by L and dt
Density (k) : total travel time spent by all vehicles within A divided by the area of A

Generalized Definition for *q* and *k*

- **Unifying the Generalized Definition of q, k, and v:**
  - "Edie's generalized definition" (Edie, 1965)

$$q(C) = \frac{d(C)}{|C|}$$

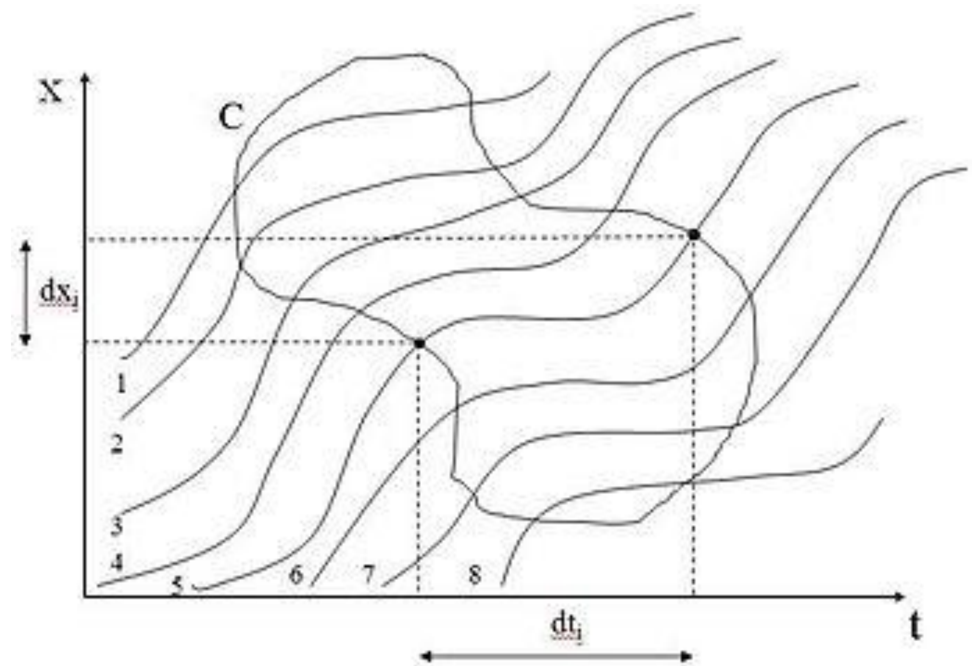
Total travel distance (veh·km) / Total space-time region (km·hrs)

$$k(C) = \frac{t(C)}{|C|}$$

Total travel time (veh·hrs) / Total space-time region (km·hrs)

$$v(C) = \frac{d(C)}{t(C)}$$

Total travel distance (veh·km) / Total travel time (veh·hrs)

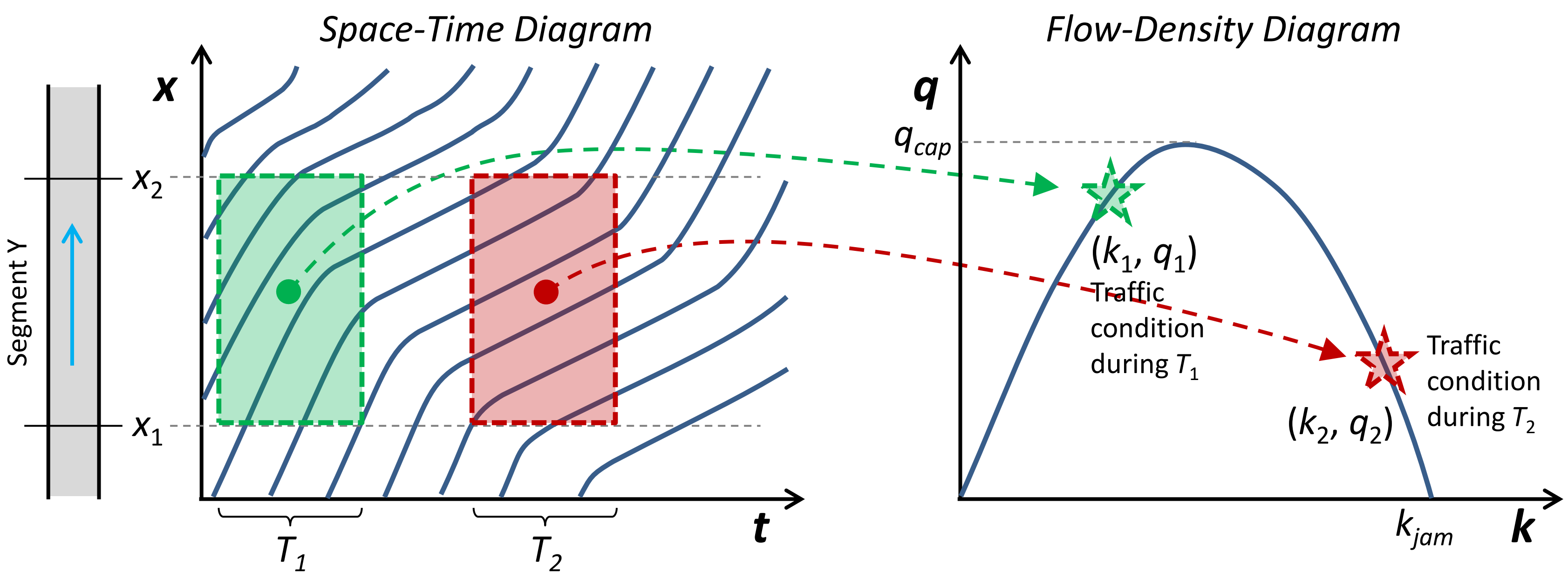


where

$$d(C) = \sum_{i=1}^{N} dx_i \qquad t(C) = \sum_{i=1}^{N} dt_i$$

Space-Time Diagram (x-*t* plot) vs. Fundamental Diagram (*q*-*k* plot)

- **Relation between Space-Time Diagram and Flow-Density Diagram**



Points on the fundamental diagram (FD) describe all possible traffic conditions on the road segment Y.

→ ***FD is a (steady-state) property of the road***.

Clicker Question 5

Edie's Generalized Definition

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

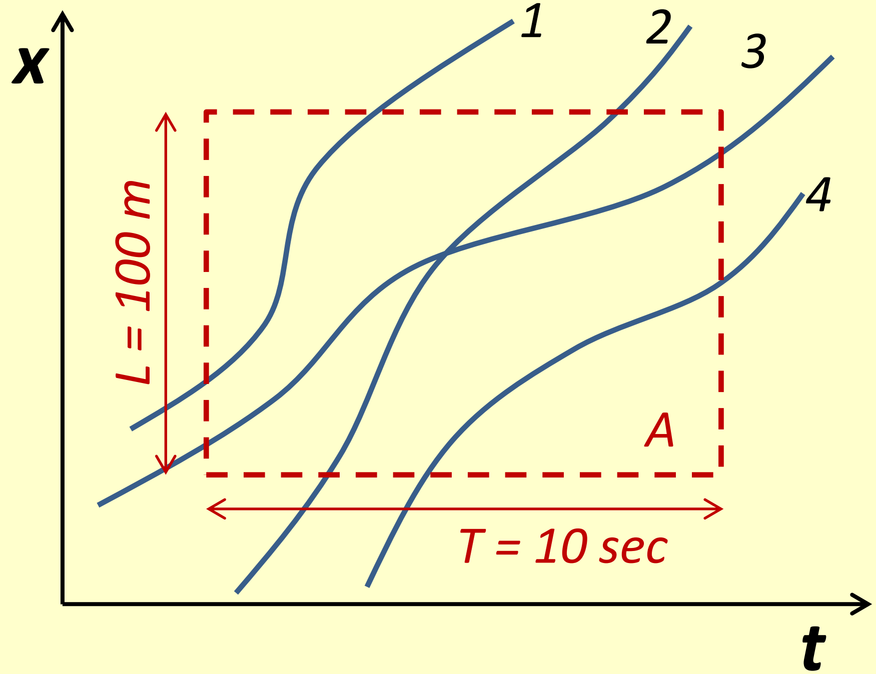
- Calculate flow q in region A using Edie's generalized definition.

Veh i	dt_i	dx_i
1	3 sec	70 m
2	6 sec	100 m
3	10 sec	80 m
4	5 sec	50 m

$$q(A) = \frac{d(A)}{|A|}$$

$$k(A) = \frac{t(A)}{|A|}$$

$$v(A) = \frac{d(A)}{t(A)}$$



A. 1080 veh/h
B. 1440 veh/h
C. 1880 veh/h
D. 2400 veh/h
E. None of the above

Next

- Tutorial on Wednesday
- Please don’t forget to request the Aimsun License!