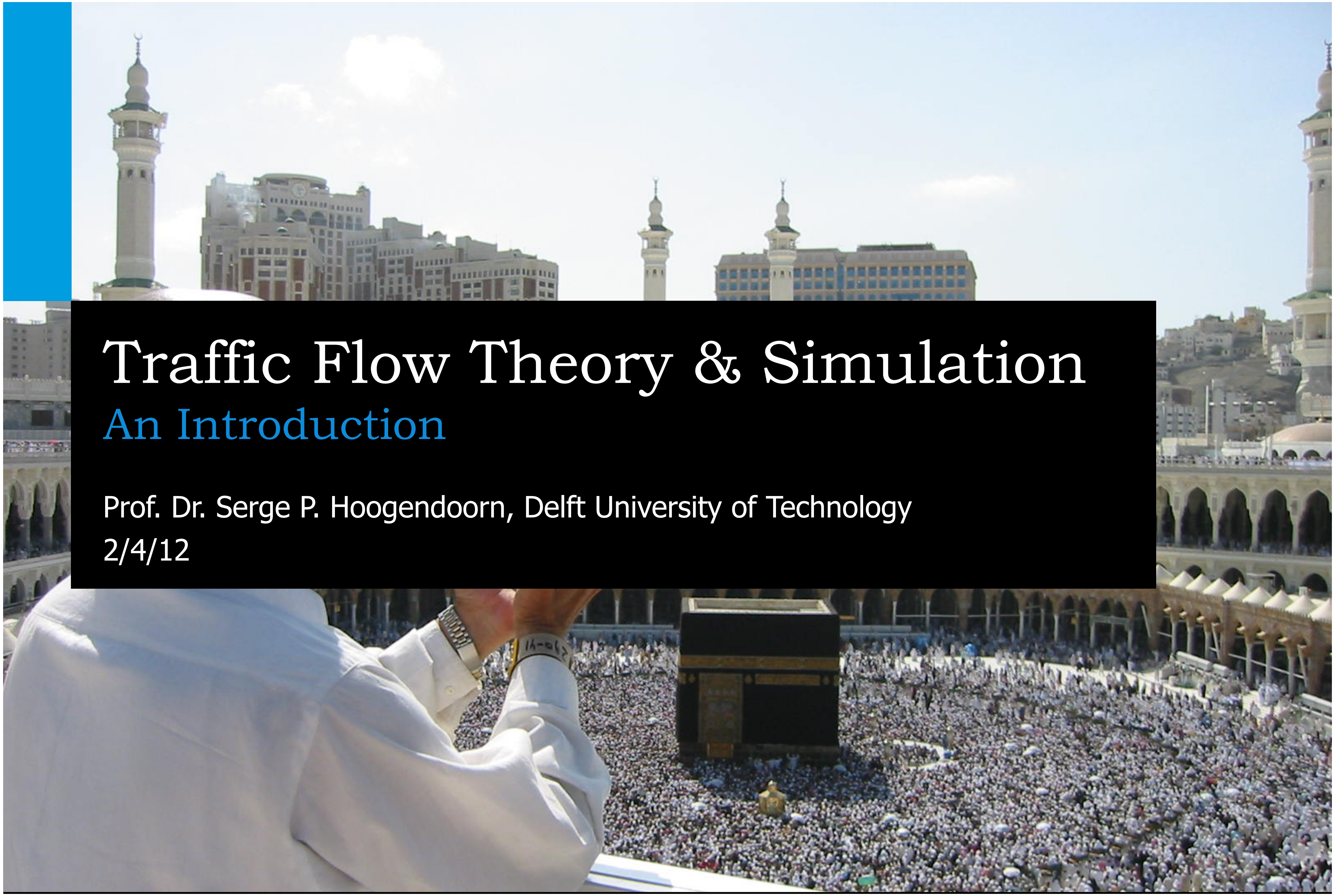
Traffic Flow Theory & Simulation

S.P. Hoogendoorn

Lecture 1
Introduction

Photo by Wikipedia / CC BY SA

Photo by wikipedia / CC BY SA



Traffic Flow Theory & Simulation

An Introduction

Prof. Dr. Serge P. Hoogendoorn, Delft University of Technology

2/4/12

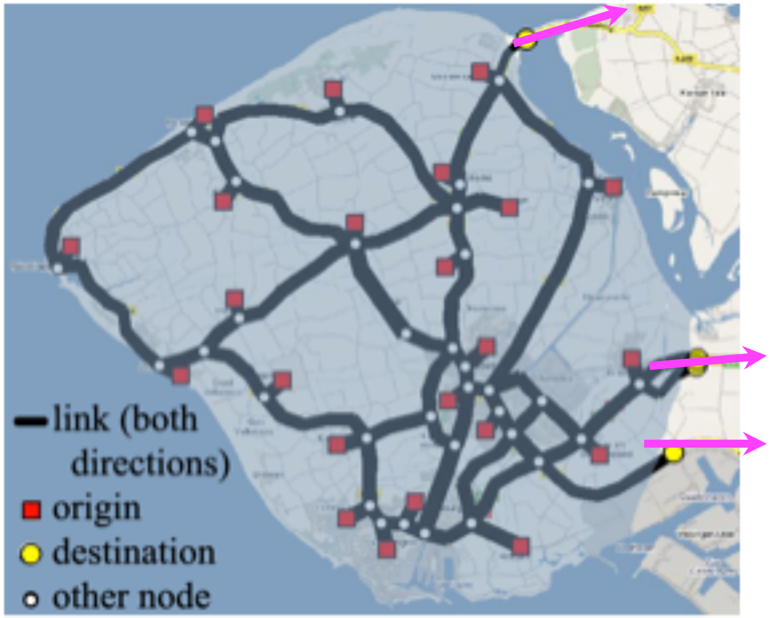
Introduction

Evacuation Walcheren in case of Flooding

- 120.000 people to evacuate
- Evacuation time = 6 hour
- 2,5 evacuees / car

- A58: 2 lanes
- N57, N254: 1 lane

- Total available capacity?
  - Each lane about 2000 veh/h
  - Total capacity 8000 veh/h



- How to calculate evacuation time

Introduction

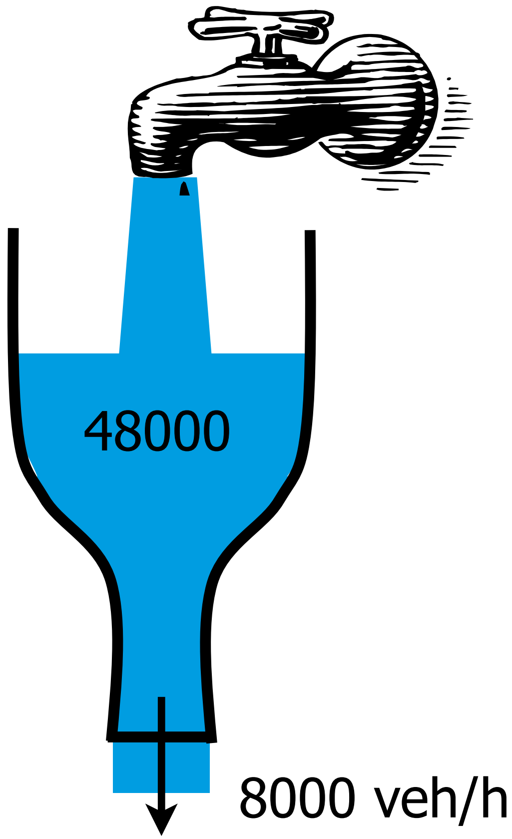
Evacuation Walcheren in case of Flooding

- 120.000 people to evacuate
- Evacuation time = 6 hour
- 2,5 evacuees / car

- A58: 2 lanes
- N57, N254: 1 lane

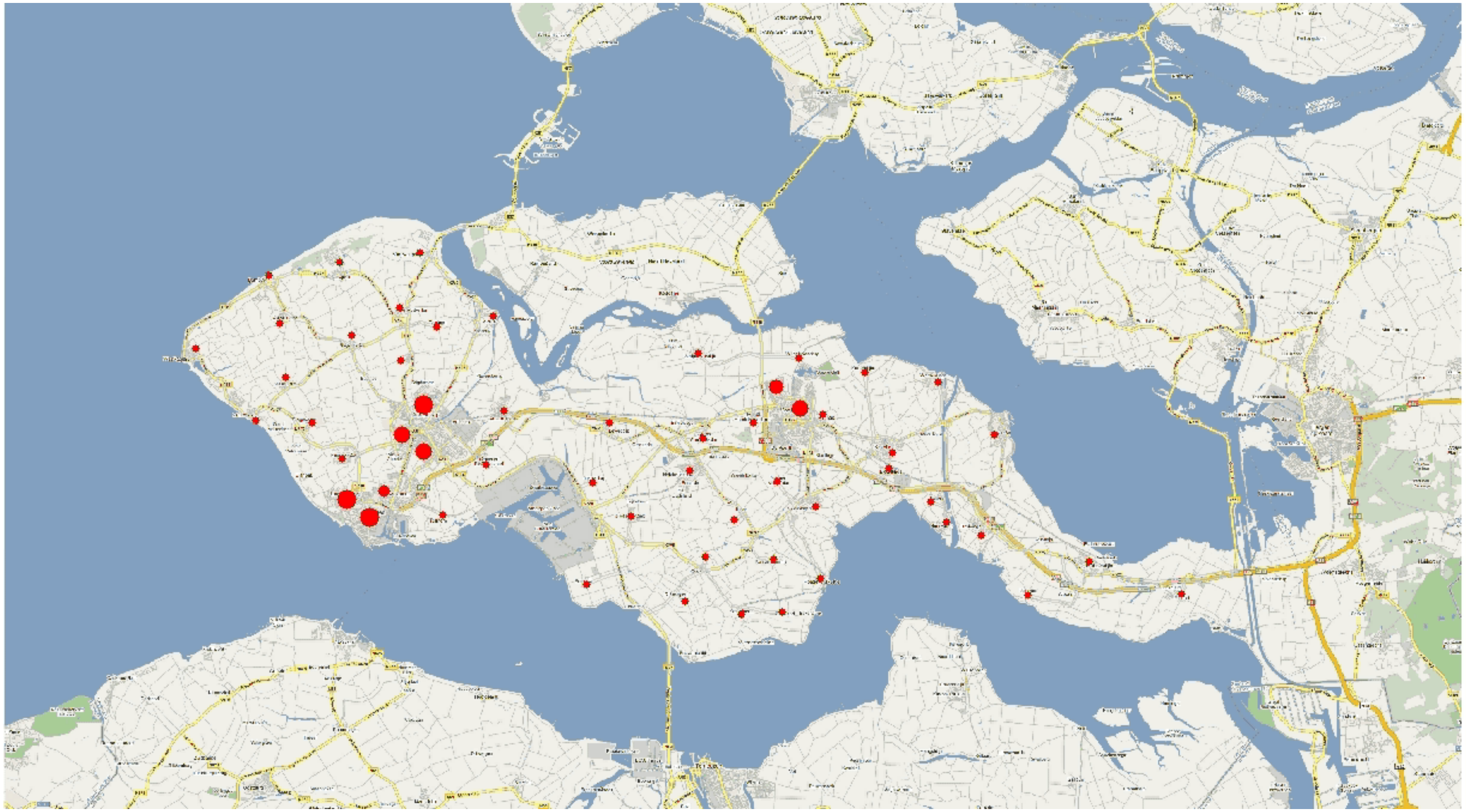
- Total available capacity?
    - Each lane about 2000 veh/h
    - Total capacity 8000 veh/h

- How to calculate evacuation time



Introduction

Evacuation Walcheren in case of Flooding



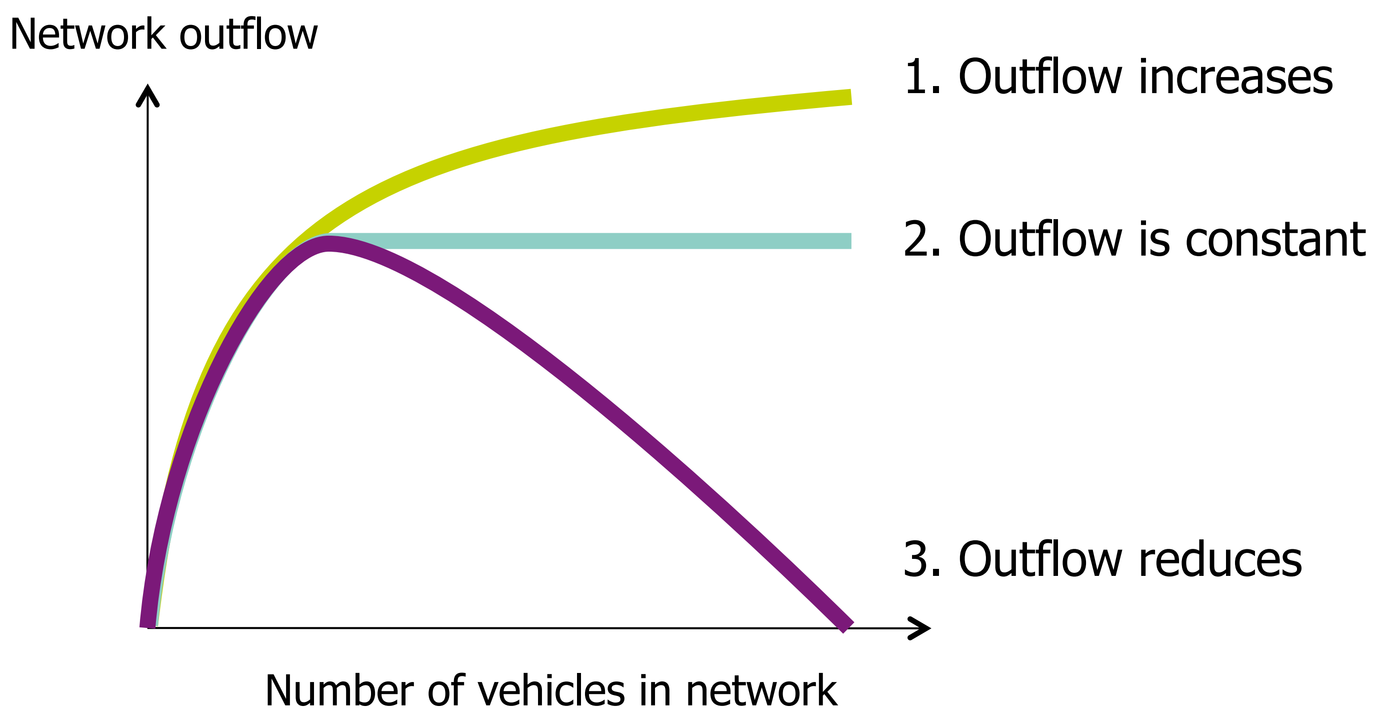
Introduction
Network load and performance degradation

- It turns out that in simulation only 41.000 people survive!
- Consider average relation between number of vehicles in network (accumulation) and performance (number of vehicles completing their trip)
- How does average performance (throughput, outflow) relate to accumulation of vehicles?
- What would you expect based on analogy with other networks?
    - Think of a water pipe system where you increase water pressure
    - What happens?

Network traffic flow fundamentals

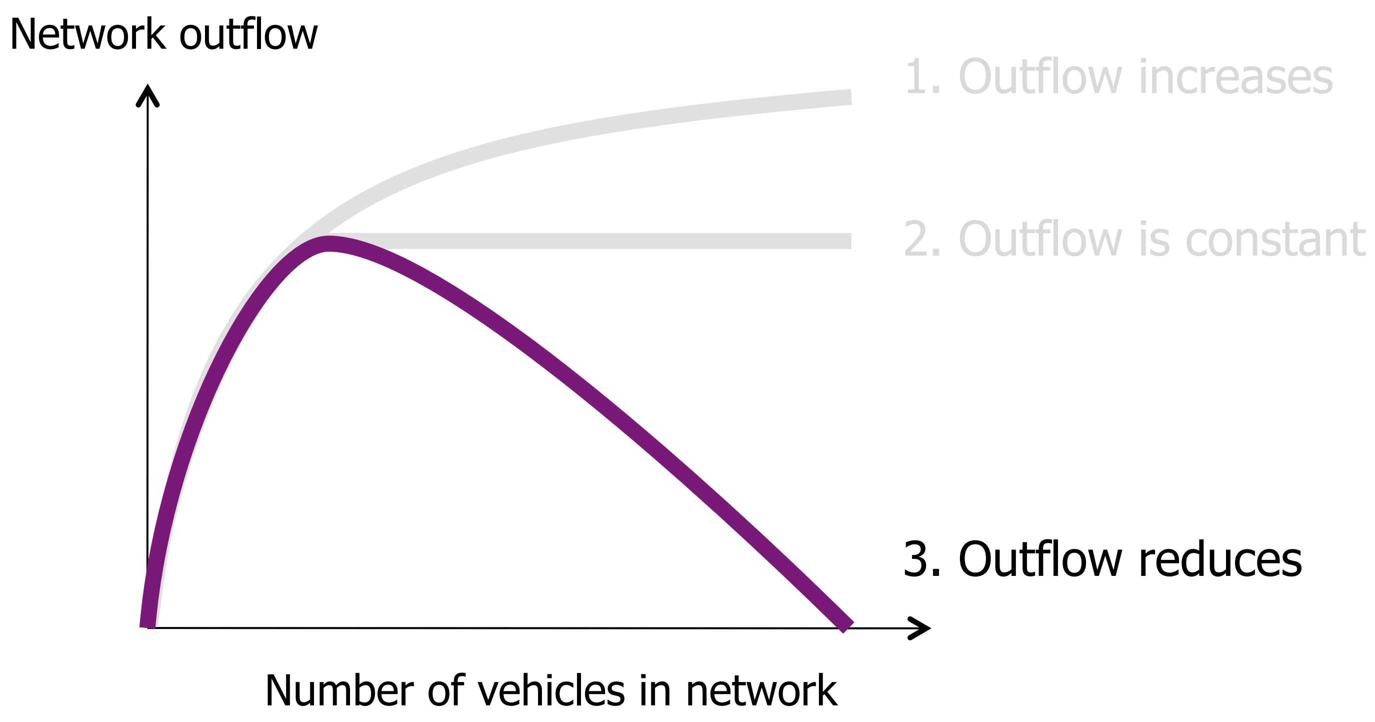
Coarse model of network dynamics

- Fundamental relation between network outflow (rate at which trip end) and accumulation

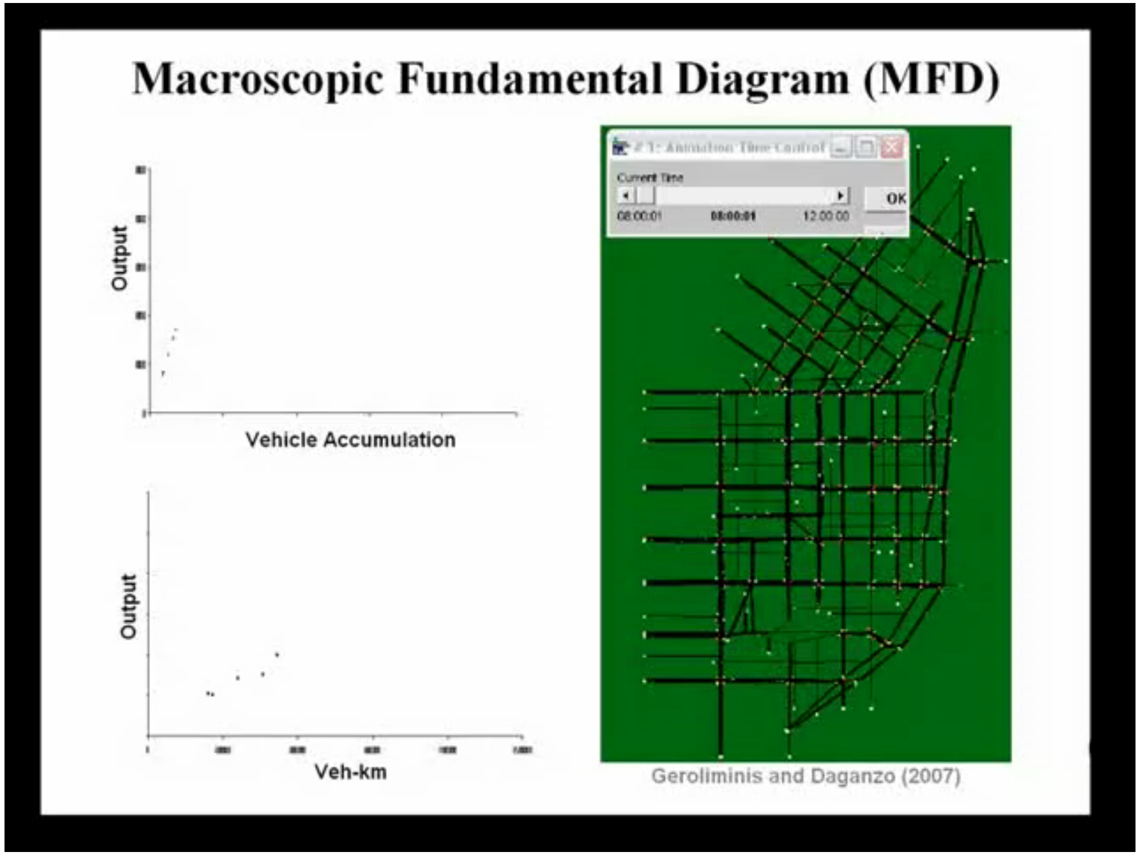


Network traffic flow fundamentals
Coarse model of network dynamics

- Fundamental relation between network outflow (rate at which trip end) and accumulation

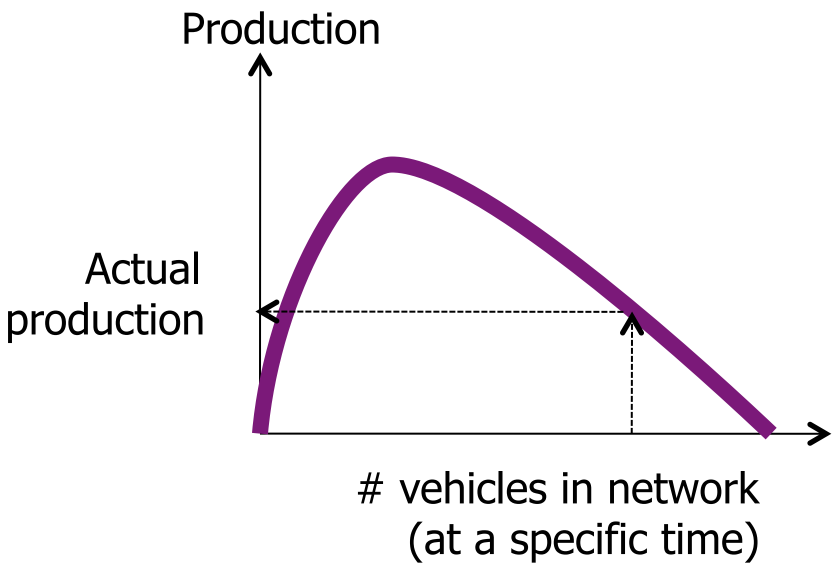


Network traffic flow fundamentals
Demand and performance degradation



Network Performance Deterioration

- Important characteristic of traffic networks:
  - Network production degenerates as number of vehicles surpasses the critical number of vehicles in the network
  - Expressed by the Macroscopic (or Network) Fundamental Diagram



Two (and only two!) causes:

Introduction

Lecture overview

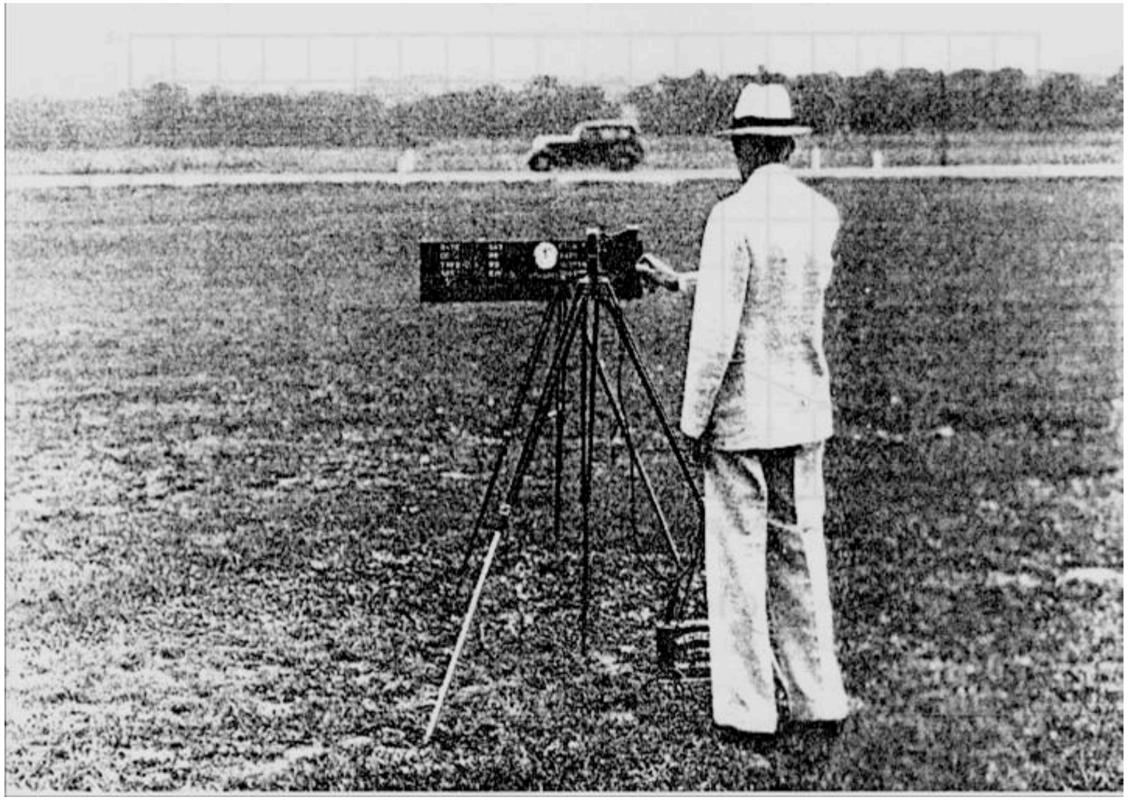
- Traffic queuing phenomena: examples and empirics
- Modeling traffic congestion in road networks
  - Model components of network models
  - Modeling principles and paradigms
  - Examples and case studies
- Model application examples
  - Traffic State Estimation and Prediction
  - Controlling congestion waves
- Microscopic and macroscopic perspectives!

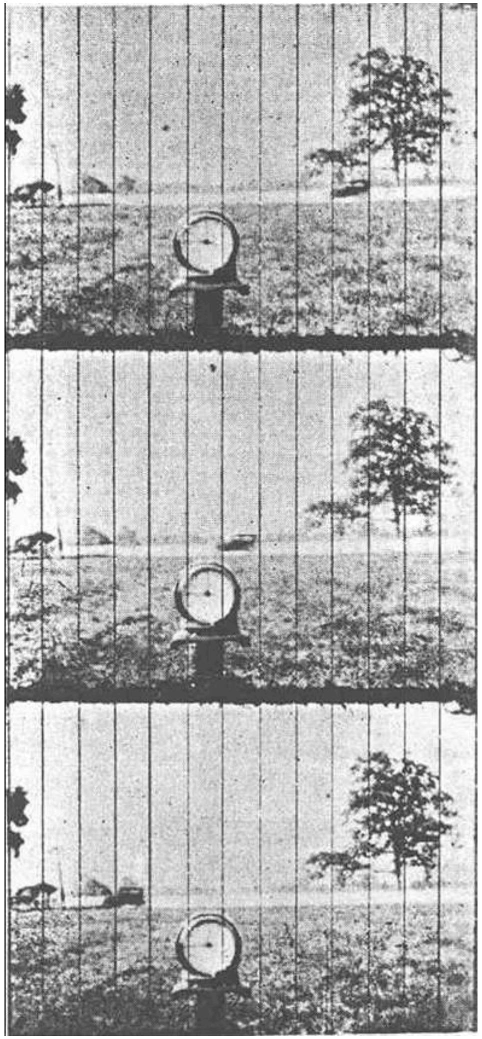
1.

Traffic Congestion Phenomena

Empirical Features of Traffic Congestion

Historical perspective
Bruce Greenshields

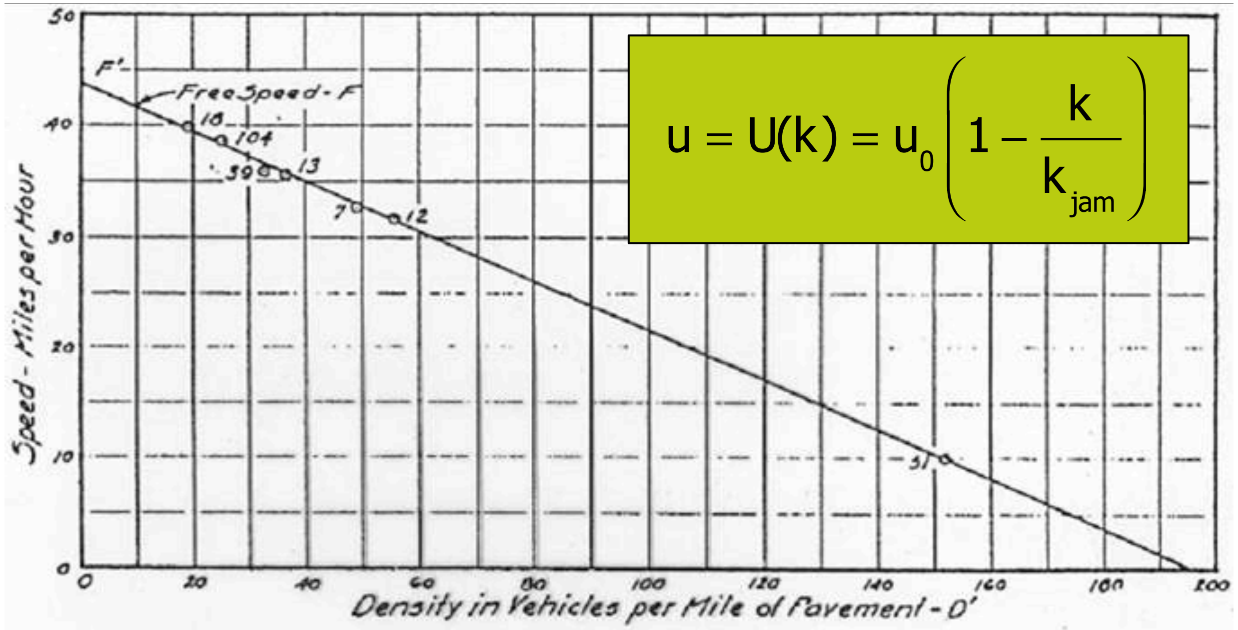




Source: Unknown

First model of traffic congestion
Fundamental diagram

- Relation between traffic density and traffic speed: u = U(k)
- Underlying behavioral principles? (density = 1/average distance)

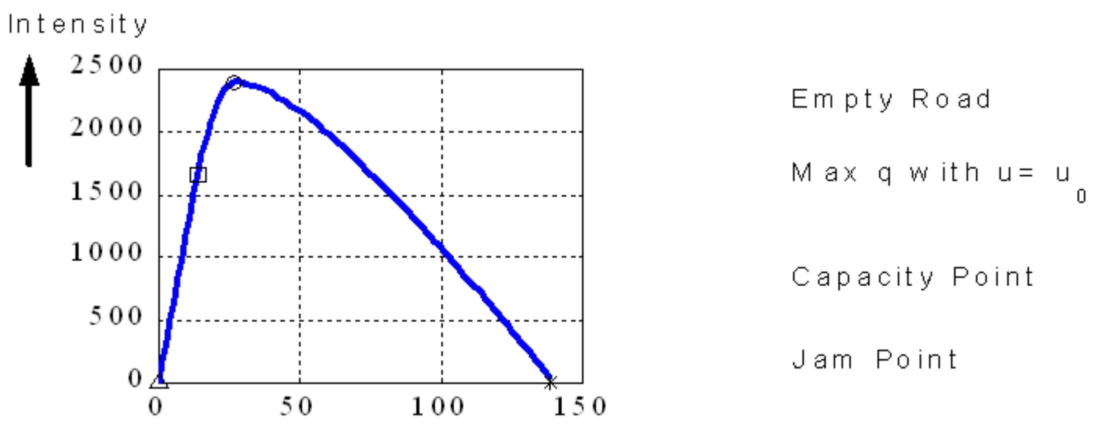


$$u = U(k) = u_0\left(1 - \frac{k}{k_{jam}}\right)$$

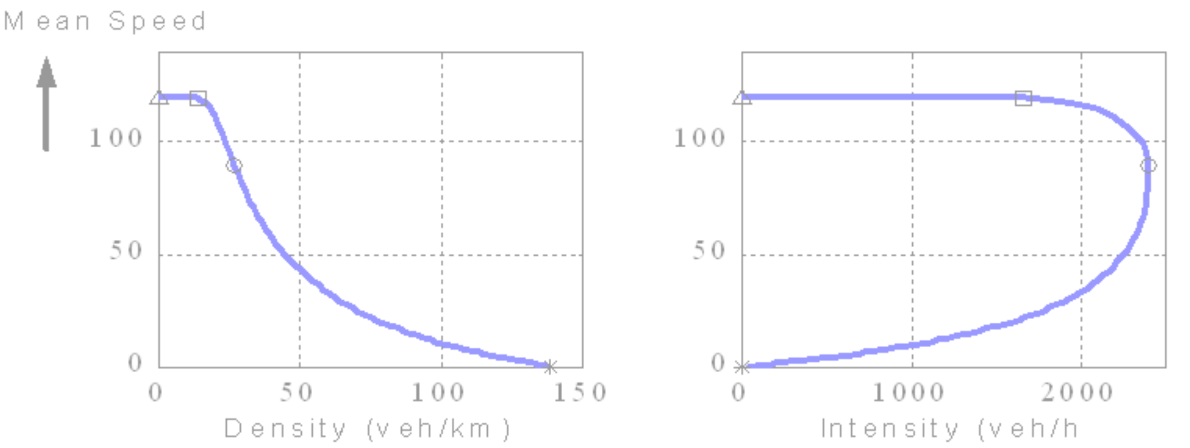
Fundamental diagrams

Different representations using q = k×u

$$q = Q(k) = kU(k)$$



$$u = U(k)$$

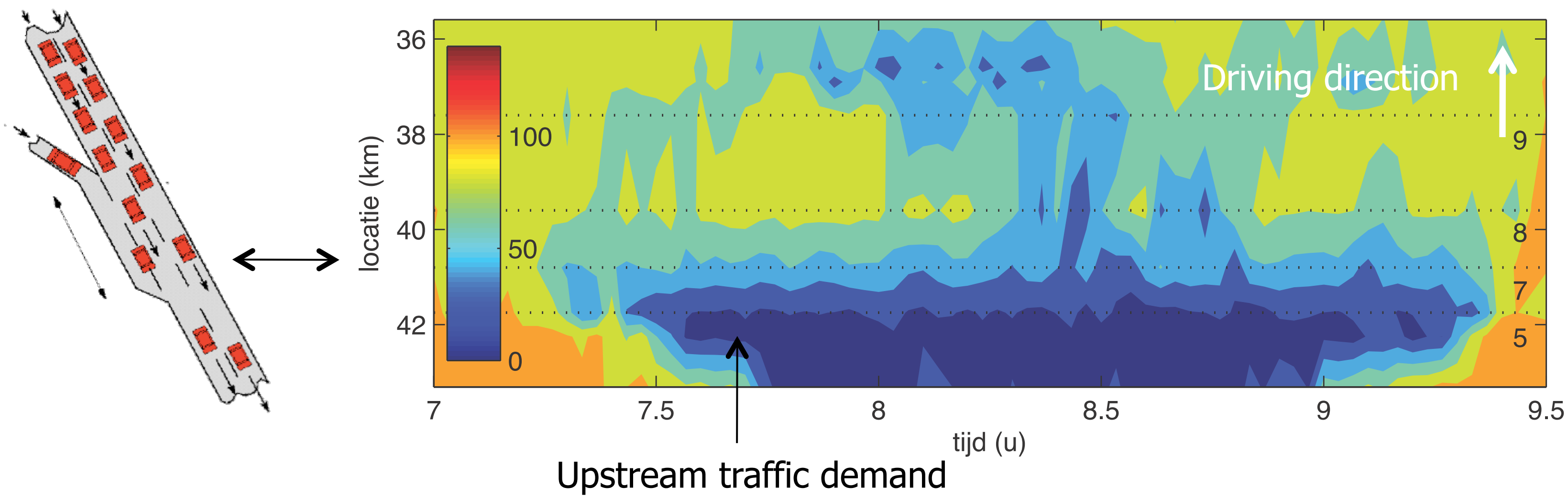


$$u = U(q)$$

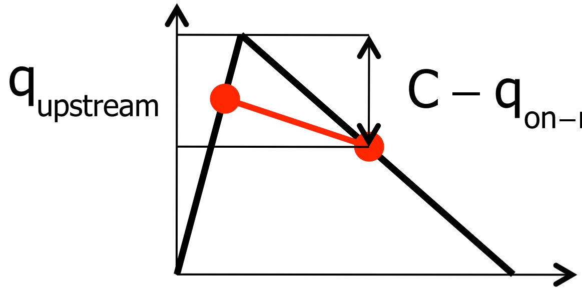
Dynamic properties

Traffic congestion at bottleneck (on-ramp)

- Consider bottleneck due to on-ramp
- Resulting capacity (capacity – ramp flow) is lower than demand
- Queue occurs upstream of bottleneck and moves upstream as long as upstream demand > flow in queue (shockwave theory)

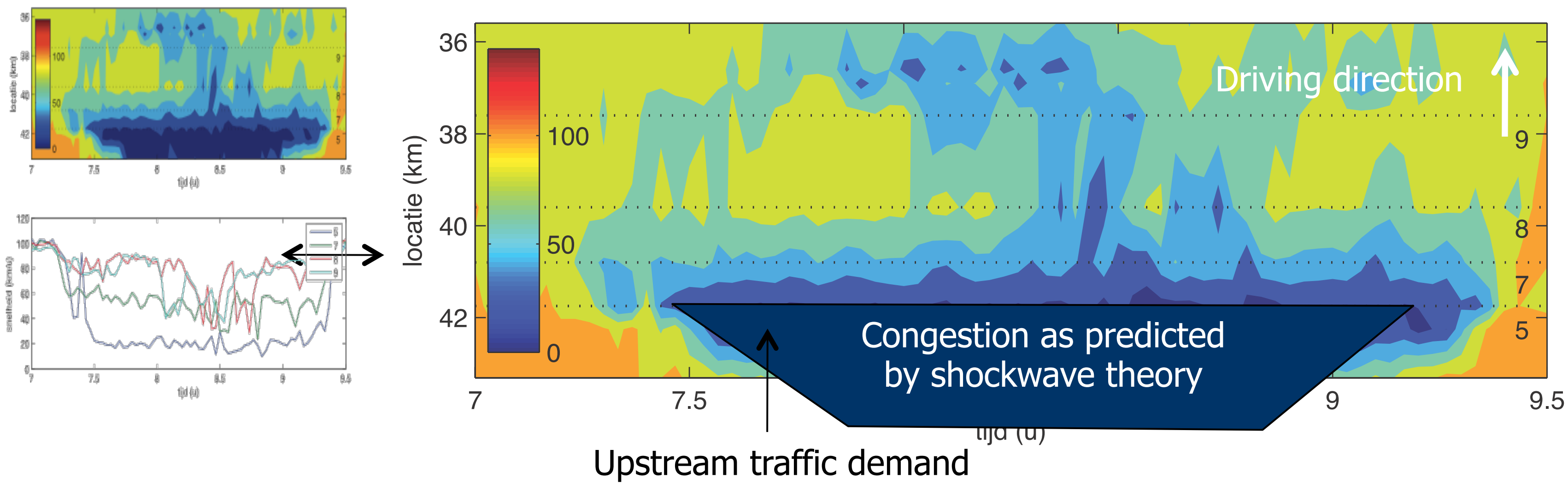


Dynamic properties
Shockwave theory



- Predicting queue dynamics (queuing models, shockwave theory)
- Predicts dynamics of congestion using FD
- Flow in queue = $C - q_{on\text{-}ramp}$
- Shock speed determined by:

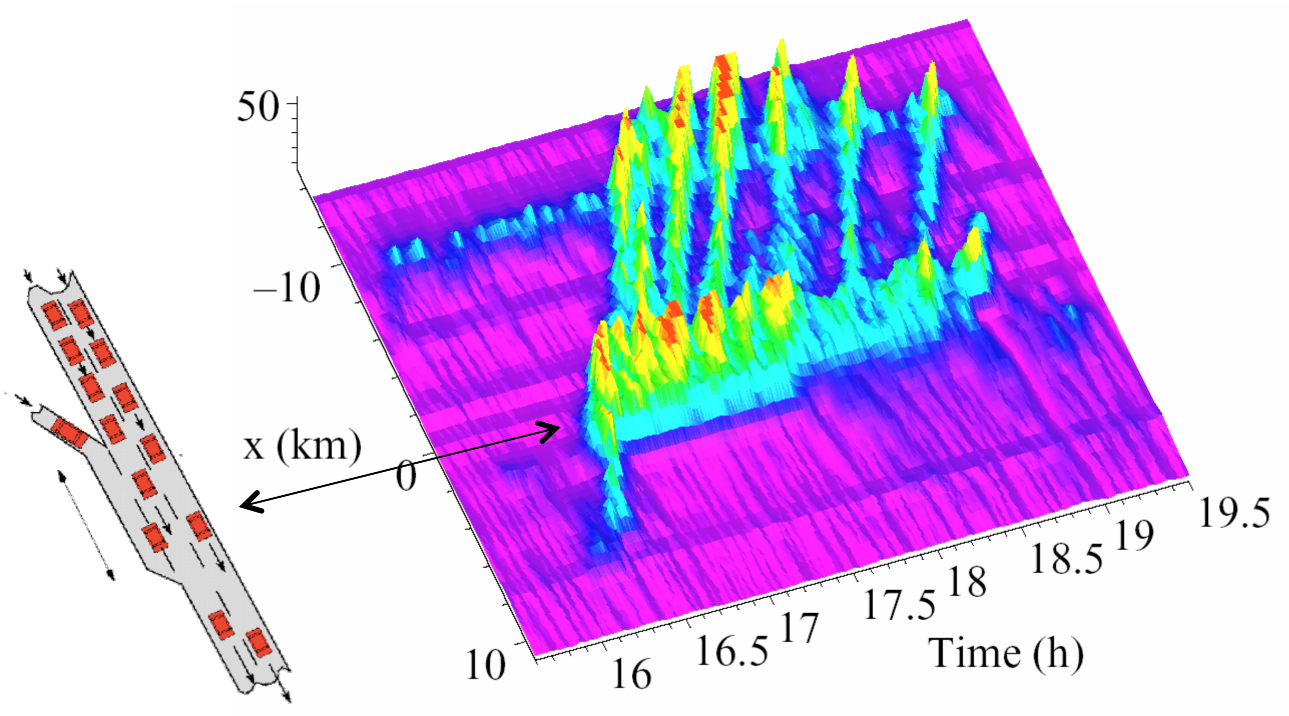
$$\omega_{12} = \frac{Q(k_2) - Q(k_1)}{k_2 - k_1}$$



Dynamic features of road congestion

Capacity funnel, instability, wide moving jams

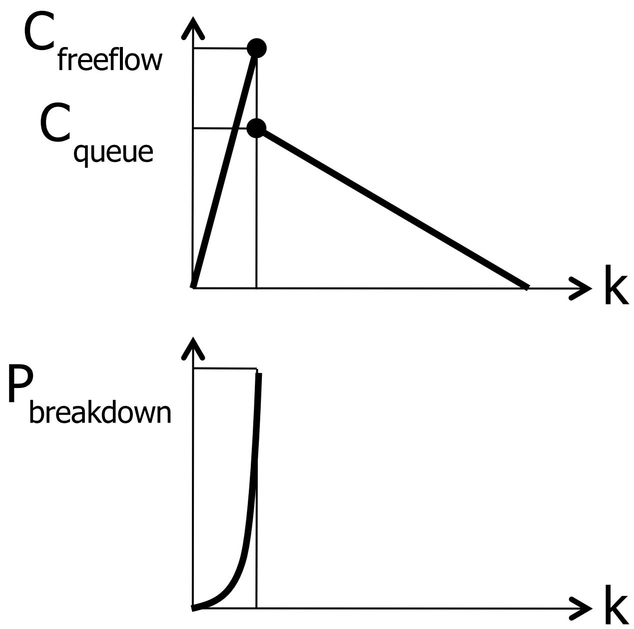
- Capacity funnel (relaxation) and capacity drop
- Self-organisation of wide moving jams

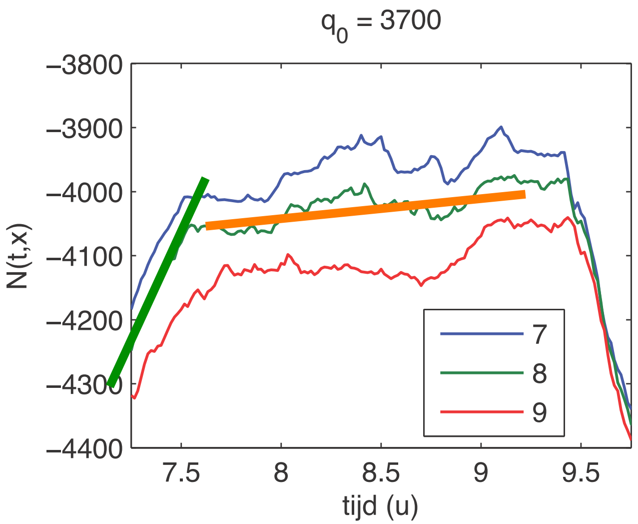


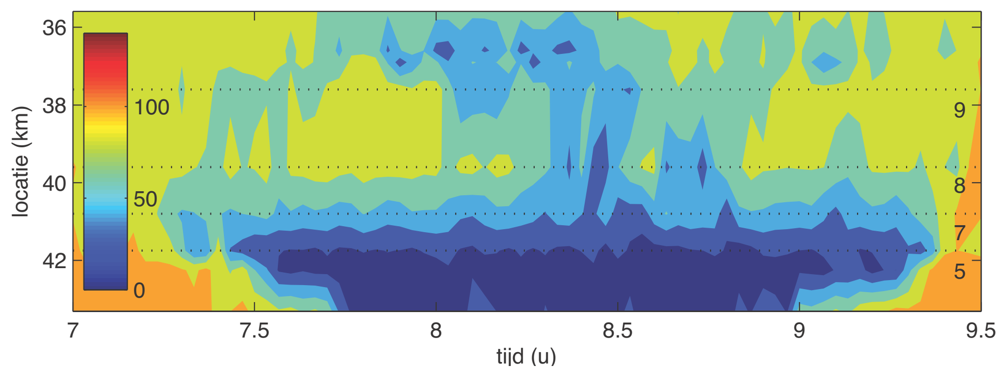
Capacity drop

Two capacities

- Free flow cap > queue-discharge rate
- Use of (slanted cumulative curves) clearly reveals this
- N(t,x) = #vehicles passing x until t
- Slope = flow





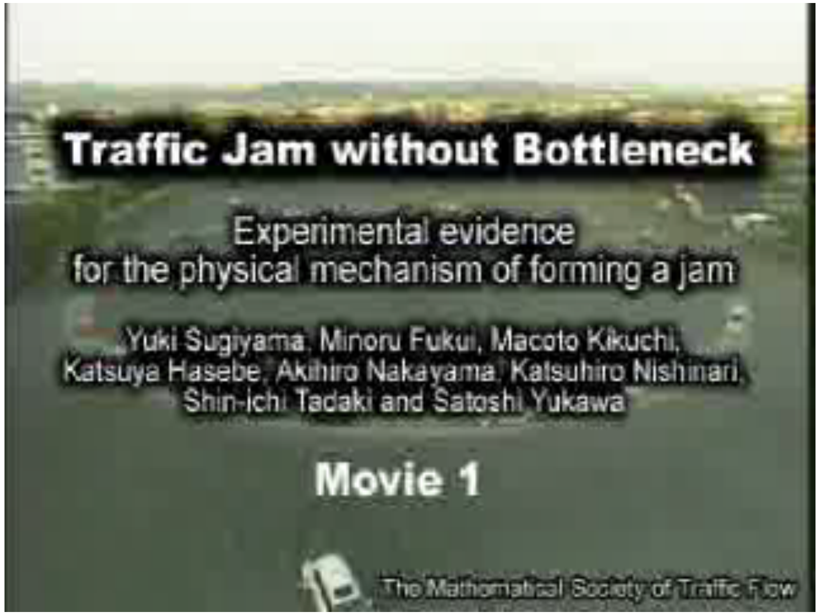


$$N'(t,x) = N(t,x) - q_0 \cdot t$$

Instability and wide moving jams

Emergence and dynamics of start-stop waves

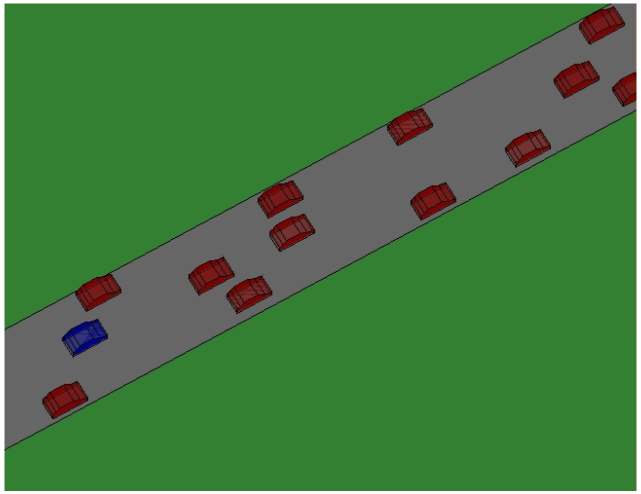
- In certain density regimes, traffic is highly unstable
- So called 'wide moving jams' (start-stop waves) self-organize frequently (1-3 minutes) in these high density regions

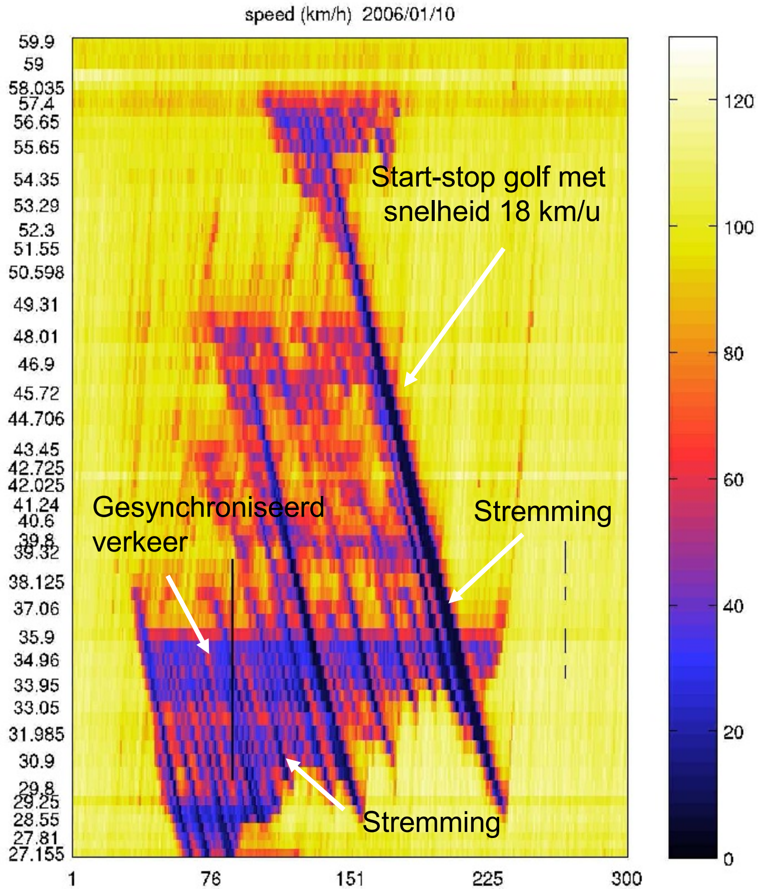


Instability and wide moving jams

Emergence and dynamics of start-stop waves

- Wide moving jams can exist for hours and travel past bottlenecks
- Density in wide moving jam is very high (jam-density) and speed is low

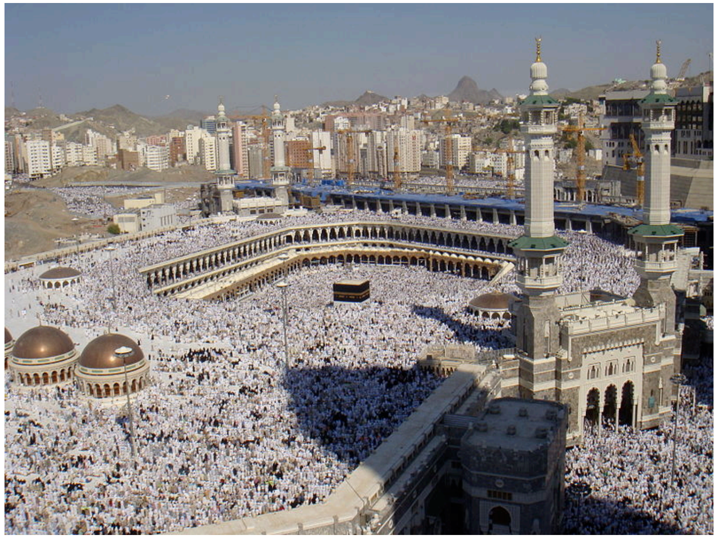




Pedestrian flow congestion

Start-stop waves in pedestrian flow

- Example of Jamarat bridge shows self-organized stop-go waves in pedestrian traffic flows



Pedestrian flow congestion
Start-stop waves in pedestrian flow

- Another wave example..

2.

Traffic Flow Modeling

Microscopic and macroscopic approaches to describe flow dynamics

Modeling challenge

Traffic theory: not an exact science!

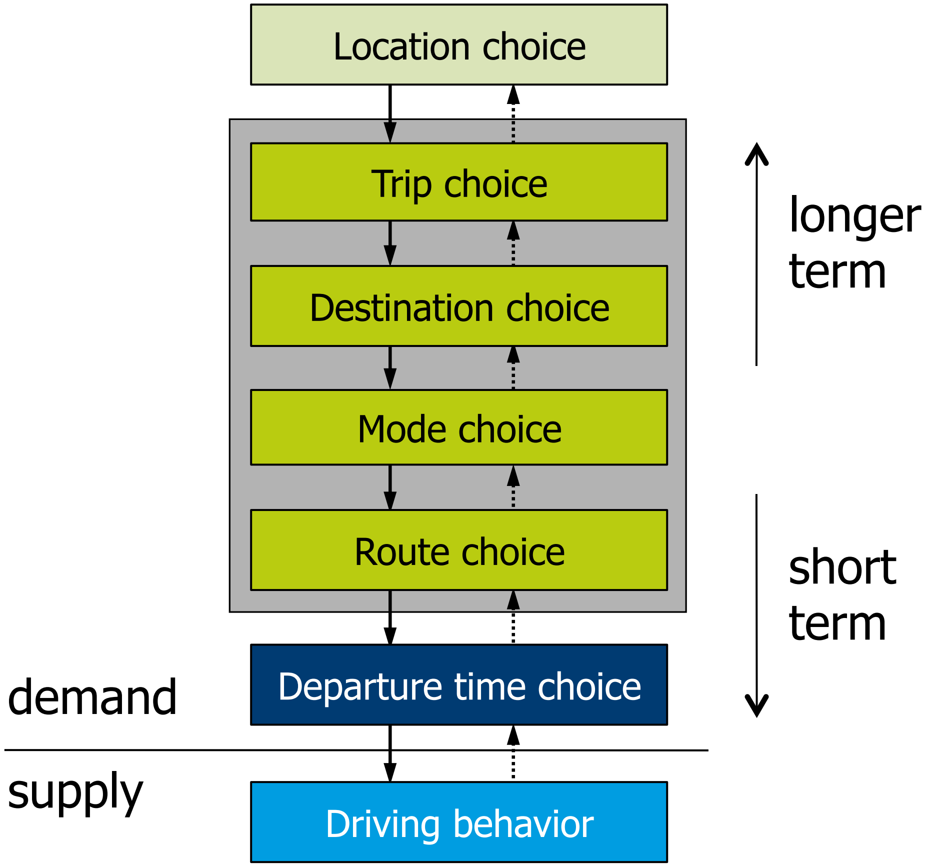
- Traffic flow is a result of human decision making and multi-actor interactions at different behavioral levels (driving, route choice, departure time choice, etc.)
- Characteristics behavior (inter- and intra-driver heterogeneity)
  - Large diversity between driver and vehicle characteristics
  - Intra-driver diversity due to multitude of influencing factors, e.g. prevailing situation, context, external conditions, mood, emotions
- *The* traffic flow theory does not exist (and will probably never exist): this is not Newtonian Physics or thermodynamics

- Challenge is to develop theories and models that represent reality sufficiently accurate for the application at hand

Network Traffic Modeling

Model components and processes

- Traffic conditions on the road are end result of many decisions made by the traveler at different decision making levels
- Depending on type of application different levels are in- or excluded in model
- Focus on driving behavior and flow operations



Modeling approaches

Microscopic and macroscopic approaches

- Two dimensions:
  - Representation of traffic
  - Behavioral rules, flow characteristics

	Individual particles	Continuum
Individual behavior	Microscopic (simulation) models	Gas-kinetic models (Boltzmann equations)
Aggregate behavior	Newell model, particle discretization models	Queuing models Macroscopic flow models

Modeling approaches

Microscopic and macroscopic approaches

Helly model: $$\frac{d}{dt} v_i(t + T_r) = \alpha \cdot \Delta v_i(t) + \beta \cdot \left(s^*(v_i(t)) - s_i(t) \right)$$

	Individual particles	Continuum
Individual behavior	Microscopic (simulation) models	Gas-kinetic models (Boltzmann equations)
Aggregate behavior	Newell model, particle discretization models	Queuing models Macroscopic flow models

Microscopic models?

Ability to described many flow phenomena

- Example of advanced micro-simulation model

Photo by Intechopen / CC BY

Modeling approaches

Microscopic and macroscopic approaches

Bando model: $$\frac{d}{dt}v_i(t) = \frac{V(1/s_i(t)) - v_i(t)}{\tau}$$

	Individual particles	Continuum
Individual behavior	Microscopic (simulation) models	Gas-kinetic models (Boltzmann equations)
Aggregate behavior	Newell model, Bando model	Queuing models Macroscopic flow models

Modeling approaches

Microscopic and macroscopic approaches

kinematic wave model:

$$\begin{cases} \dfrac{\partial k}{\partial t} + \dfrac{\partial q}{\partial x} = r - s \\ q = Q(k) \end{cases}$$

	Individual particles	**Continuum**
Individual behavior	Microscopic (simulation) models	Gas-kinetic models (Boltzmann equations)
Aggregate behavior	Newell model, particle discretization models	Queuing models Macroscopic flow models

Modeling approaches

Microscopic and macroscopic approaches

Prigogine-Herman model: $$\frac{\partial \rho}{\partial t} + v\frac{\partial \rho}{\partial x} + \frac{\partial}{\partial v}\left(\rho\frac{\Omega^0(v) - v}{\tau}\right) = \left(\frac{\partial \rho}{\partial t}\right)_{INT}$$

	Individual particles	**Continuum**
Individual behavior	Microscopic (simulation) models	Gas-kinetic models (Boltzmann equations)
Aggregate behavior	Newell model, particle discretization models	Queuing models Macroscopic flow models

3.

Example applications of theory and models

Application of models

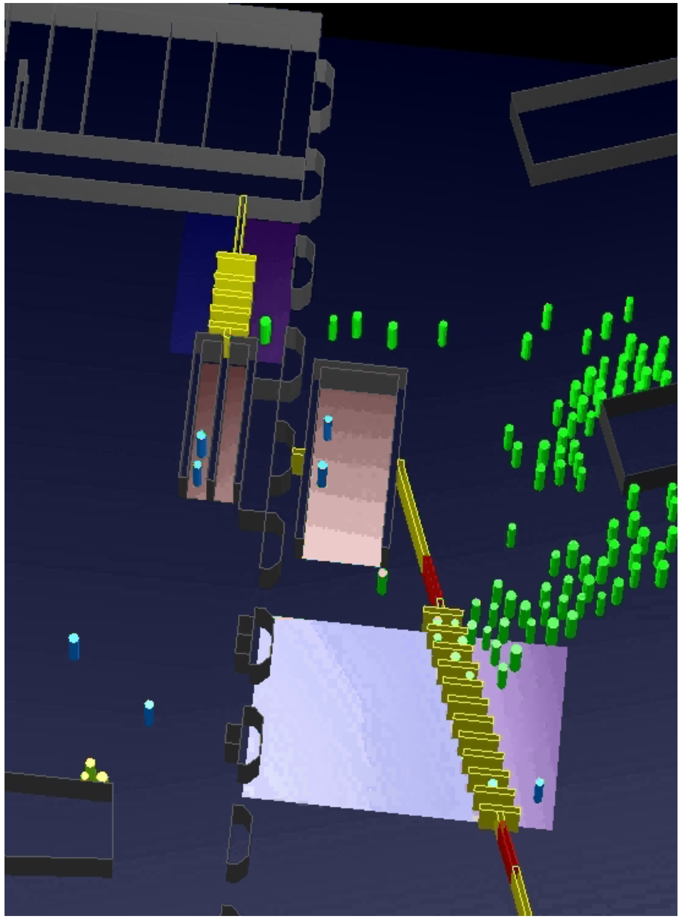
Different models, different applications

- Ex-ante studies: systematic comparison of alternatives during different phases of the design process
  - Road- and network design
  - Traffic Control / Management Strategies and Algorithms
  - Impact of traffic information
  - Evacuation planning
  - Impact of Driver Support Systems
- Training and decision support for decision makers
- Traffic state estimation and data fusion
- Traffic state prediction
- Model predictive control to optimize network utilization

Application of models

Examples

- NOMAD model has been extensively calibrated and validated
- NOMAD reproduces characteristics of pedestrian flow (fundamental diagram, self-organization)
- Applications of model:
  - Assessing LOS transfer stations
  - Testing safety in case of emergency conditions (evacuations)
  - Testing alternative designs and Decision Support Tool
  - Hajj strategies and design



NOMAD Animatie by verkeerskunde.nl

Traffic State Estimation & Prediction

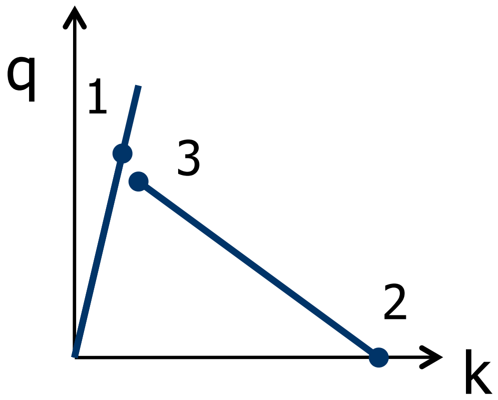
Applications of Kalman filters

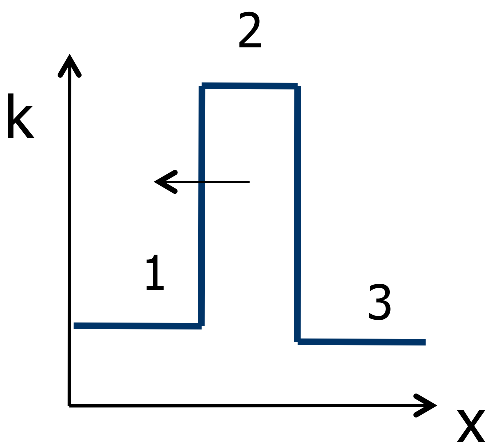
Photo by fileradar.nl

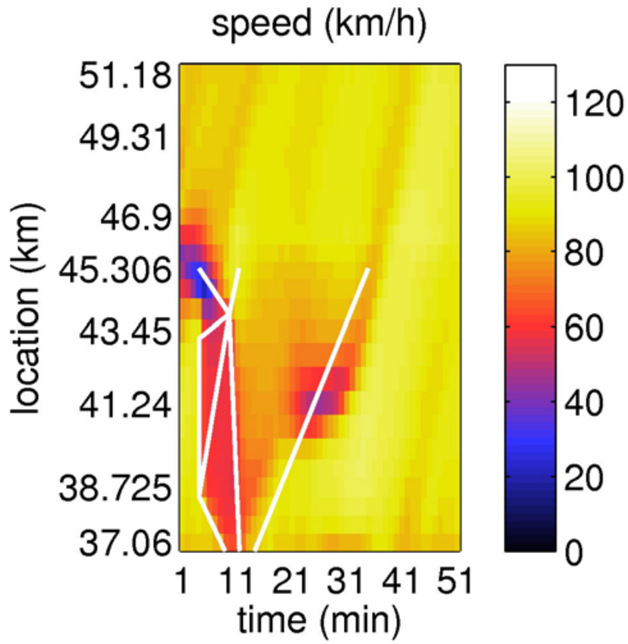
Dynamic speed limits

Using Traffic Flow Theory to improve traffic flow

- Algorithm ‘Specialist’ to suppress start-stop waves on A12
- Approach is based on reduced flow (capacity drop) downstream of wave
- Reduce inflow sufficiently by speed-limits upstream of wave







4.

Course scope and overview

Scope of course CT4821

- Operational characteristics of traffic, so *not*:
  - Activity choice and scheduling
  - Route choice and destination choice
  - Departure time or (preferred) arrival time choice
- Traffic flow theory does not exclude any transportation mode!
- Primary focus in this course will be of road traffic (cars) with occasion side-step to other modes (pedestrian flows)
- Distinction between
  - Macroscopic and microscopic (and something in the middle)
  - Flow variables, (descriptive) flow characteristics and analytical tools (mathematical modelling and simulation)

Overview of flow variables (chapter 2)

	Microscopic variables (individual vehicles)	**Macroscopic variables (traffic flows)**
Local	Time headway	Flow / volume / intensity Local mean speed
Instantaneous	Distance headway	Density Space mean speed
Generalized	**Trajectory** Path speed	Mean path speed Mean travel time

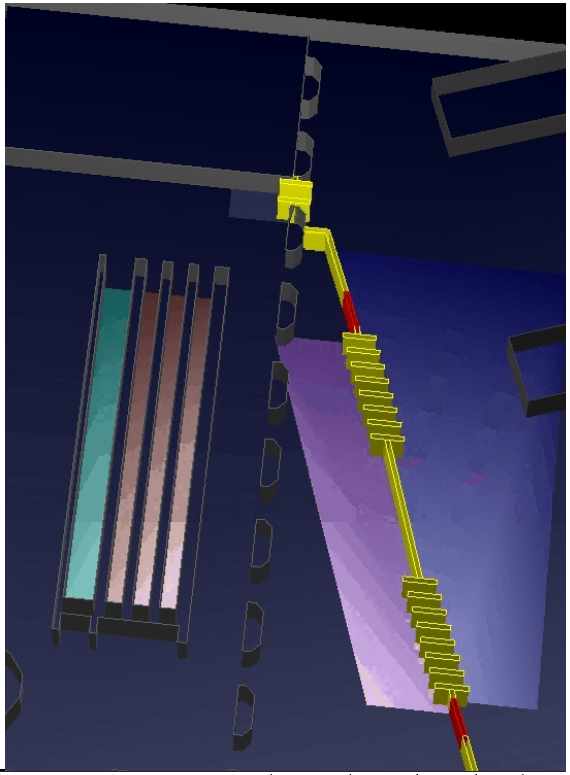
Flow characteristics

- Microscopic characteristics (chapter 3)
  - Arrival processes
  - Headway models / headway distribution models
  - Critical gap distributions

- Macroscopic characteristics (chapters 4 and 5)
  - Fundamental diagram
  - Shockwaves and non-equilibrium flow properties

Analytical tools

- Use fundamental knowledge for mathematical / numerical analysis
- Examples *macroscopic* tools
    - Capacity analysis (chapter 6)
    - Deterministic and stochastic queuing models (chapter 7)
    - Shockwave analysis (chapter 8)
    - Macroscopic flow models (chapter 9)
    - Macroscopic simulation models (13 and 15)
- Examples *microscopic* tools
    - Car-following models (chapter 11)
    - Gap-acceptance models (chapter 12)
    - Traffic simulation (chapter 13 and 14)



NOMAD Animatie by verkeerskunde.nl

Course ct4821

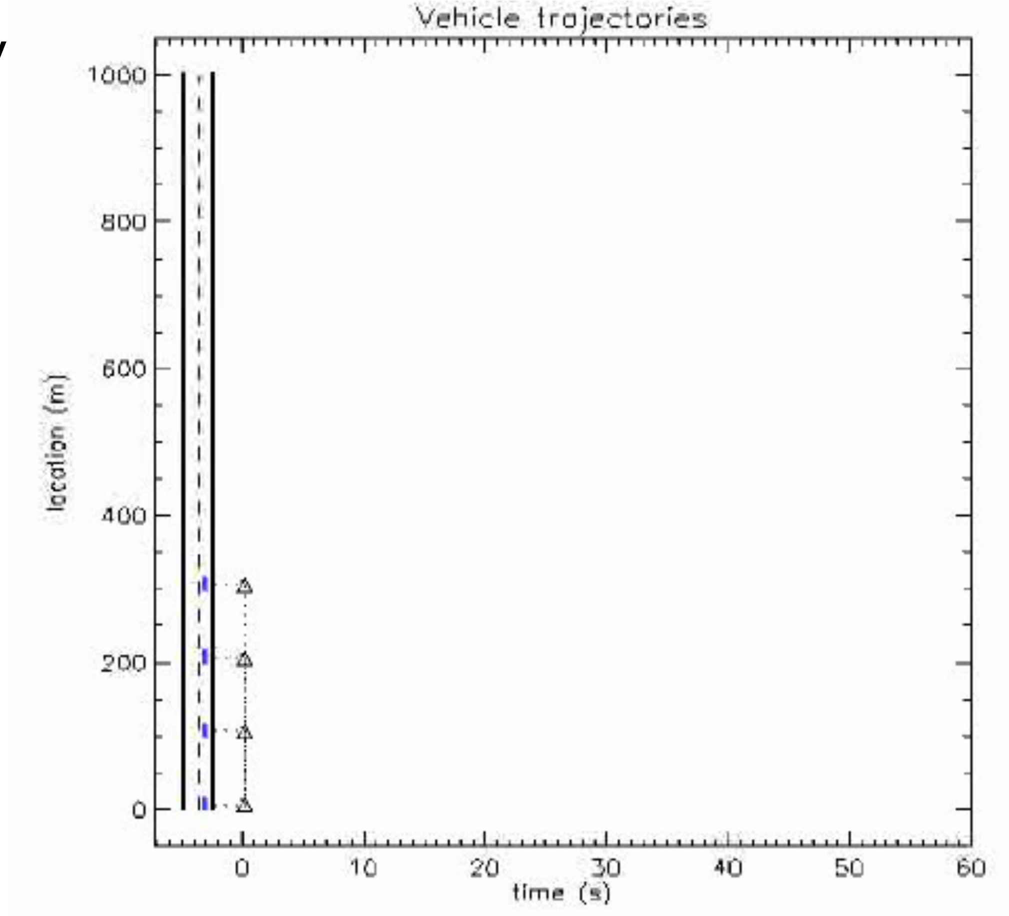
- Lectures by Serge Hoogendoorn and Victor Knoop:
  - Monday 8:45 – 10:30
  - Tuesday 8:45 – 10:30
- Mandatory assignment (Hoogendoorn, Knoop + PhD's):
  - Wednesday 13:45 – 17:30 (starting in week 1)
  - New Data analysis and FOSIM practicum (week 1-7)
  - Reports on assignment
  - Description assignment posted on blackboard beginning of next week
- Course material:
  - Parts of the reader (blackboard)
  - Assignments (blackboard)

5.

Traffic Flow Variables

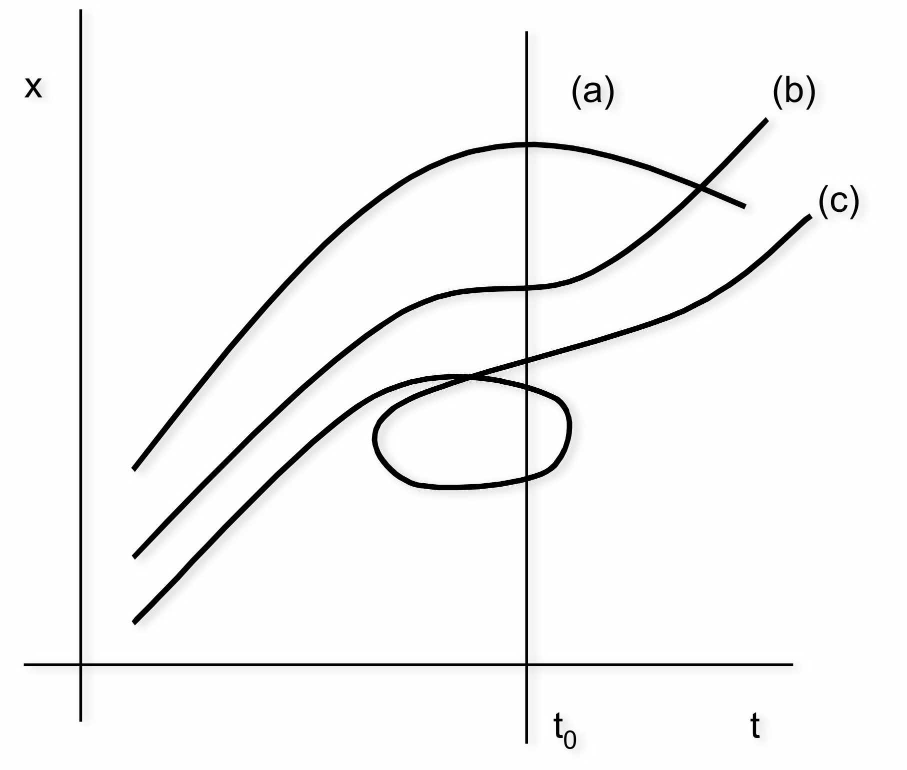
Vehicle trajectories

- Positions $x_i(t)$ along roadway of vehicle *i* at time *t*
- All microscopic and macroscopic characteristics can be determined from trajectories!
- In reality, trajectory information is rarely available
- Nevertheless, trajectories are the most important unit of analysis is traffic flow theory



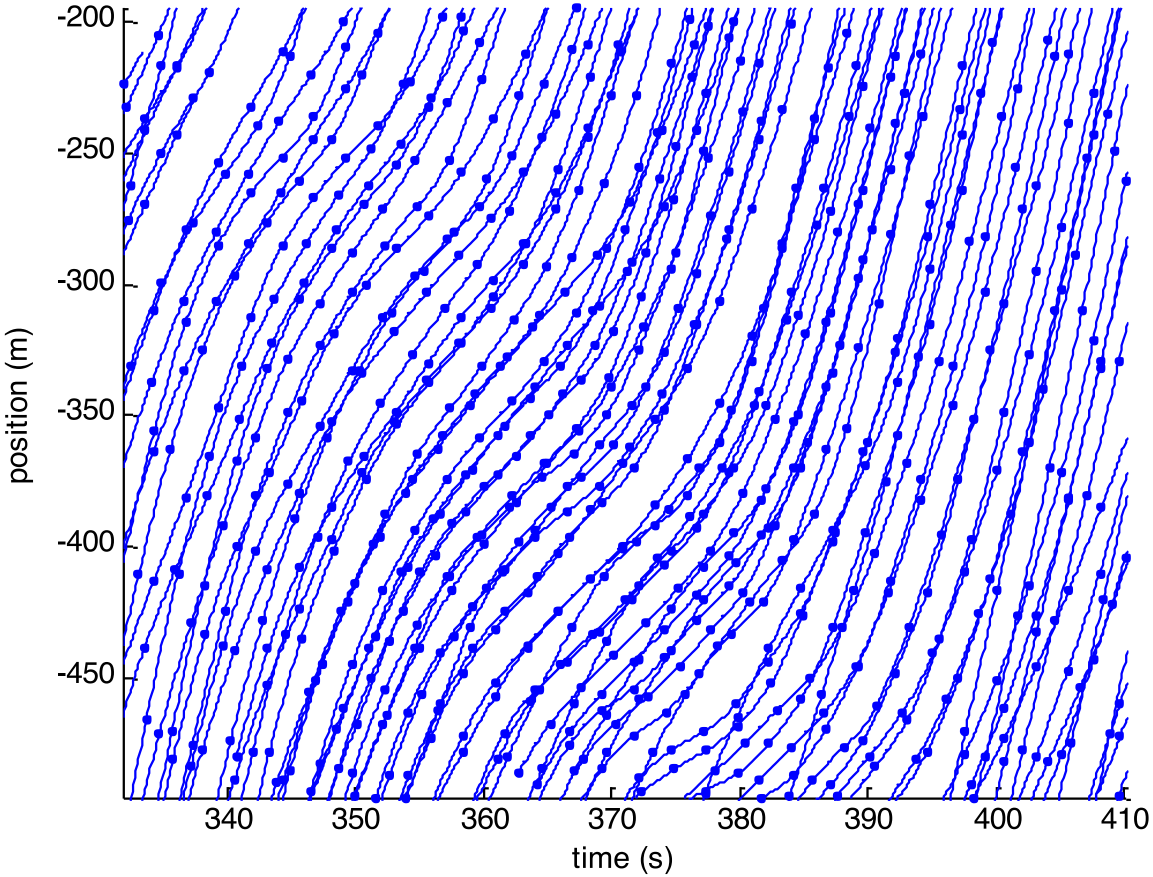
Vehicle trajectories (2)

- Which are trajectories?

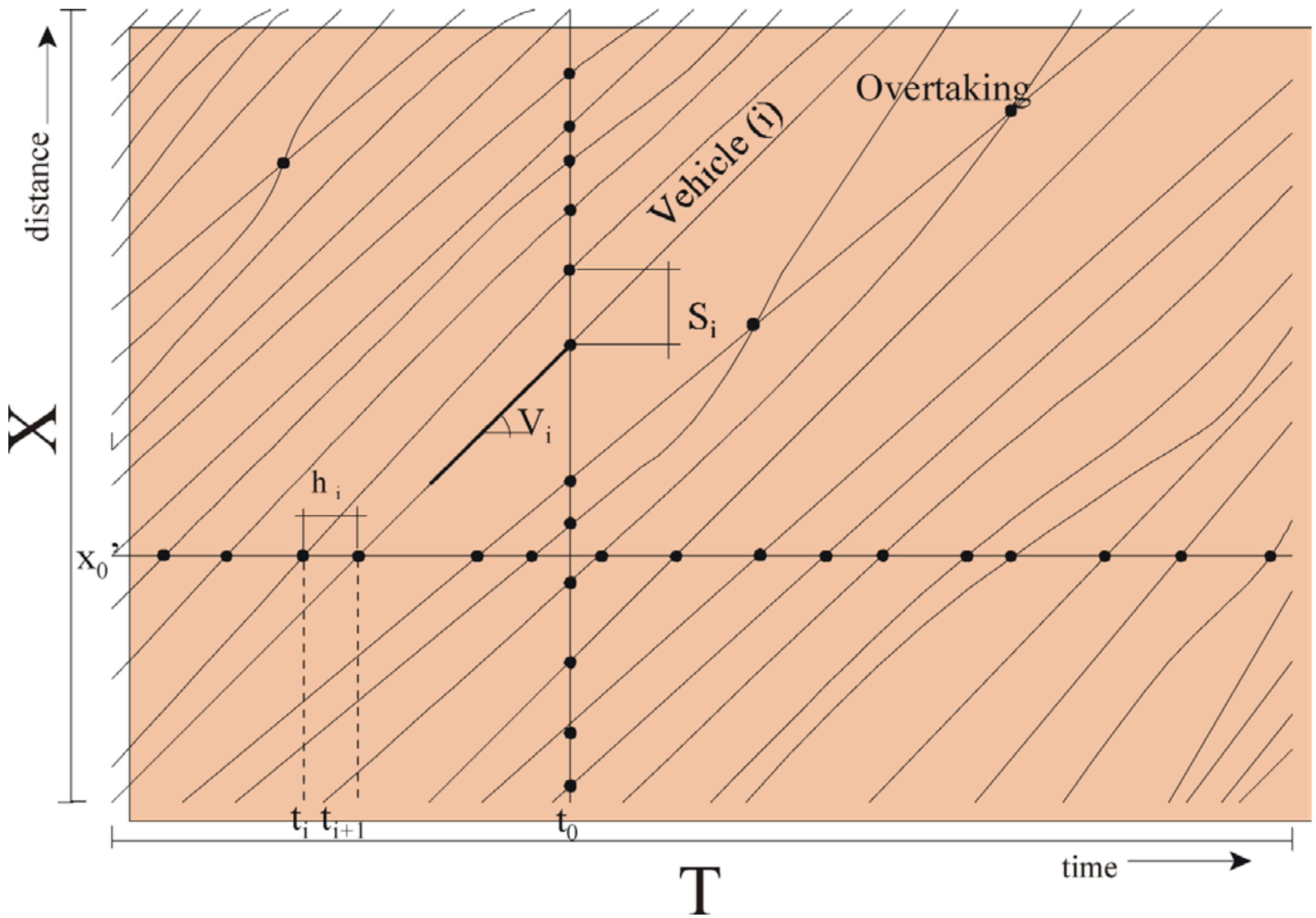


Empirical vehicle trajectories

- Vehicle trajectories determined using remote sensing data (from helicopter) at site Everdingen near Utrecht
- Dots show vehicle position per 2.5 s
- Unique dataset



Understanding trajectories



$$v_i(t) = \frac{d}{dt} x_i(t)$$

$$a_i(t) = \frac{d^2}{dt^2} x_i(t)$$

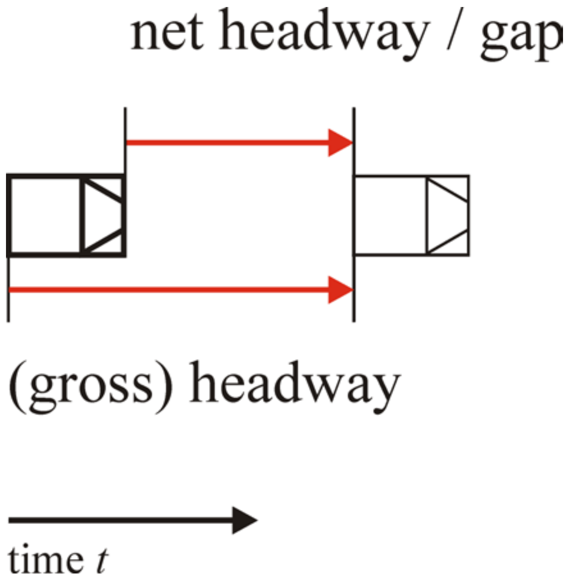
$$\gamma_i(t) = \frac{d^3}{dt^3} x_i(t)$$

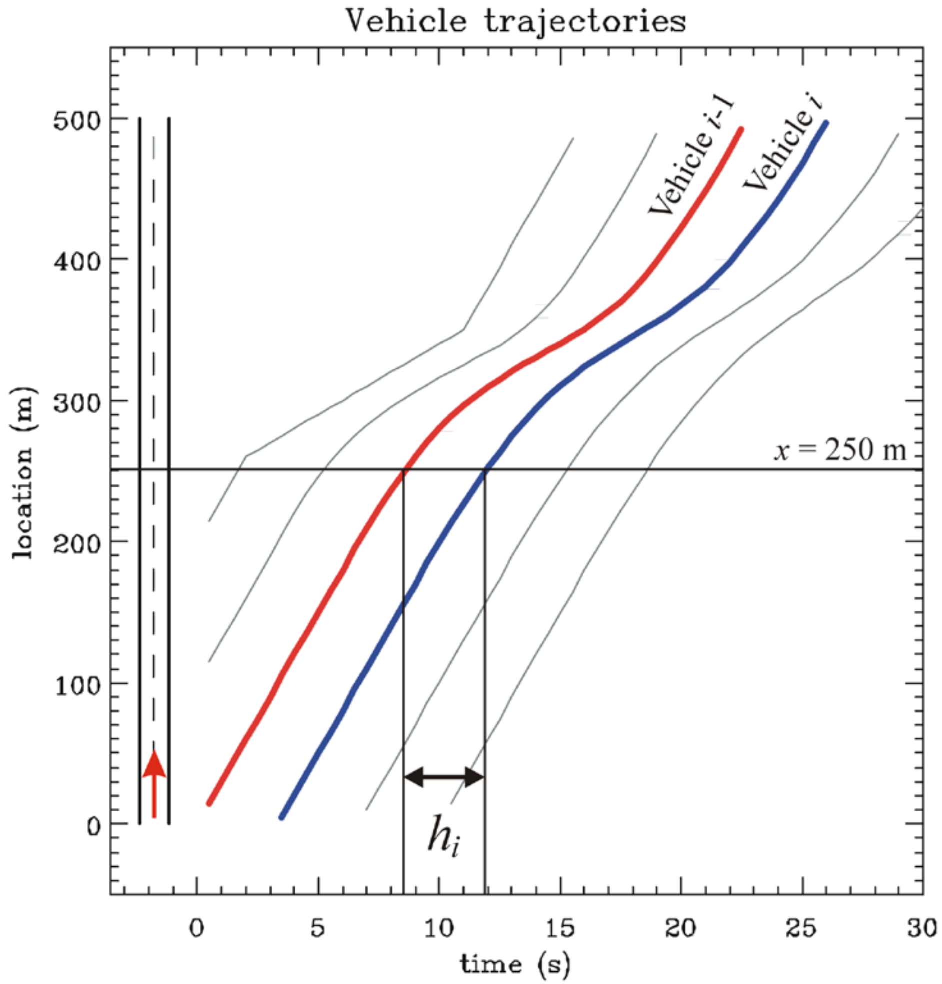
Applications of multiple trajectories

- Exercise with trajectories by drawing a number of them for different situations
  - Acceleration, deceleration,
  - Period of constant speed,
  - Stopped vehicles
  - Etc.
- See syllabus and exercises for *problem solving using trajectories*:
  - Tandem problem
  - Cargo ship problem
- Also in reader: discussion on vehicle kinematics described acceleration $a_i(t)$ as a function of the different forces acting upon the vehicle

Time headways

- **Time headway** h_i: passage time difference rear bumper vehicle i-1 and i at cross-section x (easy to measure)



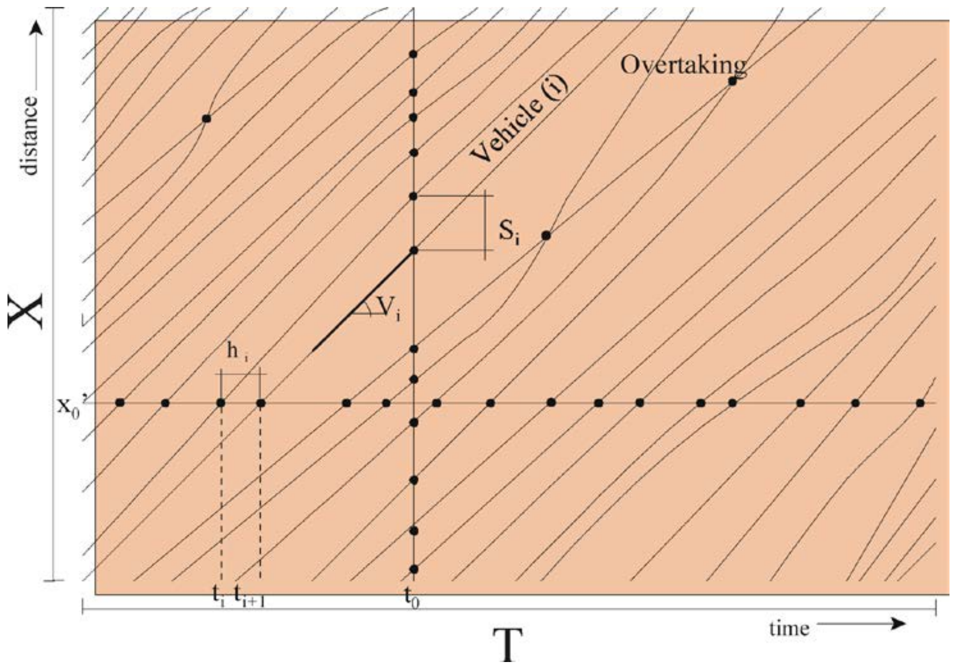


Time headways (3)

- Headways are local variables (collected at cross-section x_0)
- Mean headway for certain period T of the n vehicles that have passed x_0

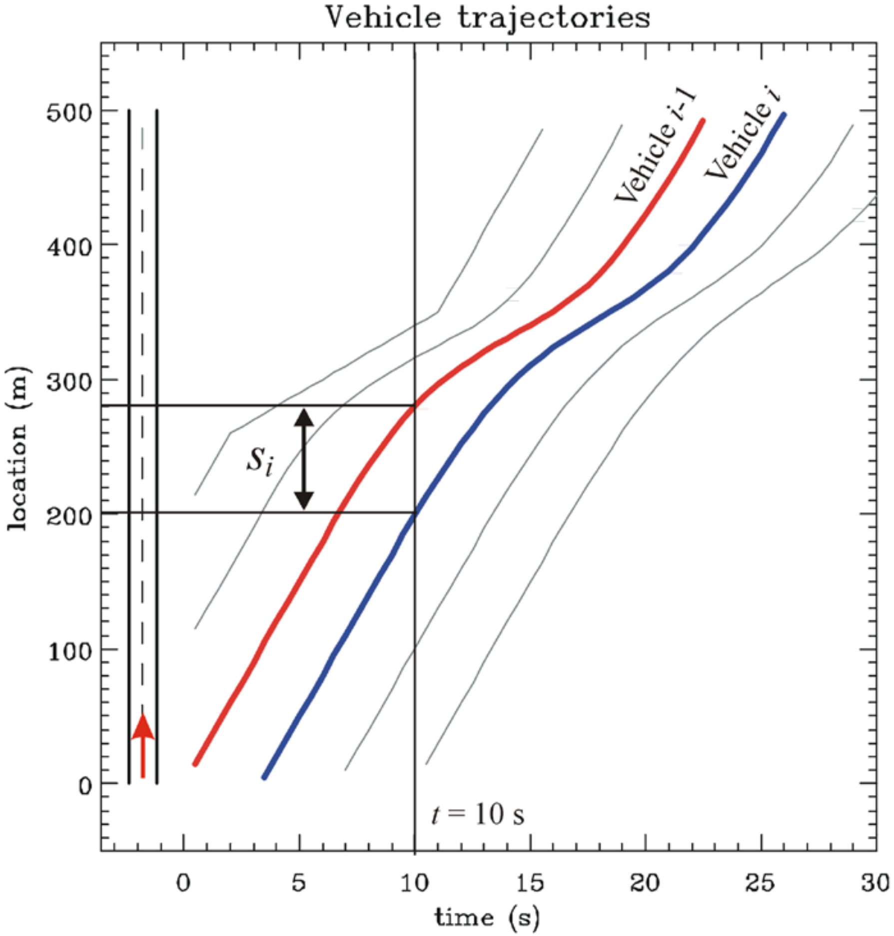
$$\bar{h} = \frac{1}{n}\sum_{i=1}^{n} h_i = \frac{T}{n}$$

- Exercise: express the mean headway for the cross-section as a function of the mean headways H_1 and H_2 per lane



Distance headways

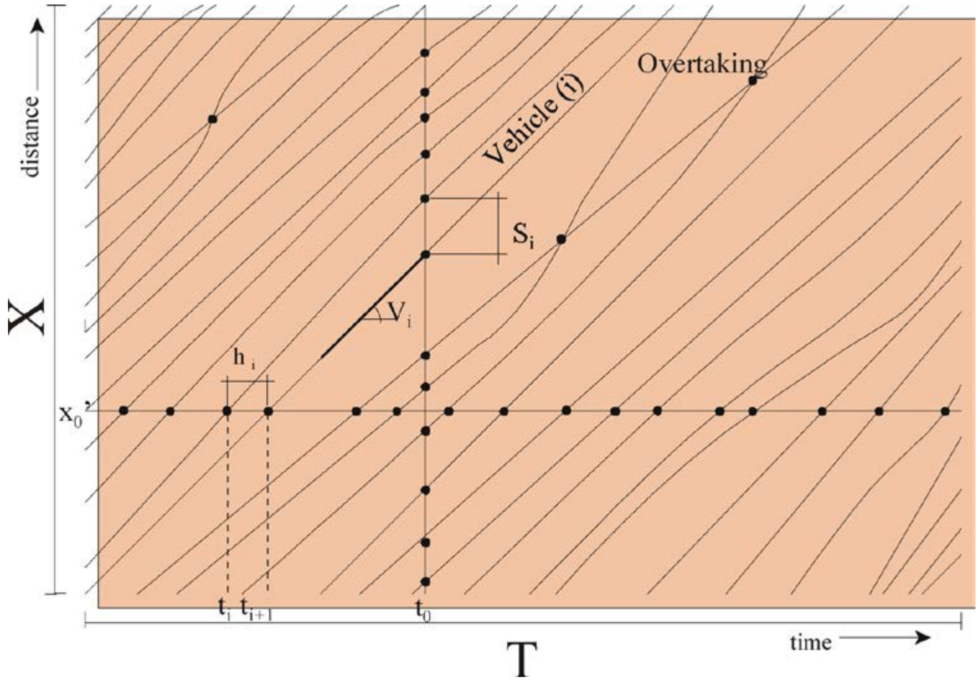
- **Distance headway** s_i: difference between positions vehicle i-1 and i at time t (difficult to measure!)
- Gross distance headway and net distance headway



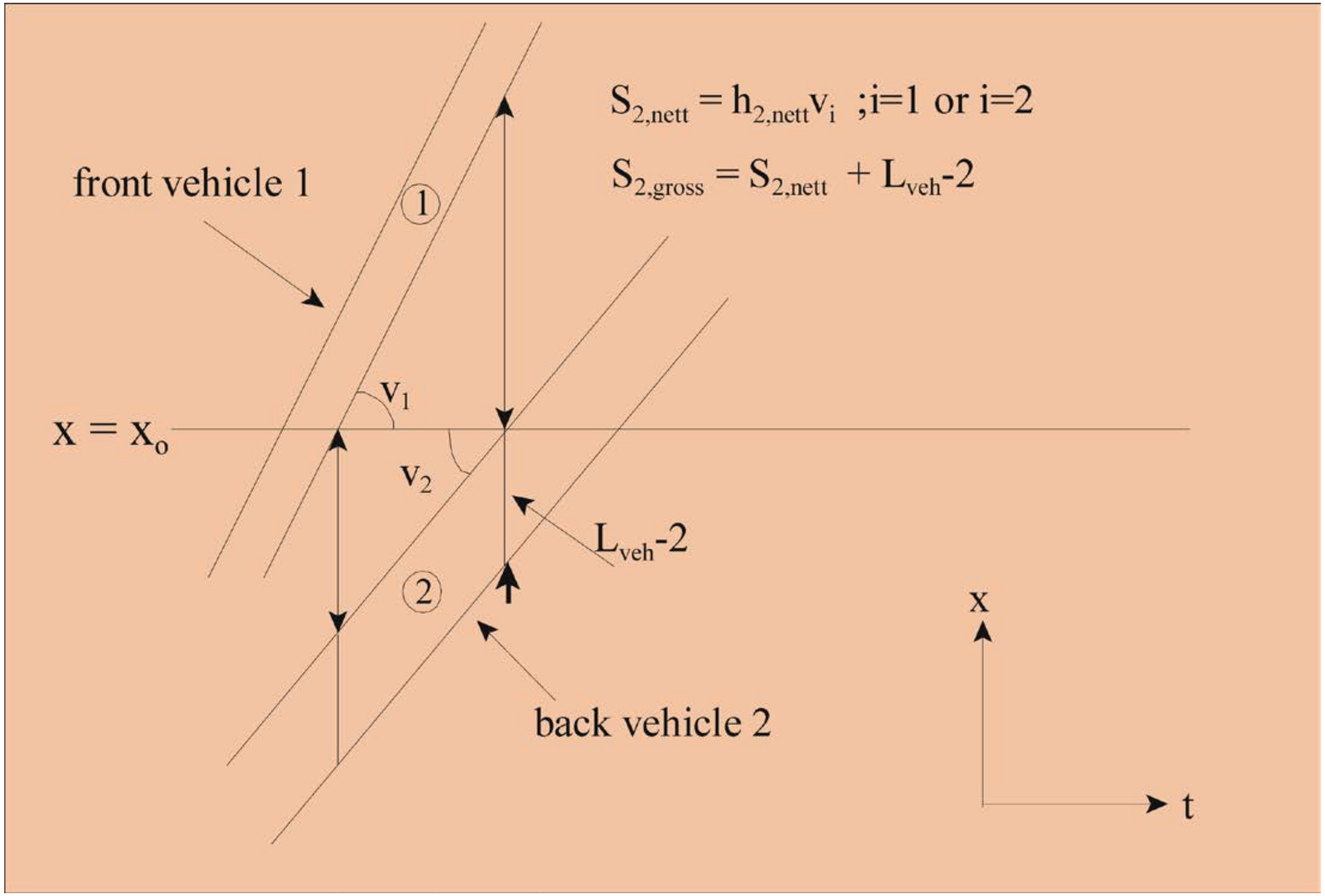
Distance headways (2)

- Distance headway: *instantaneous microscopic variable*
- Space-mean distance headway of *m* vehicles at time instant *t* for roadway of length *X*

$$\bar{s} = \frac{1}{m}\sum_{i=1}^{m} s_i = \frac{X}{m}$$



Distance headways (3)

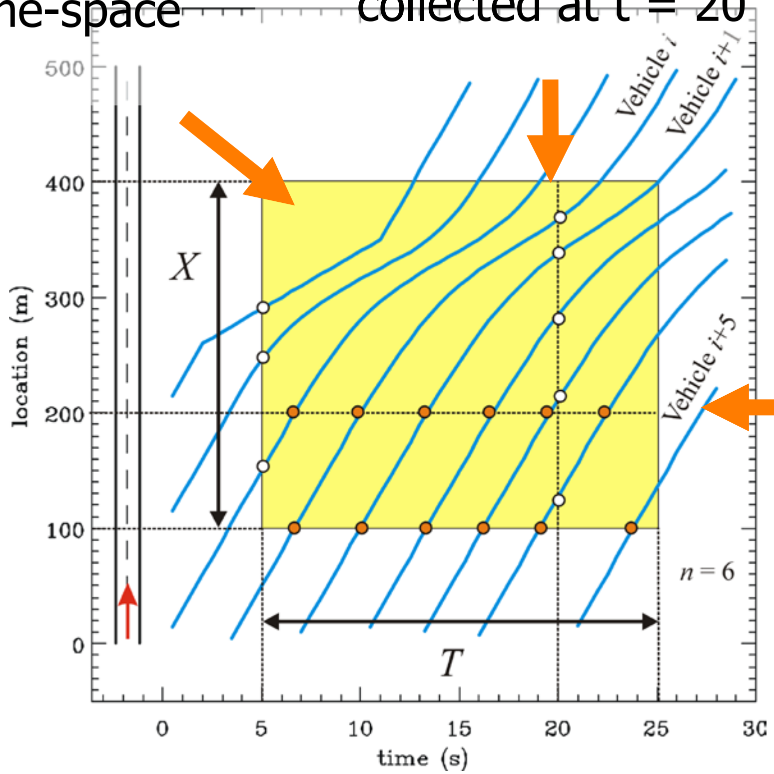


Local, instantaneous and generalized

Generalized measurements determined for time-space region

Instantaneous measurements collected at t = 20

Local measurements collected at x = 200

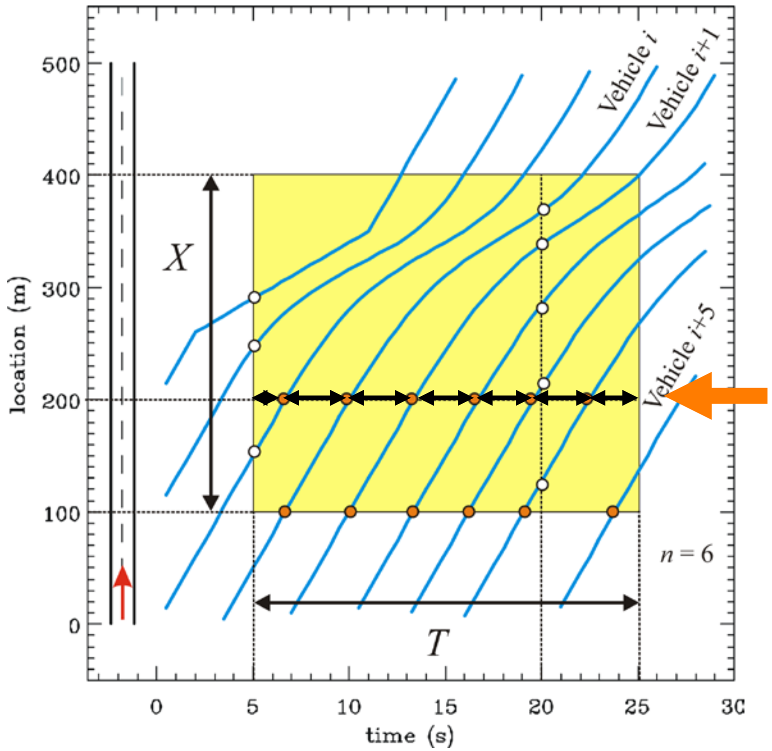


Macroscopic flow variables

- **Traffic intensity q** (local variable)
  - Vehicle number passing cross-section x_0 **per unit time** (hour, 15 min, 5 min)
  - If n vehicles pass during T, q is defined by:

$$q = \frac{n}{T} = \frac{n}{\sum_{i=1}^{n} h_i} = \frac{1}{\frac{1}{n}\sum_{i=1}^{n} h_i} = \frac{1}{\overline{h}}$$

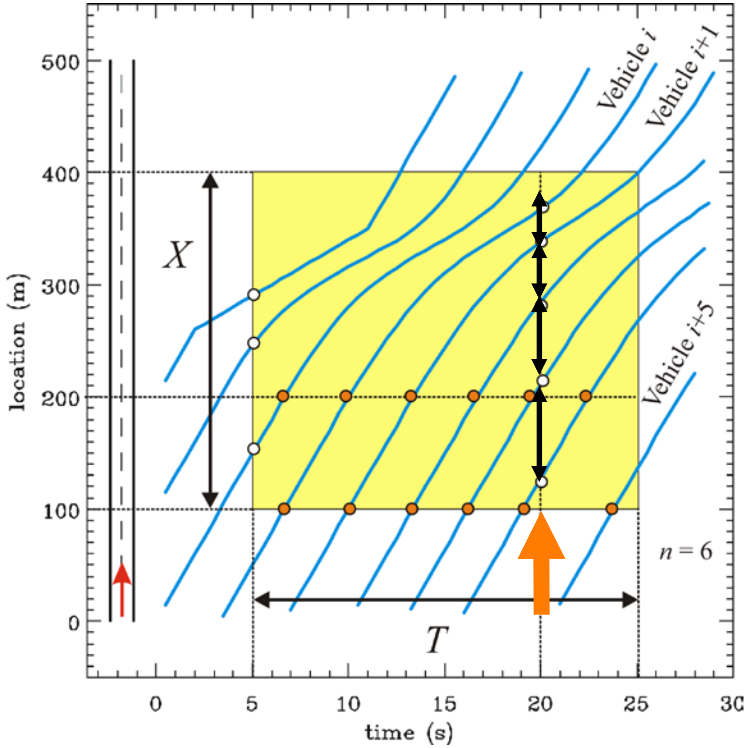
- Referred to as flow, volume (US)
- How can flow be measured?



Macroscopic flow variables (2)

- **Traffic density k** (instantaneous variable)
  - Vehicle number present **per unit roadway length** (1 km, 1 m) at instant t
  - If m vehicles present on X, k is defined by

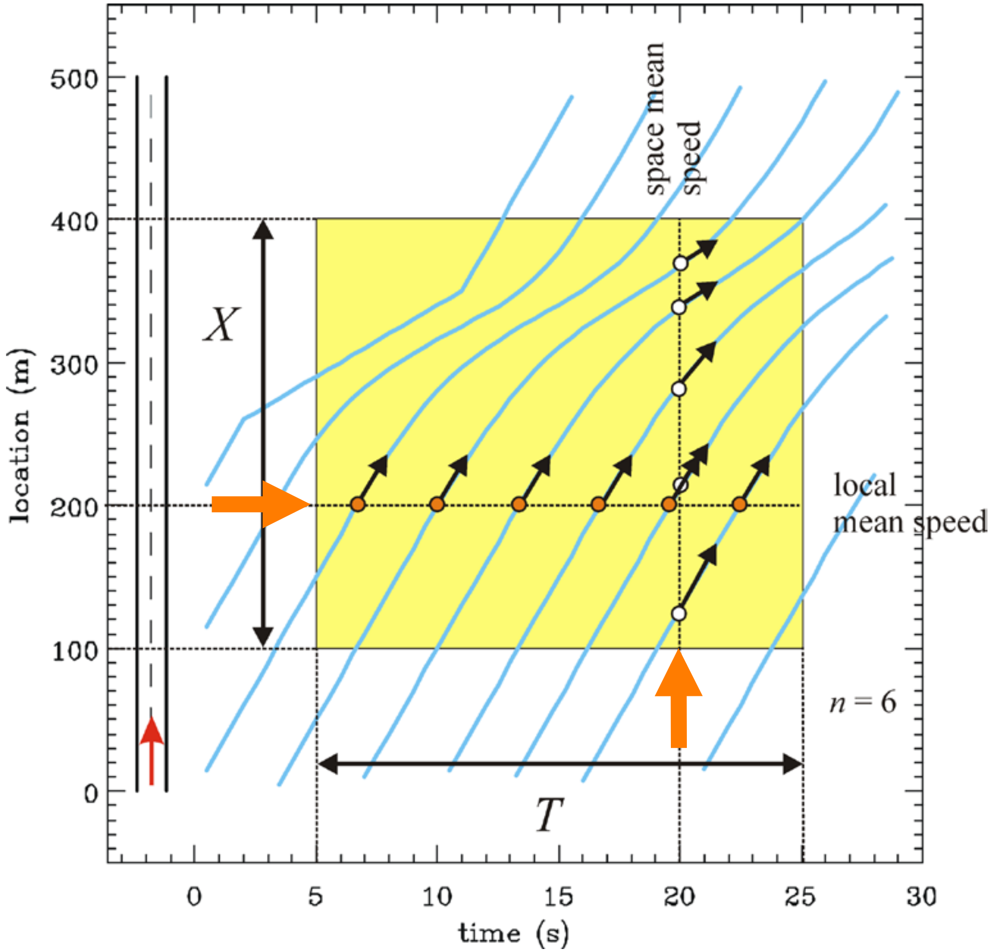
$$k = \frac{m}{X} = \frac{m}{\sum_{i=1}^{m} s_i} = \frac{1}{\frac{1}{m}\sum_{i=1}^{m} s_i} = \frac{1}{\bar{s}}$$



- Also referred to as concentration
- How can density be measured?

- **Now how about speeds?**

Mean speeds



500
400
300
200
100
0
location (m)
X
space mean speed
local mean speed
n = 6
T
0
5
10
15
20
25
30
time (s)

Mean speeds

- **Local mean speed / time mean speed (see next slide)**
  - speeds v_i of vehicles passing a cross-section *x* during period *T*

$$u_L = \frac{1}{n}\sum_{i=1}^{n} v_i$$

- **Instantaneous / space mean speed (next slide)**
  - speed v_j of vehicles present at road section at given moment *t*

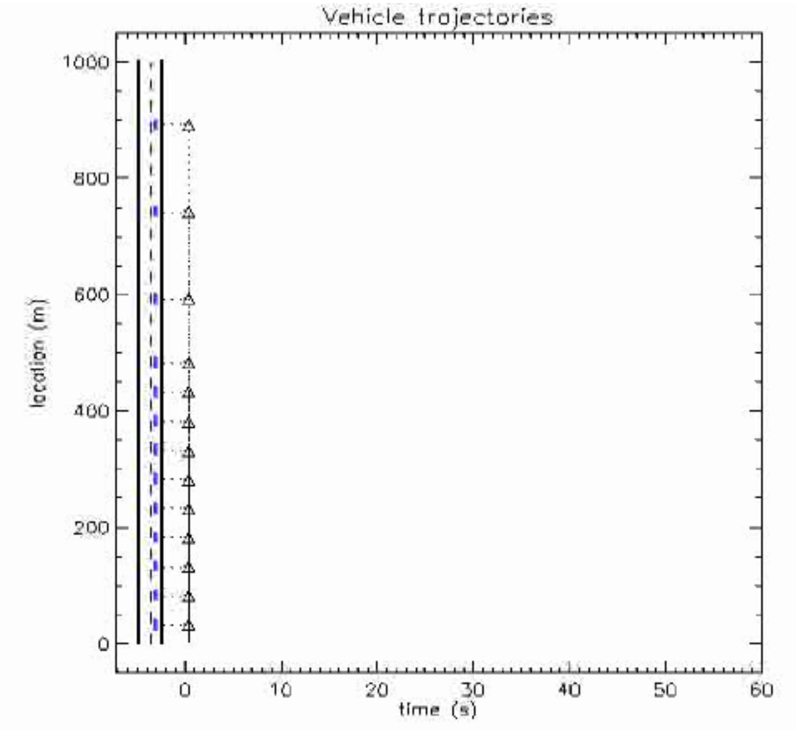
$$u_M = \frac{1}{m}\sum_{j=1}^{m} v_j$$

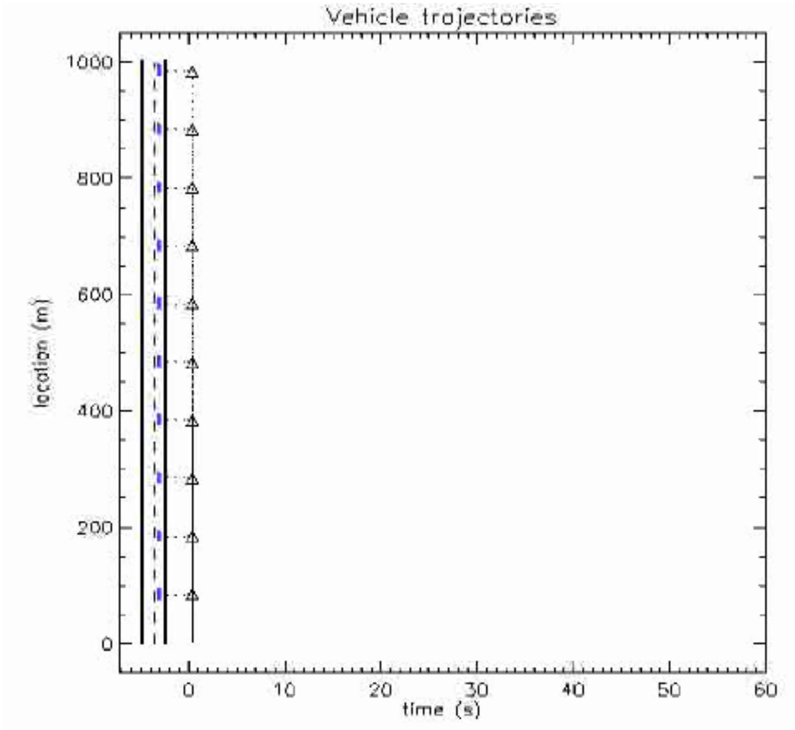
- We can show that *under special circumstances* we can compute space-mean speeds from local measurements

$$u_M = \left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{v_i}\right)^{-1} \quad \text{(harmonic average local speeds)}$$

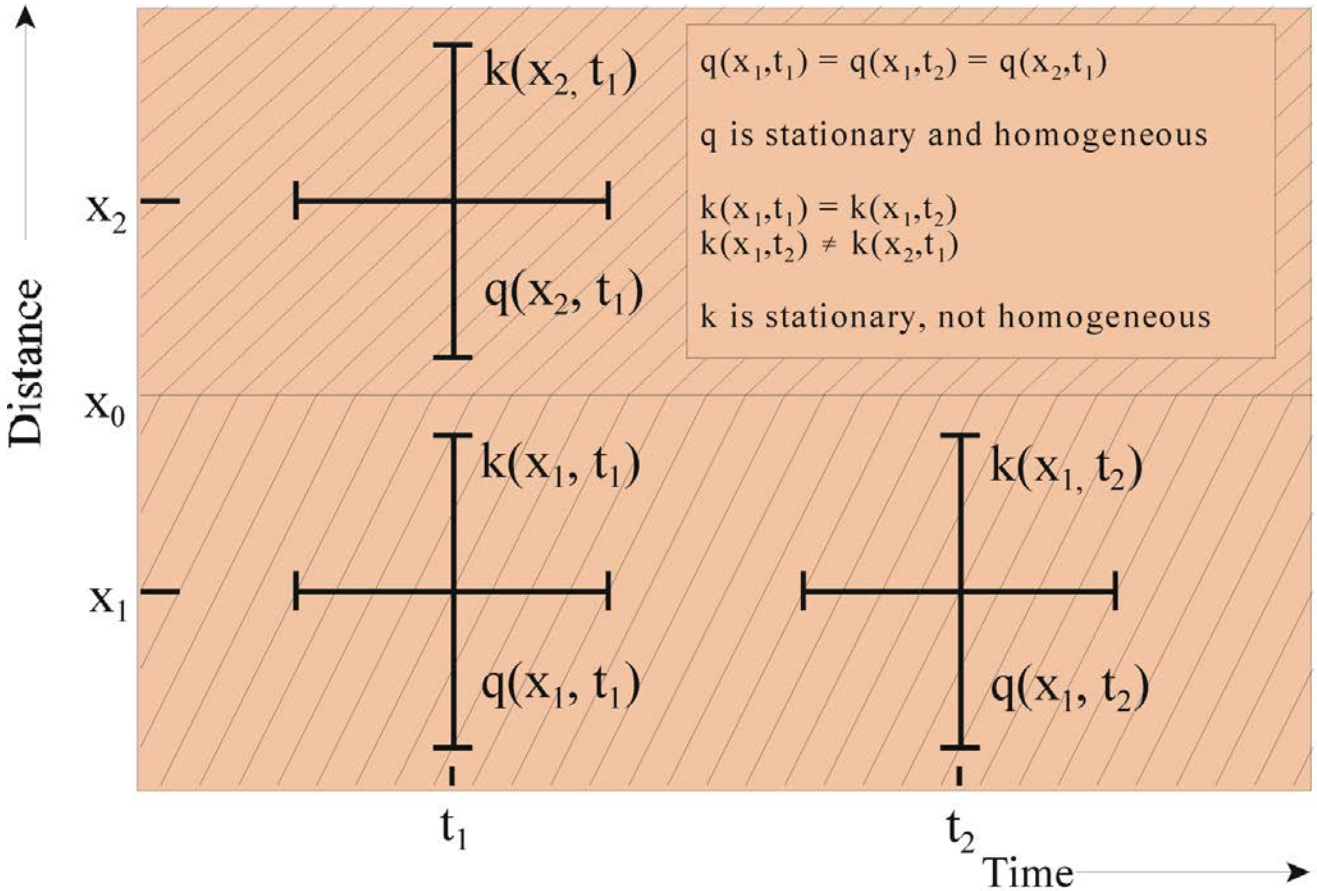
Homogeneous & stationary <u>variables</u>

- Consider any variable $z(t,x)$; z is:
  - **Stationary** if $z(t,x) = z(x)$
  - **Homogeneous** if $z(t,x) = z(t)$

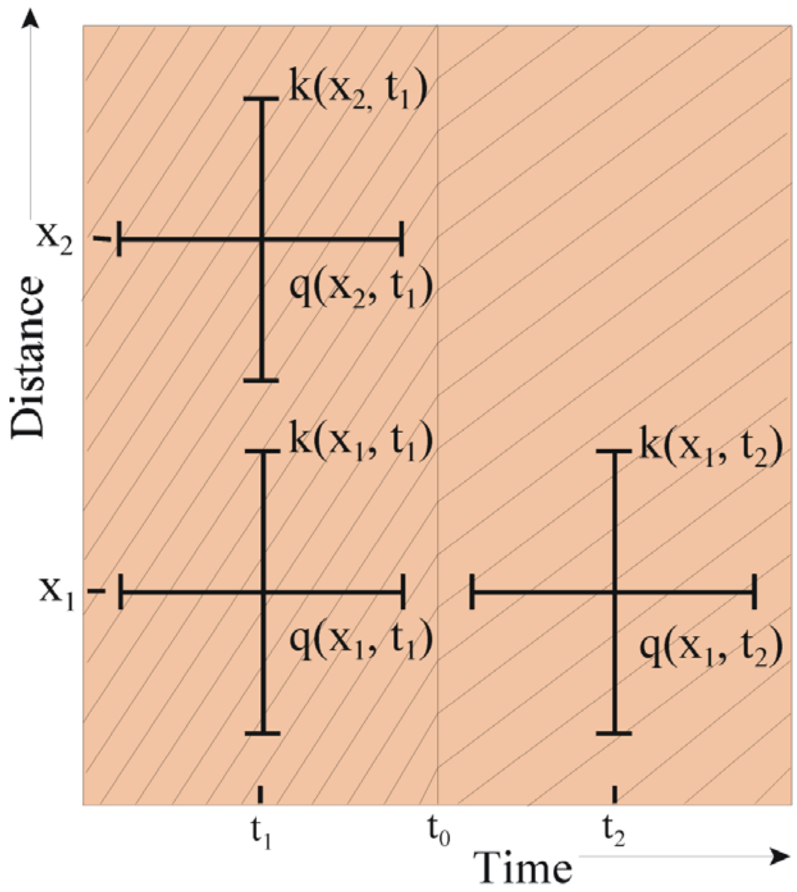




Stationary flow conditions



Homogeneous flow conditions



$q(x_1,t_1) \neq q(x_1,t_2)$
$q(x_1,t_2) = q(x_2,t_1)$

q is homogeneous, not stationary

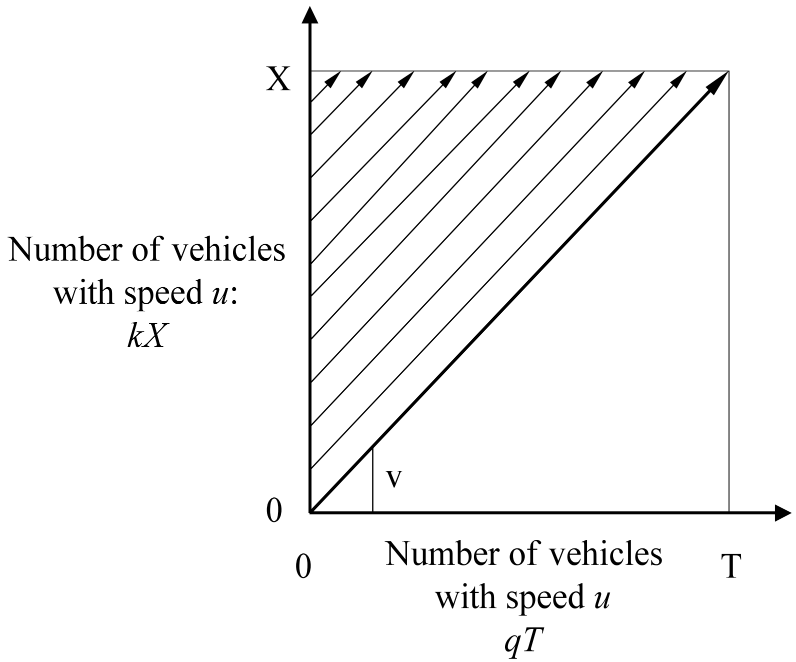
$k(x_1,t_1) = k(x_1,t_2) = k(x_2,t_1)$

k is homogeneous and stationary

The time headways change, but the distance headways remain the same

Fundamental relation

- Consider traffic flow that is in **stationary and homogeneous**
- Then the so-called fundamental relation holds $q = ku$
- Assume intensity q, density k and that **all drive with speed u**



Time needed to travel from 0 to *X*

$$T = \frac{X}{u}$$

Number of vehicles passing cross-section at X equals the number of vehicles that is on the road at t = 0, i.e.

kX = qT

With T=X/u we get fundamental relation

Which speed to use in $q = k \times u$?

- Can we apply the fundamental relation $q = ku$ for an heterogeneous driver population?
- Yes -> the trick is to divided the traffic stream into homogeneous groups j of drivers moving at the same speed u_j
- Now, what can we say about the speed that we need to use?

Which speed to use in q = k×u?

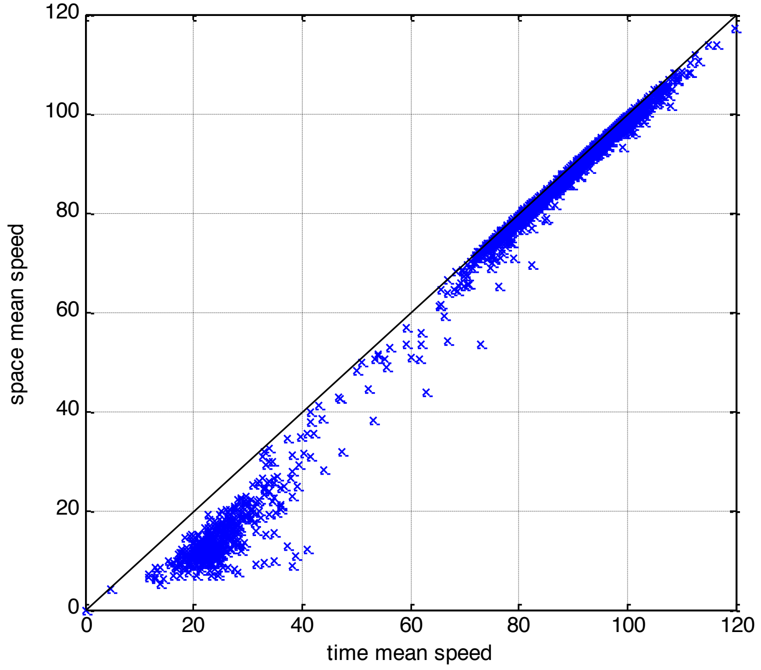
- Can we apply the fundamental relation q = ku for an heterogeneous driver population?
- For one group j (vehicles having equals speeds) we have $q_j = k_j u_j$
- The total flow q simply equals $q = \sum q_j = \sum k_j u_j$
- For the total density we have $k = \sum k_j$
- Let u = q/k, then

$$u = \frac{\sum k_j u_j}{\sum k_j} = u_M \quad \left(= \frac{\sum (q_j / u_j) u_j}{\sum q_j / u_j} = \frac{\sum q_j}{\sum q_j / u_j} \right)$$

- If we consider $q_j = 1$, then… $u = \frac{\sum 1}{\sum 1/u_j} = u_M$
- **In sum: the fundamental relation q = ku_M may only be used for space-mean speeds (harmonic mean of individual vehicle speeds)!!!**

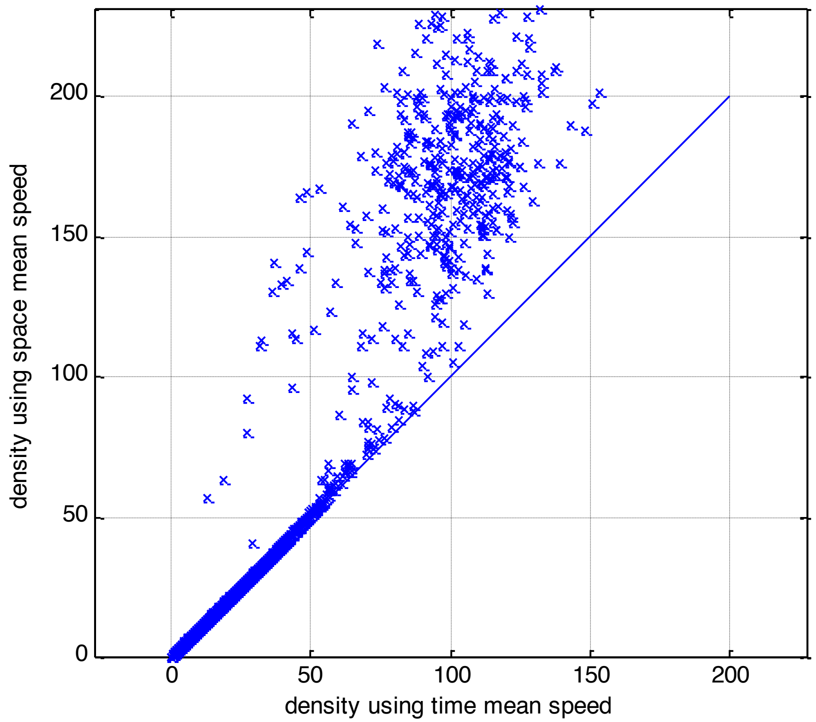
Difference arithmetic & space mean

- Example motorway data time-mean speed and space-mean speed



What about the derived densities?

- Suppose we derive densities by k = q/u…



Conclusion average speeds…

- Care has to be taken when using the fundamental relation $q = ku_M$ that the correct average speed is used
- Correct speed is to be used, **but is not always available from data!**
- Dutch monitoring system collects average speeds, but which?
- Same applies to UK and other European countries (except France)

- Exercise:
  - Try to calculate what using the wrong mean speeds means for travel time computations

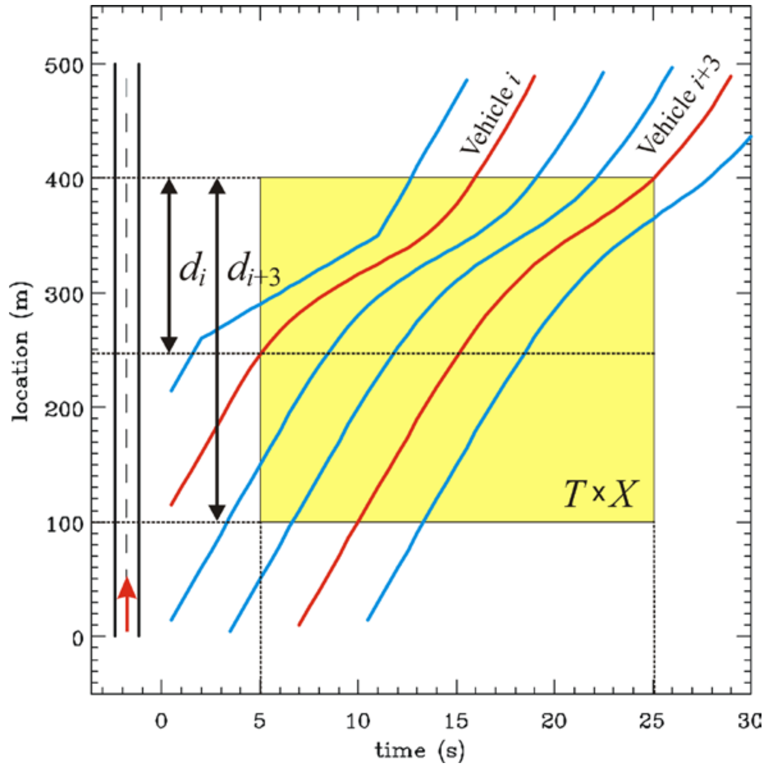
Generalized definitions of flow (Edie)

- Generalized definition flow, mean speed, and density in **time-space plane**
- Consider rectangle T × X
- Each vehicle i travels distance d_i
- Define performance $P = \sum_i d_i$
- P defines 'total distance traveled'
- Define generalized flow

$$q := \frac{P}{XT} = \frac{\sum d_i / X}{T}$$

- Let X « 1, then $d_i \leq X$

$$q = \frac{nX}{XT} = \frac{n}{T}$$



Generalized definition (Edie)

- Each vehicle *j* is present in rectangle for some period r_j
- Defined *total travel time* $R = \sum_j r_j$
- Generalized definition of density

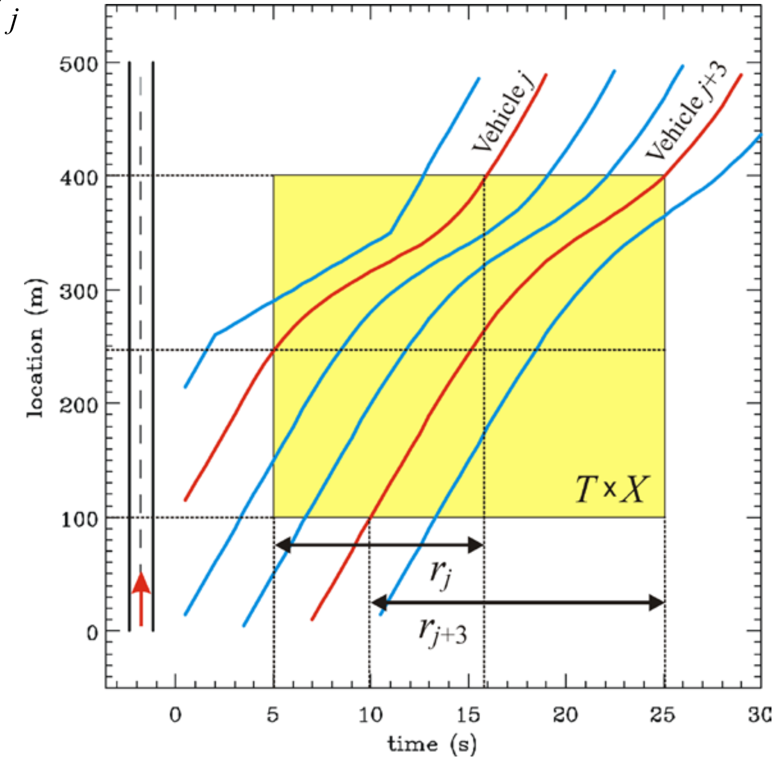
$$k := \frac{R}{XT} = \frac{\sum r_j / T}{X}$$

- When $T \ll 1$, then $r_j \leq T$

$$k = \frac{mT}{XT} = \frac{m}{X}$$

- Definition of the mean speed

$$u_G = \frac{P}{R} = \frac{q}{k} = \frac{\sum_i d_i}{\sum_j r_j}$$



Overview of variables

	Local measurements	**Instantaneous measurements**	**Generalized definition (Edie)**
Variable	Cross-section x Period T	Section X Time instant t	Section X Period T
Flow *q* (veh/h)	$q = \frac{n}{T} = \frac{1}{\overline{h}}$	$q = ku$	$q = \frac{\sum_i d_i}{XT}$
Density *k* (veh/km)	$k = \frac{q}{u}$	$k = \frac{n}{X} = \frac{1}{\overline{s}}$	$k = \frac{\sum_j r_j}{XT}$
Mean speed *u* (km/h)	$u_L = \frac{n}{\sum_i (1/v_i)}$	$u = \frac{\sum_j v_j}{n}$	$u = \frac{q}{k}$

Furthermore…

- Homework:
  - Read through preface and chapter 1
  - Study remainder of chapter 2 (in particular: moving observer, and observation methods)