Traffic Flow Theory & Simulation

S.P. Hoogendoorn

Lecture 5
Moving Bottlenecks and Queuing

Shockwave analysis

Chapter 8

Course Traffic Flow Theory and Simulation

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February 20, 2012

Faculty of Civil Engineering and Geosciences

TU Delft

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Short recap of Tuesday's lecture

- Applications of the fundamental diagram
- Introduction shockwave theory:
  - Main assumptions
  - Shockwave equations
  - Graphical interpretation
- Examples:
  - Temporary blockade
  - Use of non-triangular fundamental diagrams (e.g. capacity drop)
- Today:
  - Application of Shockwave Theory to Moving Bottlenecks
  - With and without overtaking

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Moving bottlenecks

Moving bottlenecks with and without passing opportunities

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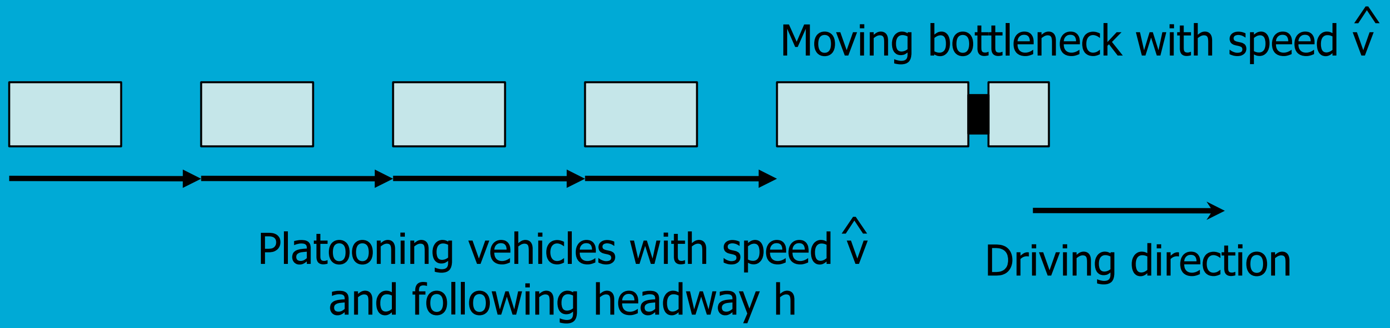
Moving bottleneck examples

- Slow moving vehicle, e.g. an agricultural tractor with a speed of 20 km/h, on a two-lane road.
- Capacity of b-n is determined by
  - Speed of the moving bottleneck
  - Overtaking opportunities, dependent on e.g. opposing flow / overtaking sight distance.
- We assume that those two factors can lead to a more or less constant capacity of b-n
- Other examples of moving bottlenecks:
  - Platoon of trucks on a long grade on a motorway. In such conditions trucks form a slow platoon and more or less block the right hand lane, causing a substantial capacity reduction.
  - Actions of protesting farmers or truck drivers that from a temporary slow platoon on one or more lanes of a motorway.

Fundamental diagram at the MB

- Assume no overtaking opportunities



- Headway h is determined by speed of MB
- Since $q = 1/h$, the flow upstream of the MB is determined by the speed of the MB
- Upstream flow can be determined from FD easily

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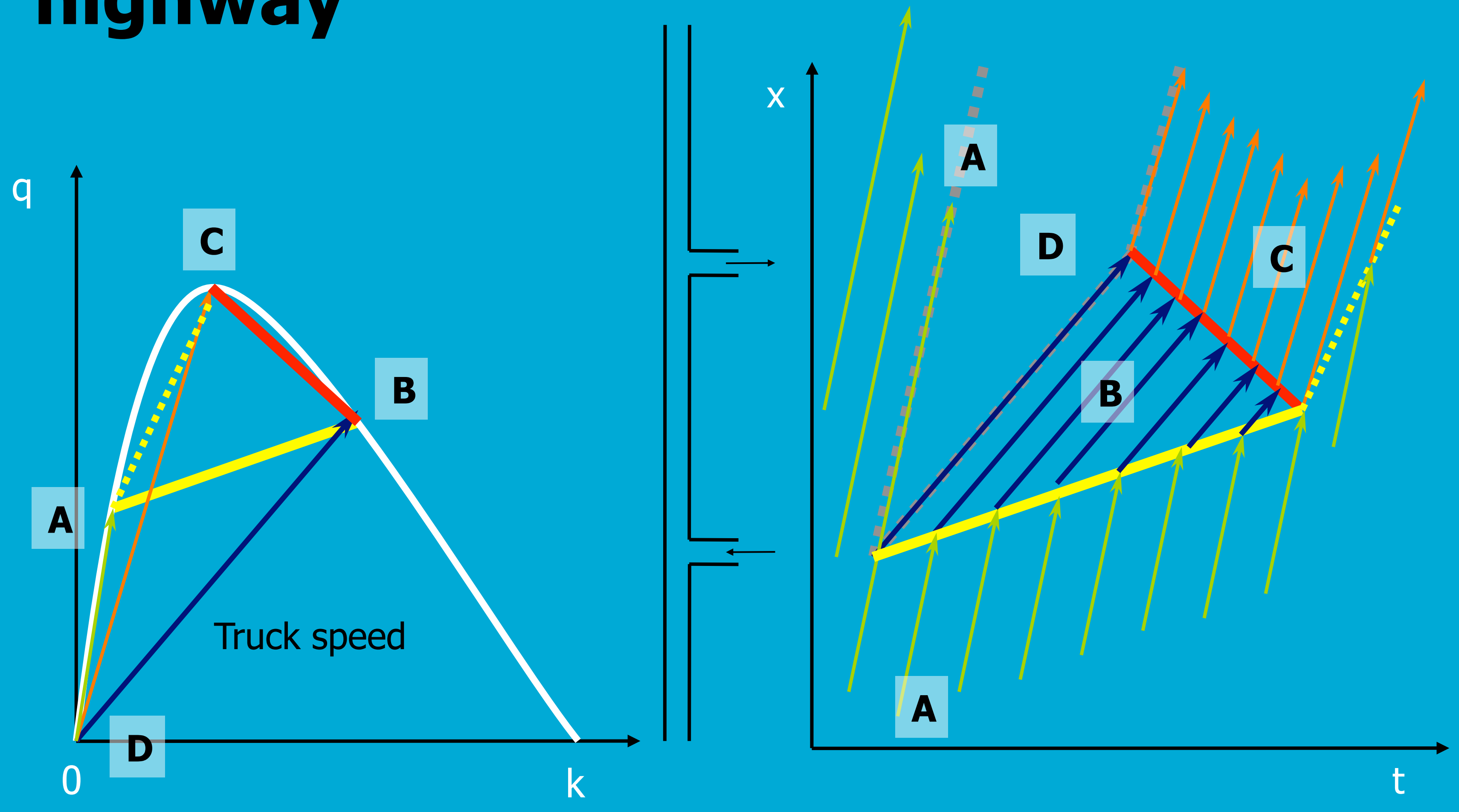
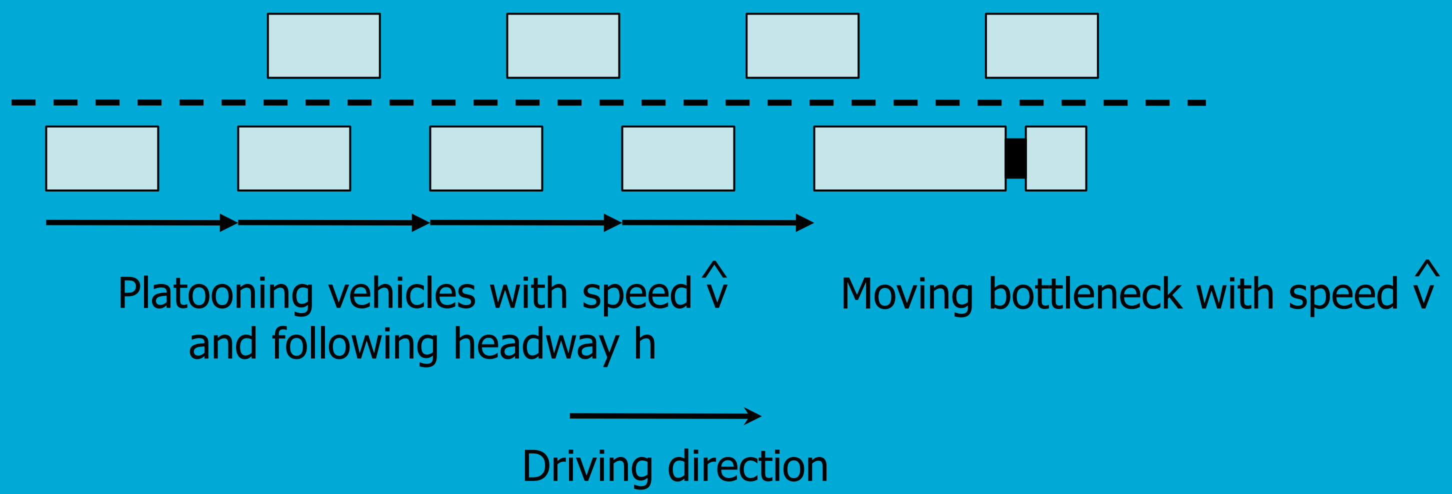
Example MB: slow truck entering highway



Fundamental diagram at the MB

- Now assume overtaking possibilities at the MB

In oversaturated conditions, flows are determined by flows on lane of MB and maximum flow given passing opportunities



- Example: two-lane motorway (one lane operating at capacity)

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Fundamental diagram at the MB

- Suppose C_{lane} = 2000 veh/h and $C_{MB} = k\hat{v}$ = 1000 with $\hat{v}$ = 20 km/h and k = 50 veh/km/lane

- Assume optimal use of available capacity
- For flows < 2000 veh/h speed reductions are only moderate
- Flows between 2000 and 3000: part of traffic will have to follow MB at speed $\hat{v}$: speed reductions are then major
- Determination of Q(k) for 2000 < Q < 3000?
- If demand higher that 3000, speeds are reduced further, but this cannot occur at the MB itself (only upstream of the MB), so region is not relevant

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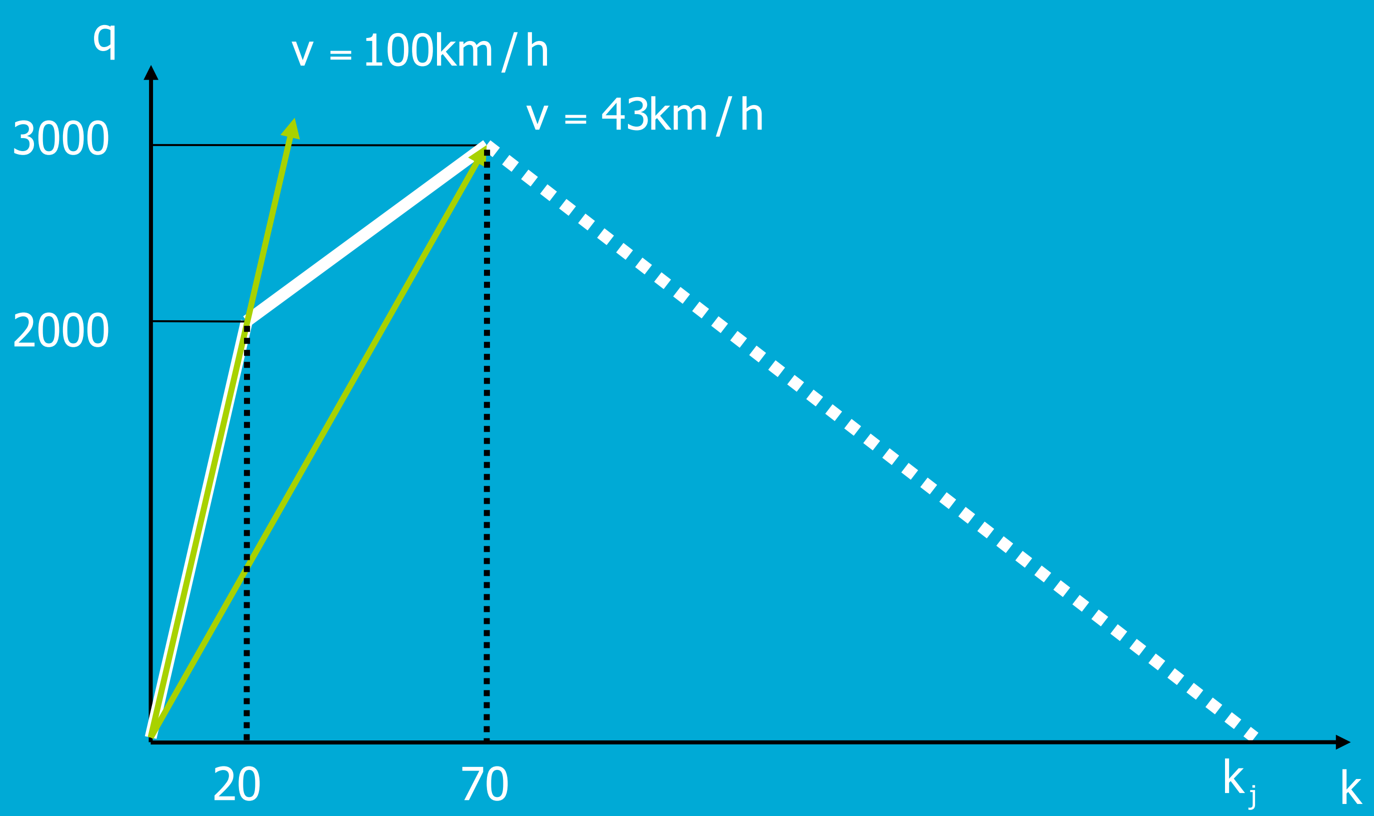
Fundamental diagram at the MB



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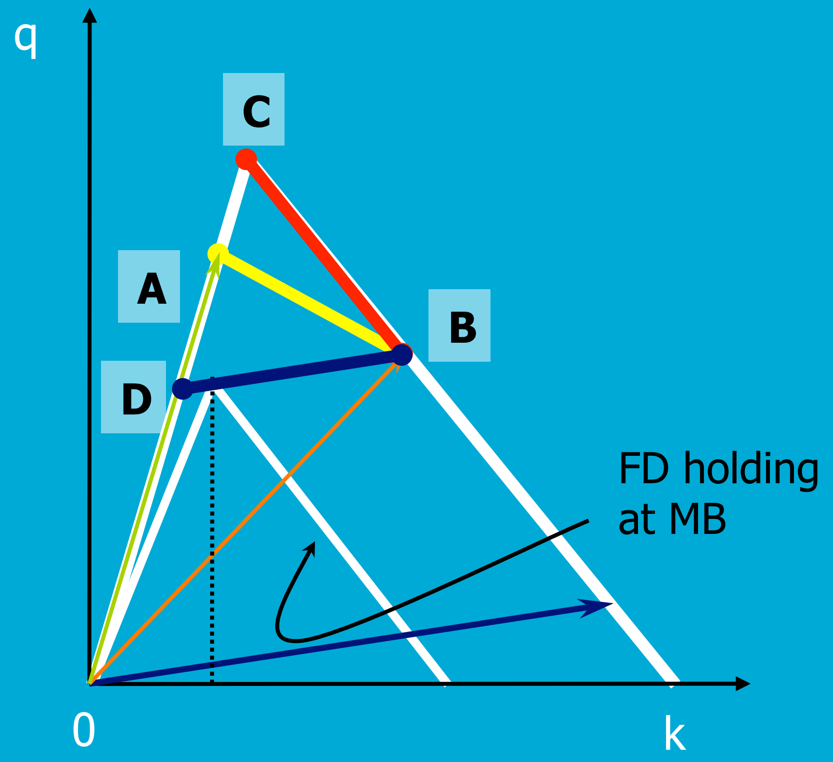
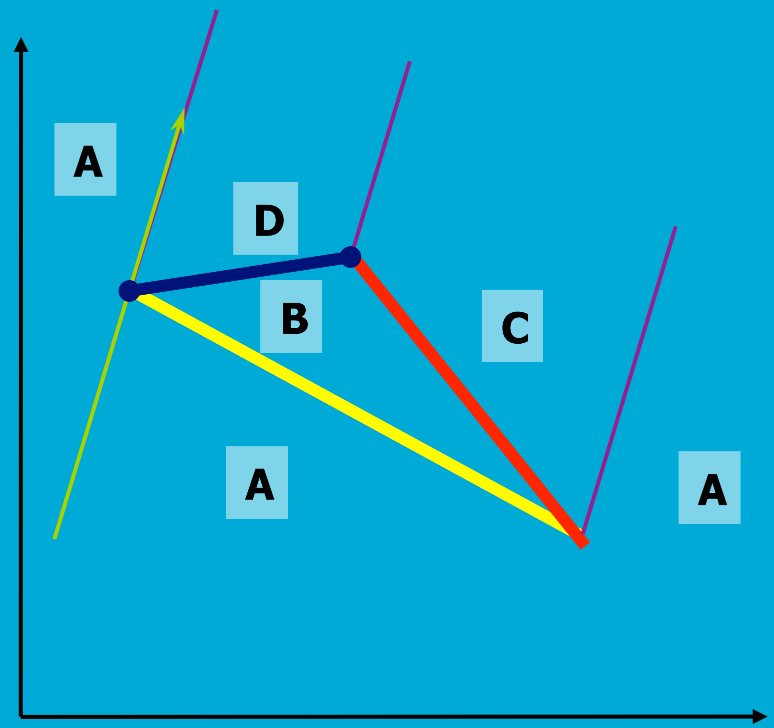
Moving bottleneck – with overtaking

- Overtaking slow vehicle (20 km/h) possible





Easy way to remember MB principle

- In most exercises, the traffic conditions at the MB will be given

- MB itself is a small region E at which a certain traffic state holds
- A shock separates both
  - High-density region B upstream of the MB E
  - Low-density region D downstream of the MB E
- Speed of the shock is equal to the speed of the MB
- Traffic conditions B and D can be determined directly from that!

Queuing Analysis

Chapter 7

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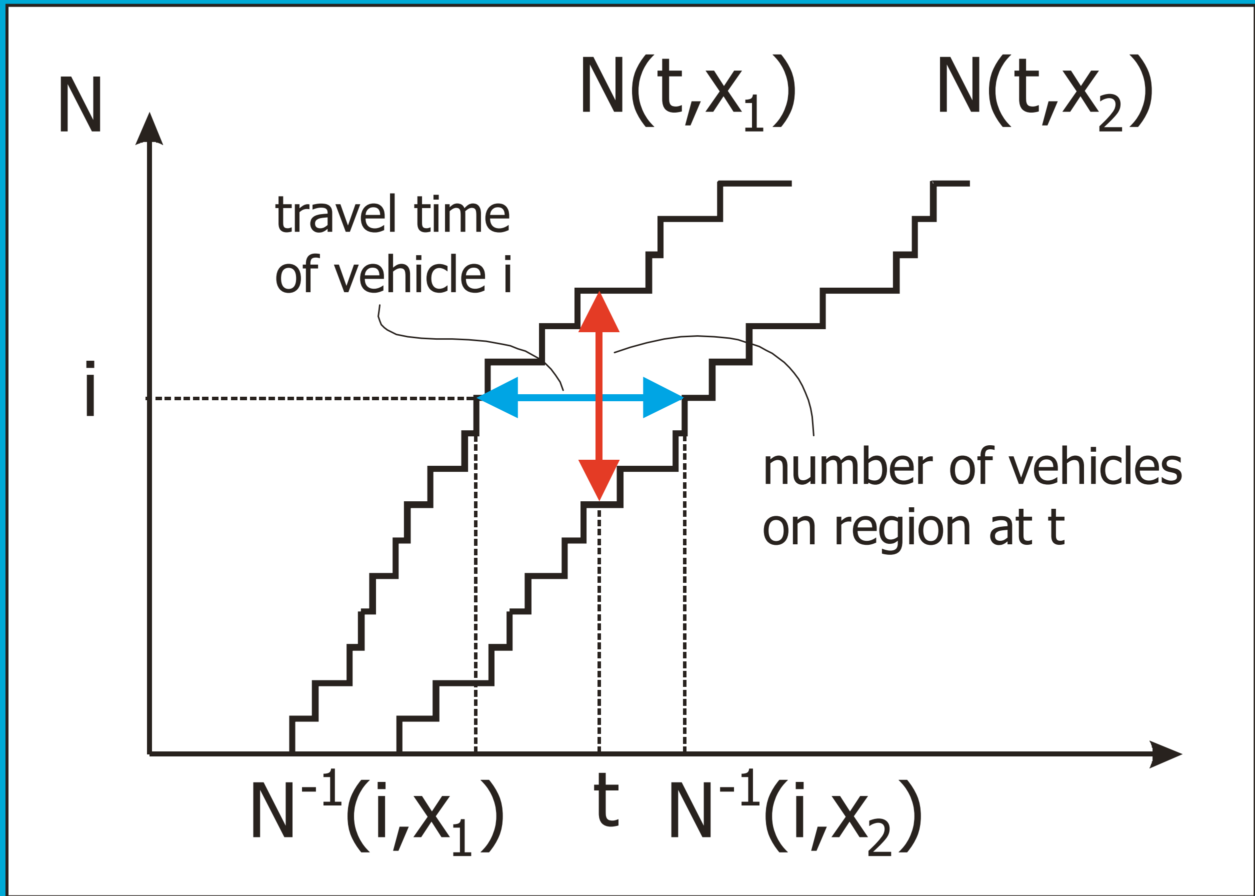
Cumulative flow curves preliminaries



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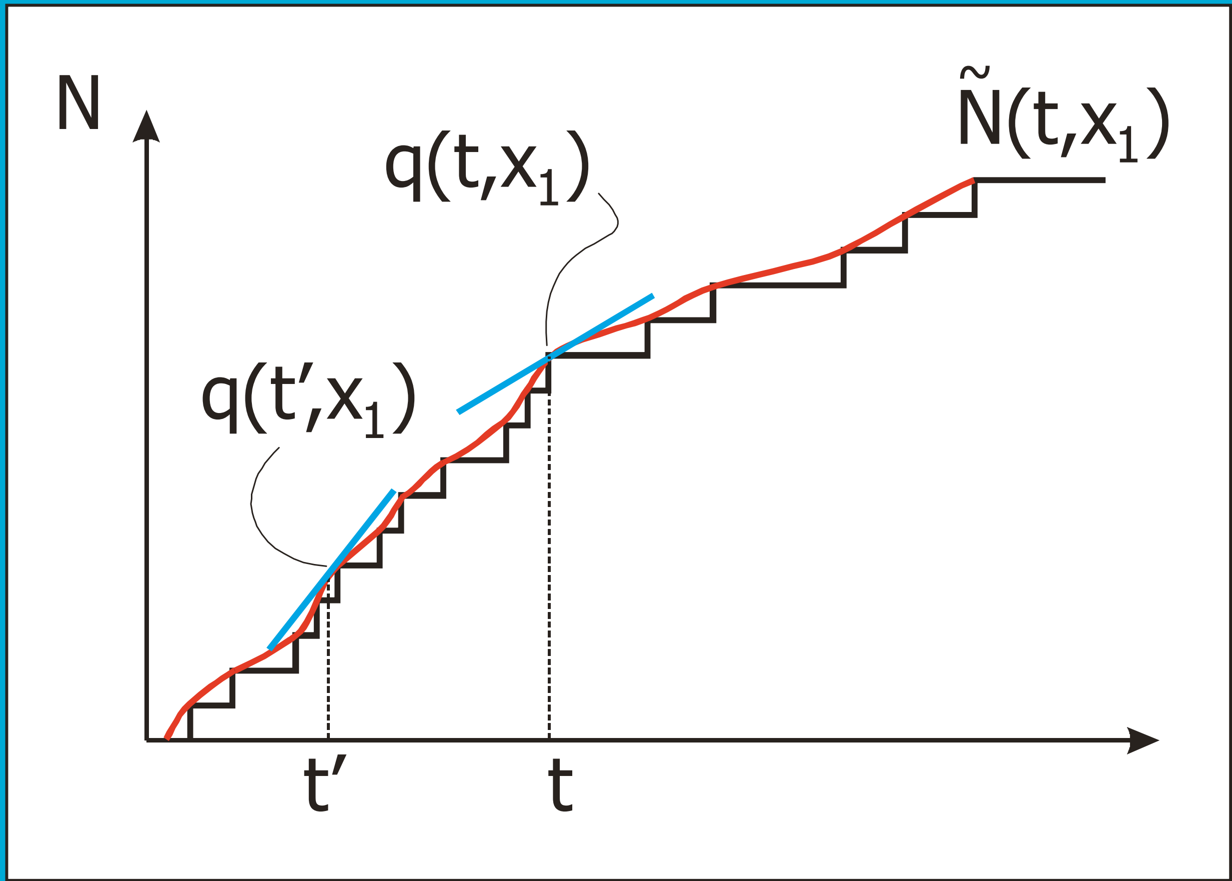
Smooth approximation



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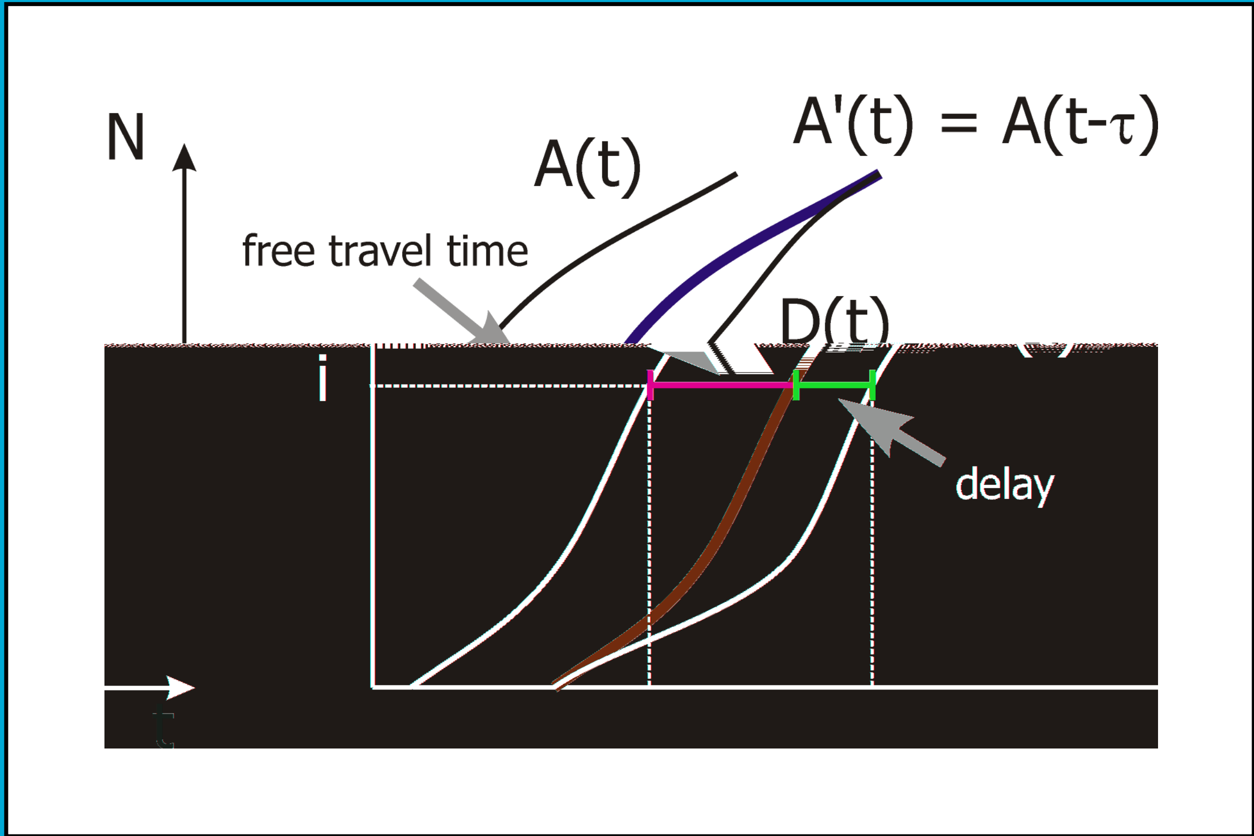
Individual and total delays (2)



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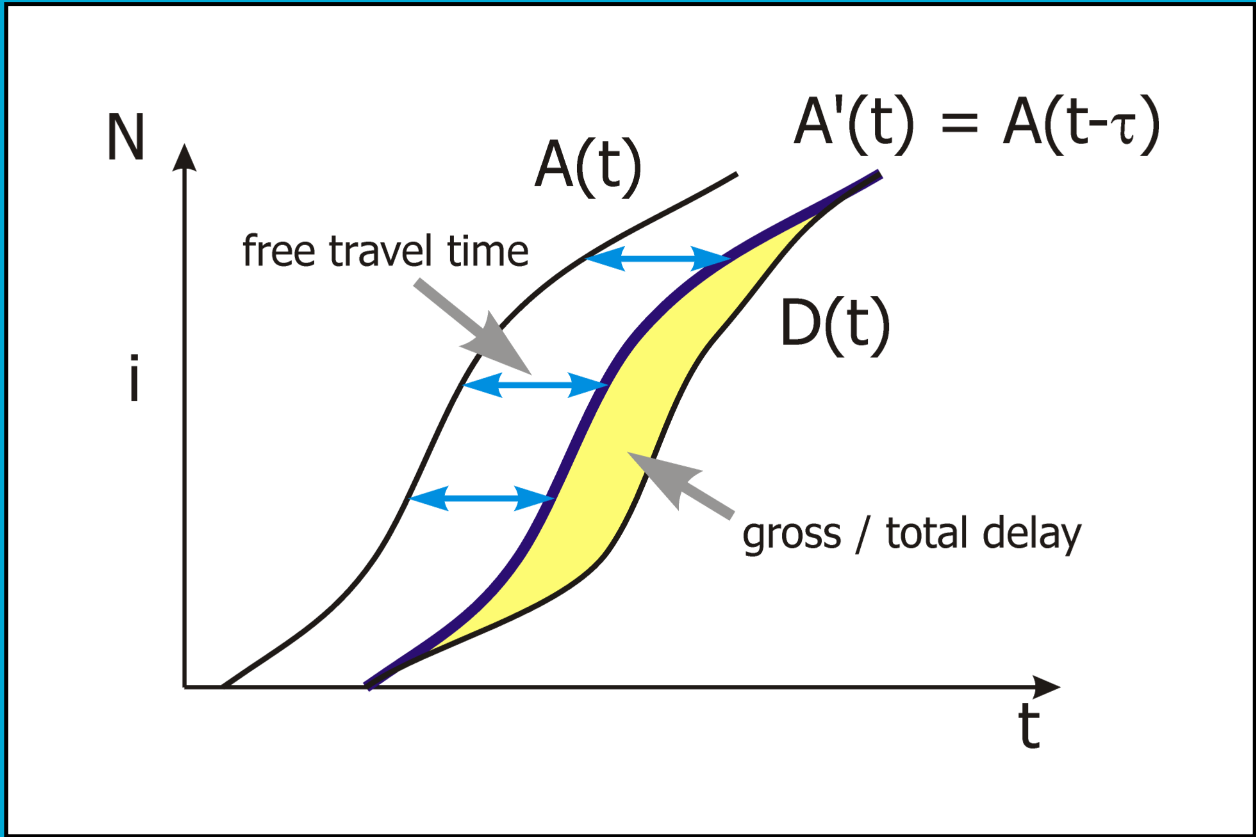
Individual and total delays (3)



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Queuing models

Application to delay modeling

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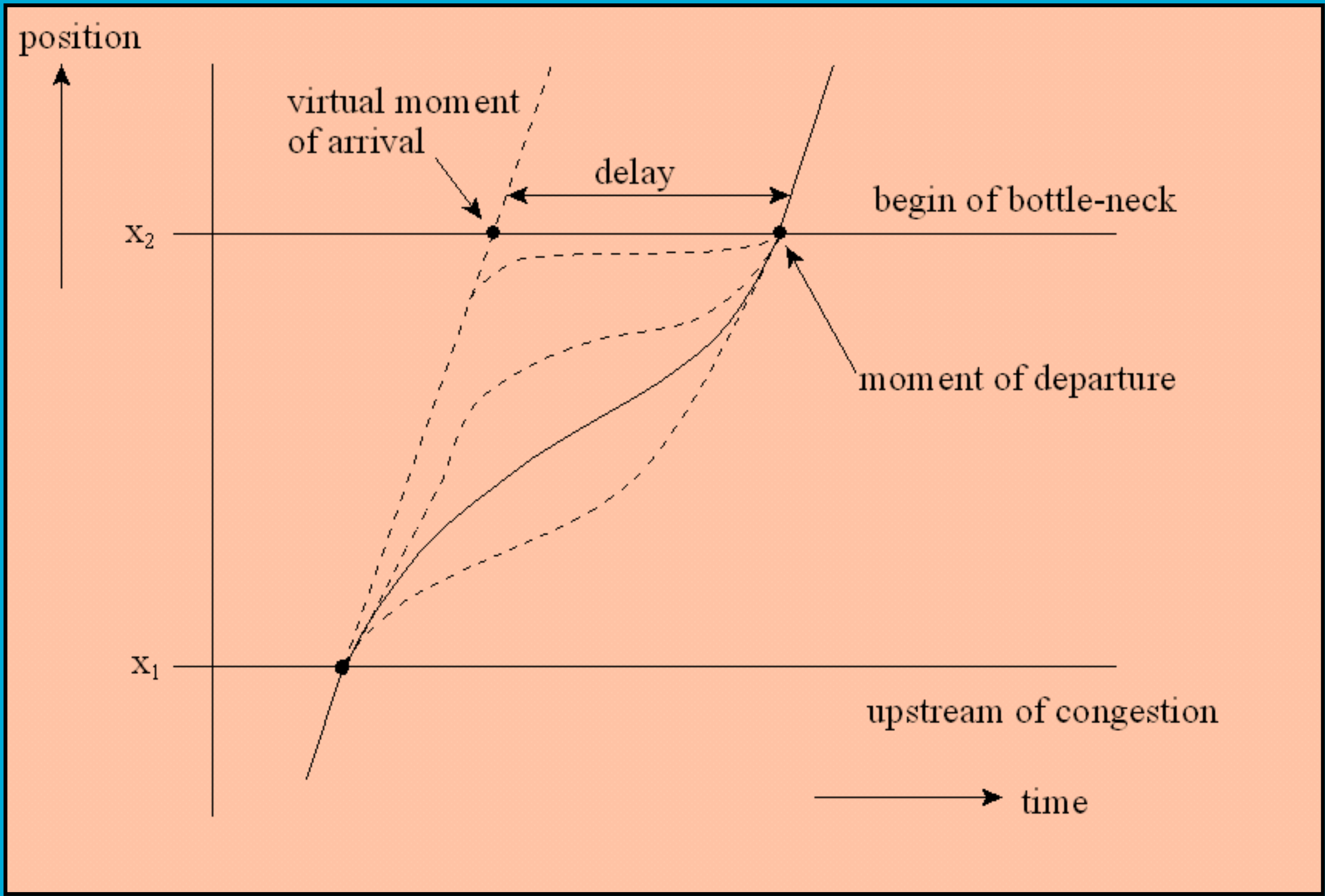
Queuing models

- Schematized representation of queuing
  - Not considering queue's spatial dynamics (shockwaves)
  - Not considering (small) delays experienced in 'flow-less-than-capacity' regions
- Assumptions
  - Vehicles drive to the cross-section where the bottleneck starts (free travel time τ)
  - Vehicles either form or join a vertical queue (no consideration of spatial dimension)

- Consider schematized situation

Fitness of queuing approach



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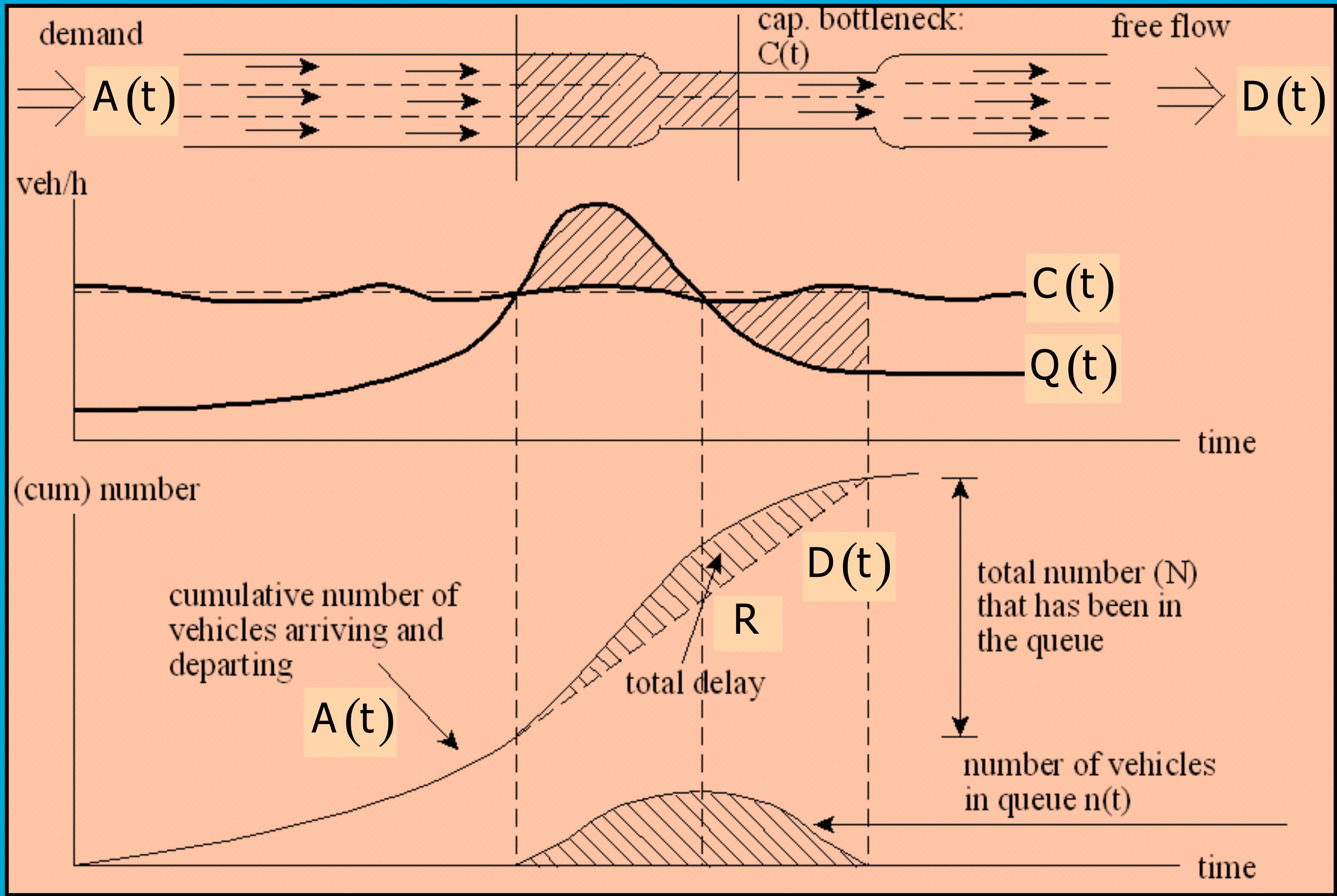
Queuing models

- Arrival curve A(t) (virtual)
  - Number of vehicles that want to pass bottleneck / want to be served by bottleneck at time t ('arrive at bottleneck')
  - Has slope Q(t) (= traffic demand)

$$A(t) = \int_{t_0}^{t} Q(s)ds$$

- Departure curve D(t):
  - Number of vehicles that have passed the bottleneck / were actually served by the bottleneck
  - If all vehicles can be served (no queue and Q(t) < C), departure curve has same slope as the arrival curve (=Q(t))
  - IF not all vehicles can be served, it has slope C

Queuing models



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Application of Queuing Models

- **The X-factor**: how much traffic must we get rid of (during the peaks) to reduce the maximum delay at the major bottlenecks in the Netherlands to 10 minutes

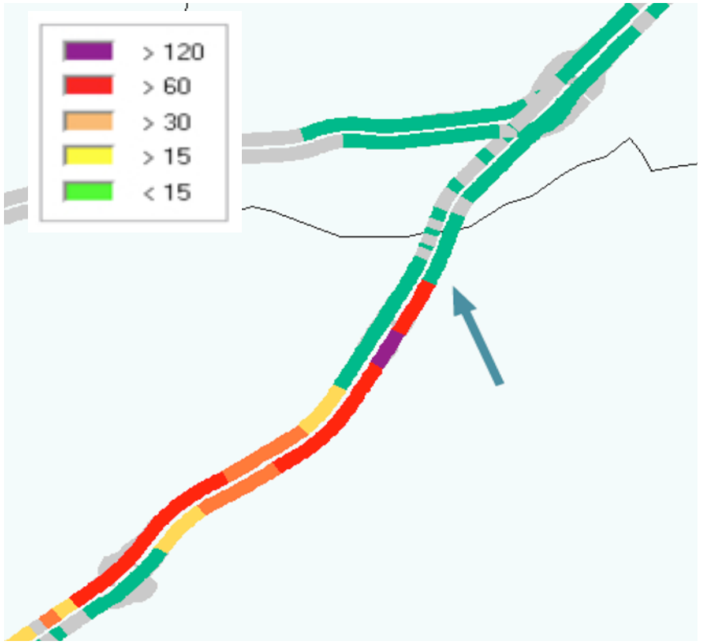
- Consider a bottleneck
- Determine the traffic demand Q(t) at this bottleneck:
  - By measuring flows sufficiently far away from the bottleneck
  - By reconstructing demand using (simple) model assumptions (e.g. tonenmethode, OD estimation, etc.)

- Example A4 bottleneck

Example A4, Delft Amsterdam

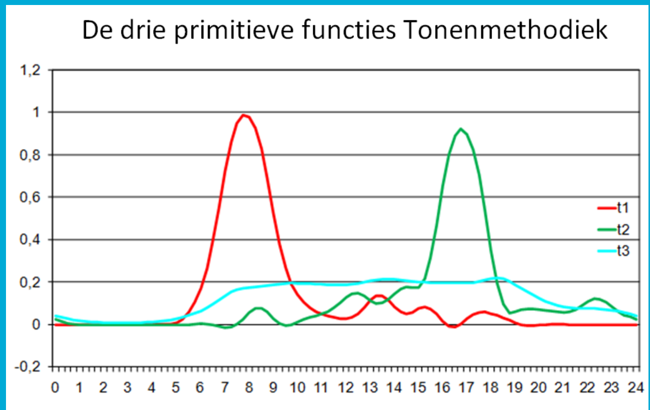
Delft - Amsterdam, morning peak

- Congestion A4 is caused by bottleneck 'Ringvaartaquaduct'
- Nr. 40 in the vehicle-loss-hours of all bottlenecks in NL
- How much are the total delays and what are the societal cost?
- For morning peak:
  - Total delay 2,650 hour/day
  - Total cost 42,000 Euro/day (about 9.3 million/year)
- Other costs besides delay?

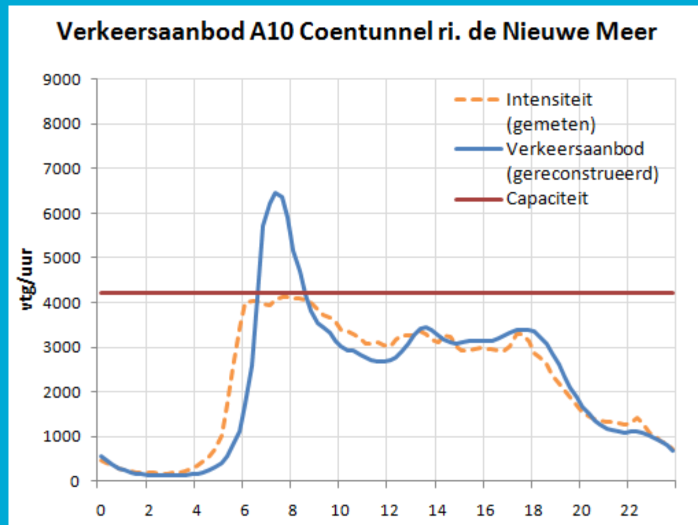


Example A10 West - Coentunnel

- Reconstruction of traffic demand



Figuur 1



Figuur 3

$$Q(t) = \sum_{i=1}^{3} \alpha_i \cdot Q_i(t)$$

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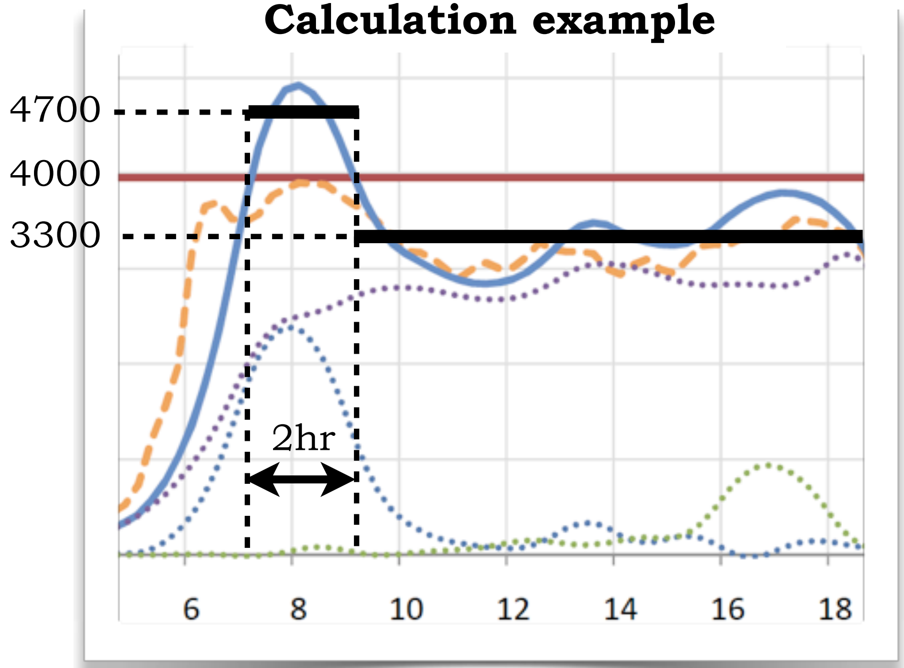
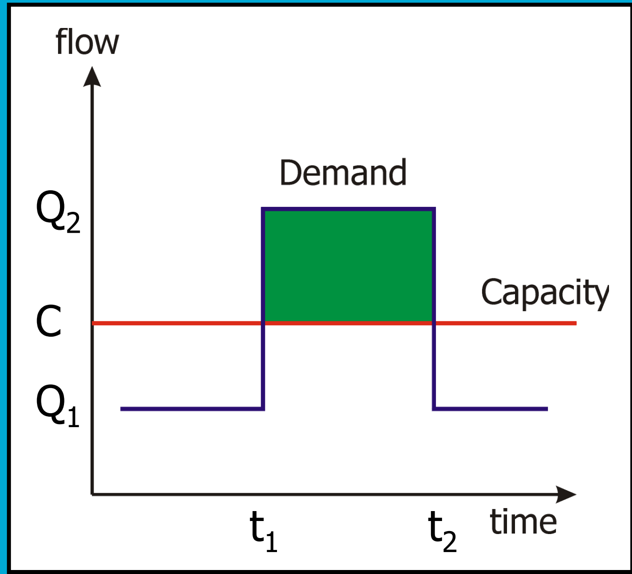
Example calculations

For the A4 bottleneck

- Piece-wise constant approximation of demand profile
- A simple recipe:
  - Draw arrival curve D(t) using demand profile
  - Draw departure curve S(t) using knowledge of C
- Answer simple questions
  - Congestion duration T
  - Delays of vehicle i
  - Total nr of vehicles queued
  - Total and average delay



Queuing models (3)



- Schematized example

$$Q(t) = \begin{cases} Q_1 & t < t_1, t \geq t_2 \\ Q_2 & t_1 \leq t < t_2 \end{cases}$$

where $Q_2 > C$ and $Q_1 < C$

- Time t_1 is the time congestion starts
- Using queuing modelling, determine:
  - What is the maximum queue length?
  - What is the maximum delay?
  - How long will the queue last?
  - What is the total delay? Mean delay?

Hint:
draw the arrival curve
and the departure curve

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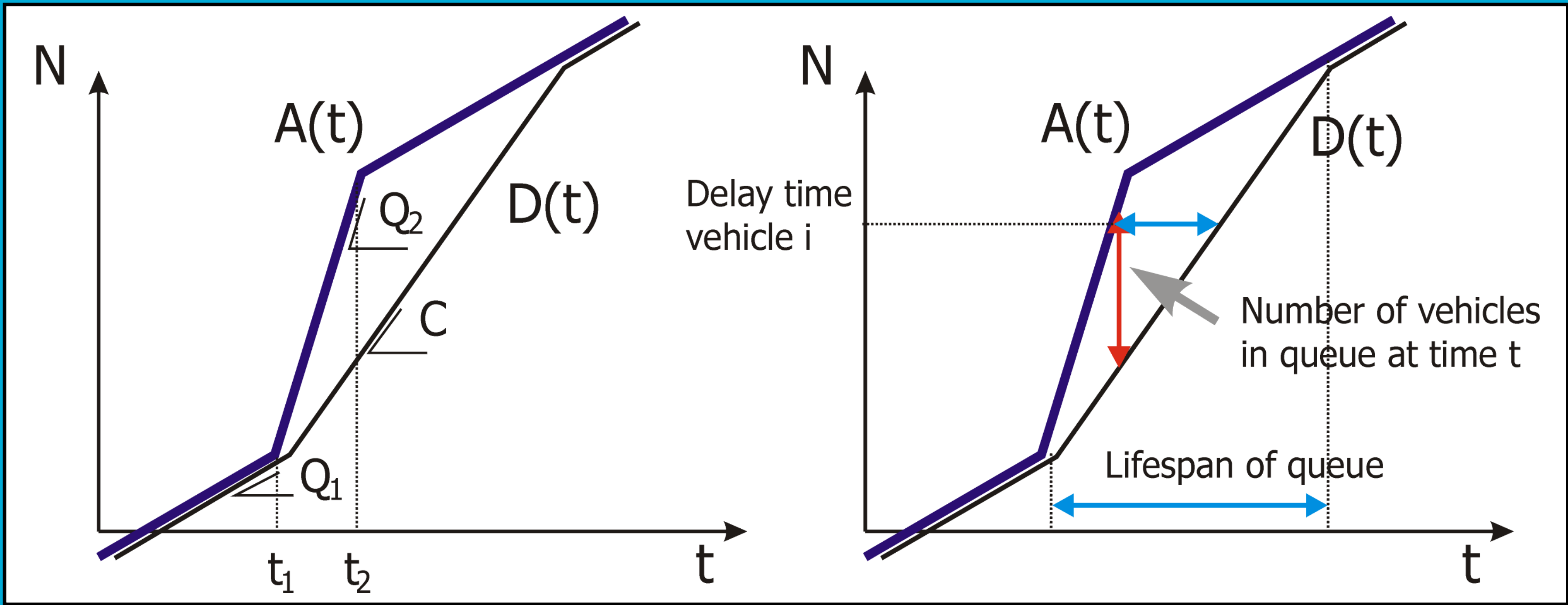
Queuing models (4)

- Modeling with vertical queues



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Computations queuing model

- Maximum length of the queue
  - From graph: occurs at t_2
  - Number of vehicles in the queue at t_2

$$\text{Max} = A(t_2) - D(t_2) = \int_{t_1}^{t_2} (Q_2 - C)\,dt = (t_2 - t_1) \times (Q_2 - C)$$

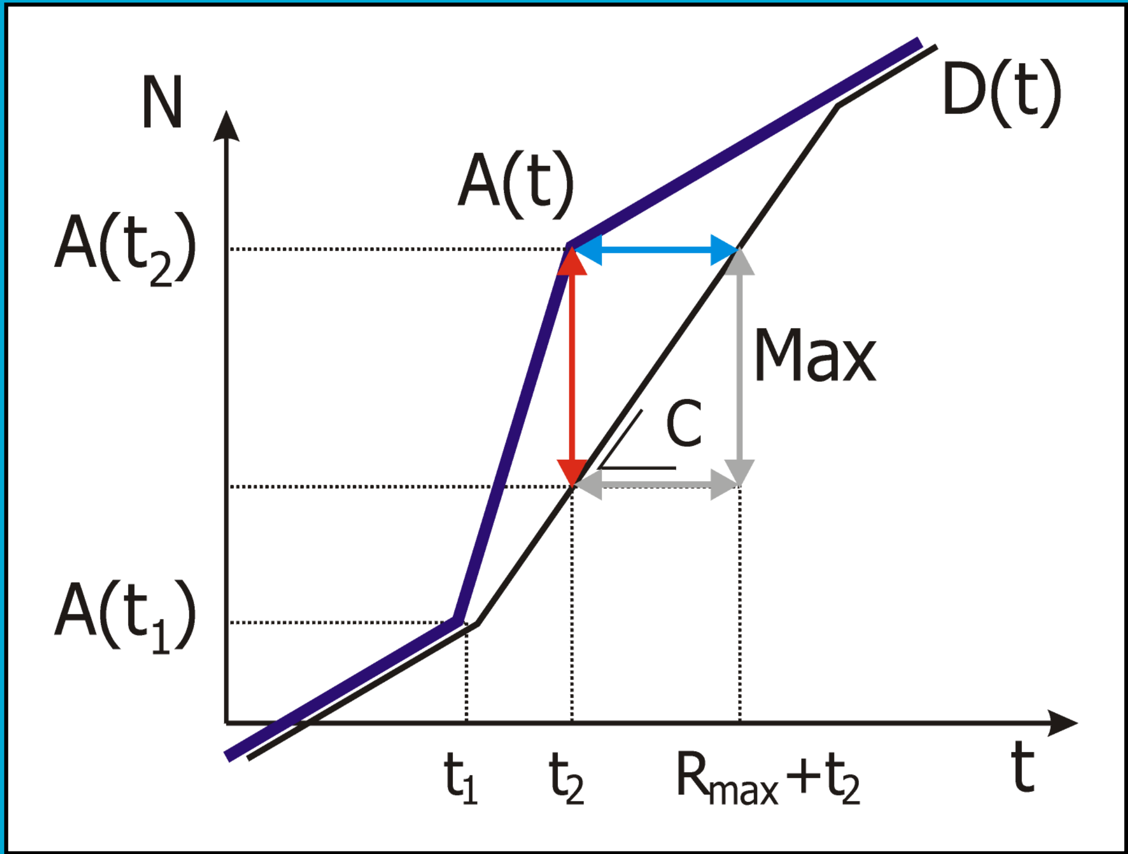
  - Maximum delay (at time t_2)

$$D^{-1}[A(t_2)] - A^{-1}[A(t_2)] = D^{-1}[A(t_2)] - t_2$$

From figure:

$$C \cdot R_{max} = \text{Max} \quad \rightarrow \quad R_{max} = \frac{\text{Max}}{C} = (t_2 - t_1) \cdot \left(\frac{Q_2 - C}{C} \right)$$

Computations queuing model (2)



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Computations queuing model (3)

- Duration of congestion
- Intersection of arrival and departure curve

$$A(t) = A(t_2) + Q_1(t - t_2) \quad \text{for} \quad t > t_2$$

$$D(t) = A(t_1) + C \cdot (t - t_1) \quad \text{for} \quad t > t_1$$

yields:

$$A(t_2) + Q_1(T - t_2) = A(t_1) + C \cdot (T - t_1)$$

$$\Leftrightarrow$$

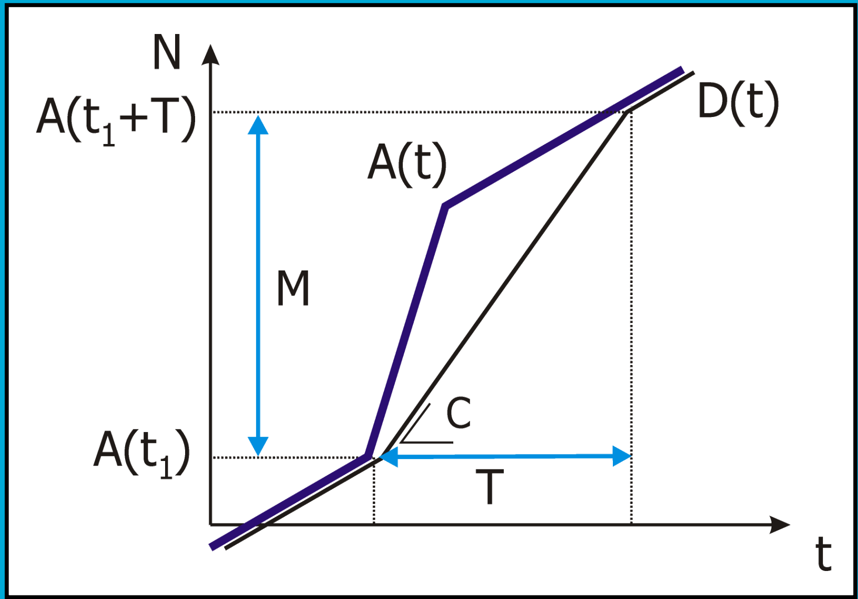
$$T = \frac{A(t_2) - A(t_1) + Ct_1 - Q_1 t_2}{C - Q_1} = \frac{(t_2 - t_1)Q_2 + Ct_1 - Q_1 t_2}{C - Q_1}$$

Computations queuing model (4)

- Total number of vehicles that have been in the queue

$$M = C \times T$$

$$= C \times \frac{(Q_2 - Q_1)t_2 - (Q_2 - C)t_1}{C - Q_1}$$



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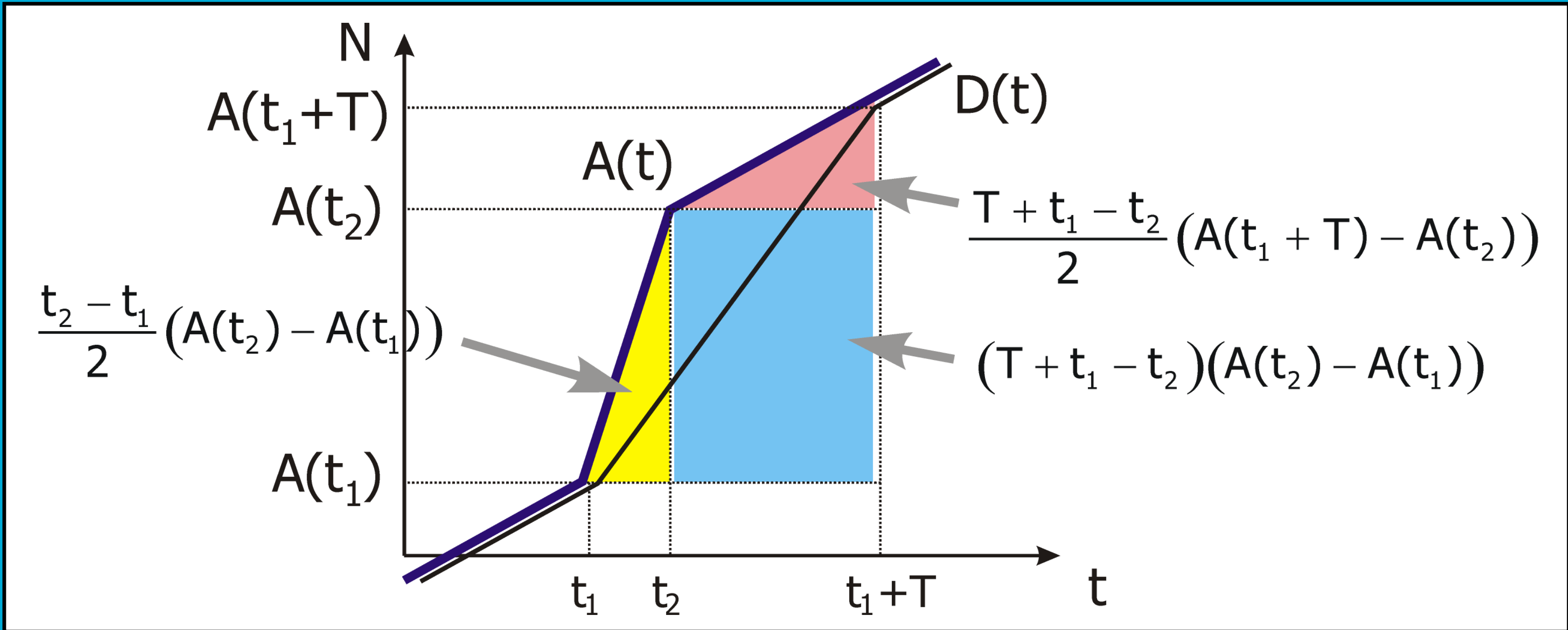
Computations queuing model (5)

- Total collective loss



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Computations queuing model (6)

- Total collective loss
- Sum of three areas

$$\tfrac{1}{2}(T-(t_2-t_1))C\cdot T+\tfrac{1}{2}T(Q_2(t_2-t_1))$$

- Subtract fourth area $-\tfrac{1}{2}C\cdot T\cdot T$
  yields total collective loss

$$R=\frac{t_2-t_1}{2}(Q_2-C)T=\frac{Max}{2}T \qquad R=\frac{Max}{2}T=\frac{Max}{2}\frac{M}{C}=\frac{M}{2}R_{max}$$

- Mean loss time $R_{mean}=\frac{R}{M}=\frac{1}{2}R_{max}$

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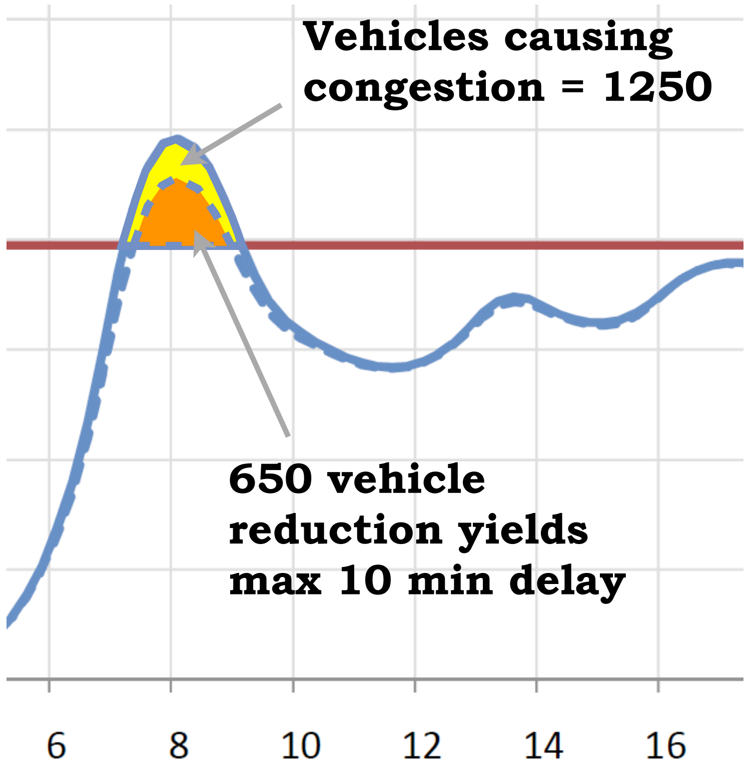
Congestion costs

An impact of demand reduction in Morning Peak (MP)

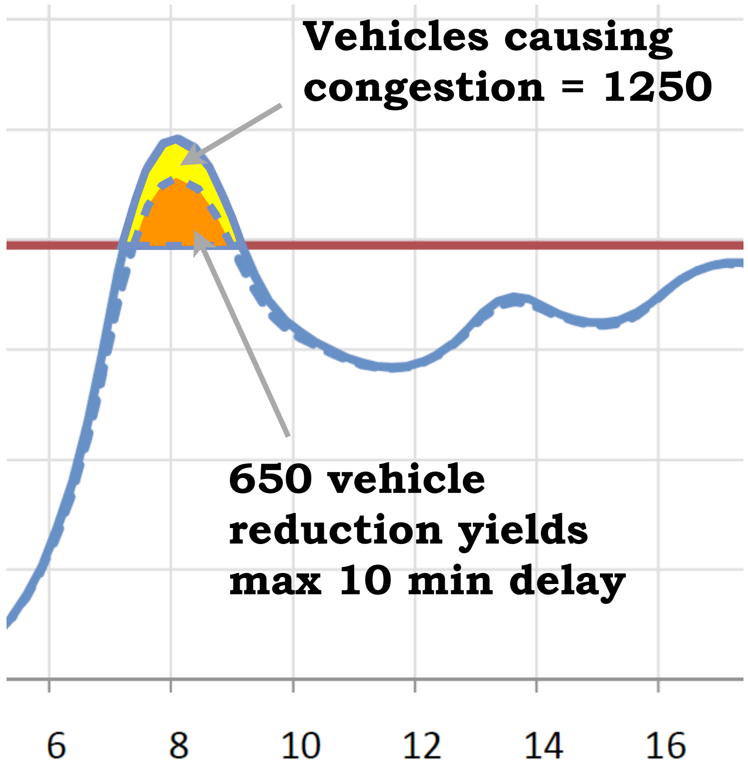
- Congestion characteristics can be easily computed (queue duration, maximum delay, total delays), showing that this is sizable bottleneck!
- How many vehicles to remove to:
  - get rid of all congestion
  - ensure 10 min maximum delay (so-called x-factor)



Congestion costs

An impact of demand reduction in Morning Peak (MP)

- Getting rid of 650 veh during MP (=4% of total demand) reduces vehicle loss hours by 1610 hour (i.e. saves 25,450 Euro/day)
- Getting rid of 1250 veh during MP (=8% of total demand) reduces vehicle loss hours to 0
- Same applies to relative increases in bottleneck capacity
- Improvements in the TM range!



QUAST model

- Congestion variability
- Stochastic version of vertical queuing model:
  - Stochastic capacity
  - Stochastic demand
- See reader for details and Dutch application to Level-Of-Service computations

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