Fundamentals of Traffic Operations and Control

Jack Haddad

Jack.haddad@epfl.ch

(based on Nikolas Geroliminis’ slides)
Course Information

**Format:** 2 hrs of lecture per week + 1 hour of exercise or laboratory per week

**Instructor in Charge:** Jack Haddad
- Office: GC C2 383, Phone: [021 69] 32481

**Grading**
- Exercises 0% Labs (2) 30%
- Mid-term 30% Final Exam 40%

**Textbook**
- Lecture notes, book chapters and handouts will be distributed throughout the semester, or posted on web.

**The team**
- Claudia Bongiovanni, Isik Sirmatel, Anouk Allenspach, Jose Rodriguez Camino, Reza Saeedmanesh, Tasos Kouvelas, Mor Kaspi
Educational Goals

• High level of technical expertise to succeed in positions in transportation engineering practice/research in CH and worldwide

• Produce engineering designs that are based on sound principles and consider functionality, safety, cost effectiveness and sustainability

• Fundamental knowledge to pursue life long learning such as graduate work
Course Objectives

• Introduce the major elements of transportation and create awareness of the broader context
• Develop basic skills in applying the fundamentals of the transportation field
• Be prepared for further study in this field
Transportation Infrastructure

• Critical Components of Transportation Infrastructure System
  • Drivers
  • Vehicles
  • Roads and highways
    Freeway system
    Rural highway system
    Arterial and street systems
  • General environment Traffic control devices ITS infrastructures

• Need tools to design, evaluate, and operate such complex systems.
Course description

• **Transportation Data Analysis and Performance evaluation**
  Observation, Measurement, Stochastic Processes, Estimation methods;. Performance quality, Estimation of queue lengths, travel times, Estimation of emissions

• **Traffic Modeling**
  How congestion changes over time and space at different levels of scale. Micro- (Car following), Meso- (Cell Transmission Model), Macro- (city level)

• **Control of Traffic Signals**
  Schemes to affect traffic stream properties in some desirable way(s). Technology, Adaptive control, Coordination, Ramp metering

• **Intro to Logistics and Scheduled transportation systems**
  Basic principles in operating fleets, Allocation of urban space, Instabilities, Intro to Travel Salesman Problem and Vehicle Routing Problem.
Lecture 1 - Traffic Stream Characteristics (Revisions) - System Monitoring and ITS
## Data analysis

![Graph showing data analysis](image)

### Table

<table>
<thead>
<tr>
<th>Date</th>
<th>5 min</th>
<th>L1 Flow (Vh/5 min)</th>
<th>L1 Occ</th>
<th>L2 Flow (Vh/5 min)</th>
<th>Flow (Vh/5 min)</th>
<th>Occ</th>
<th># Lane Points</th>
<th>% Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/10/2007</td>
<td>0:00</td>
<td>24</td>
<td>0.0154</td>
<td>33</td>
<td>95</td>
<td>0.0178</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>0:05</td>
<td>27</td>
<td>0.0193</td>
<td>47</td>
<td>124</td>
<td>0.0223</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>0:10</td>
<td>25</td>
<td>0.0159</td>
<td>43</td>
<td>121</td>
<td>0.0206</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>0:15</td>
<td>27</td>
<td>0.0188</td>
<td>51</td>
<td>126</td>
<td>0.0228</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>0:20</td>
<td>15</td>
<td>0.0103</td>
<td>43</td>
<td>109</td>
<td>0.0215</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>1:30</td>
<td>16</td>
<td>0.0103</td>
<td>34</td>
<td>87</td>
<td>0.0153</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>1:35</td>
<td>20</td>
<td>0.0128</td>
<td>38</td>
<td>101</td>
<td>0.0187</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>11/10/2007</td>
<td>1:40</td>
<td>10</td>
<td>0.0061</td>
<td>27</td>
<td>77</td>
<td>0.0137</td>
<td>4</td>
<td>100</td>
</tr>
</tbody>
</table>
Different scales of traffic modeling
Macroscopic and control flow models provide the basis for the route choice. Microscopic models describe individual “driver-vehicle particles” locally aggregated. Hence, they are sometimes called car-following models. Hydrodynamic models including typical model equations describe traffic flow analogously to liquids or gases in motion. Traffic flow modeling and transportation planning are intertwined in these applications: Traffic states such as the traffic density and most collective phenomena are updated over smaller time intervals. They can be distributed via traffic message channel, variable-message signs, or serve as input for connected navigation devices.

Macroscopic models are useful, as the evolution of congested regions or the propagation velocity of traffic waves. Multiple real-time speed and the capability to incorporate heterogeneous data sources are particularly important for traffic state estimations if the available input data come from heterogeneous sources and/or are inconsistent. If effects that are difficult to describe macroscopically need not to be considered, the future traffic state is predicted over a time horizon, so data fusion is necessary. If one is interested in macroscopic quantities, only, traffic state estimations and the predictions are processed such that the aggregation is local, these collectively form the traffic field, and the dynamic variables are generally vary across space and time, i.e., they correspond to dynamic fields. Thus, macroscopic models are able to describe traffic flow analogously to liquids or gases in motion.

Optimal Perimeter Control Synthesis for Two Urban Regions with Boundary Queue Dynamics

Comparison of various model categories (with respect to the way they represent reality)
Intro to Traffic Management

- Traffic Signal Control
- Urban Space Allocation
- Parking
- Bus Priority

Transport for London Congestion charging guide:
Mon - Fri
7 am - 6 pm
Traffic management and control: challenges in urban transport

Transport Demand Management shall

- reduce the total volume of traffic
- promote shifts towards more sustainable modes of transport

with the objectives to

- reduce traffic congestion
- reduce adverse effects on the environment or public health
- generate additional revenue to improve public transport and NMT by pricing mechanisms

- Urban areas require proper road networks
- New roads attract more traffic and reduce the viability of public transport
- Transport benefits will be offset by future congestion
Transportation systems management

Traffic Control
- Ramp metering
- Optimal timing design for signal lights
- Coordination of signalized intersections

Design of Facilities
- Road-geometric design (lane addition, removing bottlenecks)
- Improvement in car technologies
Demand management

**Demand reallocation**
Flexible work hours and telecommuting, Different work schedule, Vehicle use restrictions

**Decreasing demand**
work from home, decrease of week workload, change home place, change land use

**Demand “compression”**
car pooling, minibus, transit

**Pricing**
Road/Congestion pricing, Parking policies
Performance evaluation
Scheduled Transportation Systems

Vietnam
Design of logistics systems

- Sorting
- Storage
- Handling

• Vehicle Routing Problem
  • One-to-Many
  • Many-to-Many

inbound

outbound
REVIEW OF TSE Class

• Traffic Stream Characteristics
• See Notes (Please review and come back with questions next week)
Trajectories with moving stop-and-go waves on a British motorway segment and on the California State Route 99.
Urban Streets: Vehicle Trajectories
Headway and Spacing Definitions
Flow definition
Density Definition
Flow = density *+/- speed
Group of vehicles
Methods of Observation
Construction of the \((t, x)\) diagram from data

(a) Roadside observers at various locations.
(b) aerial photographs at different instants.
(c) moving observers.
# Methods of Observation

<table>
<thead>
<tr>
<th>Method of Observation</th>
<th>Aerial Photograph</th>
<th>Stationary Observer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( n/L )</td>
<td>( \frac{1}{T} \sum_{i=1}^{m} \frac{1}{v_i} )</td>
</tr>
<tr>
<td>Flow</td>
<td>( \frac{1}{L} \sum_{i=1}^{n} u_i )</td>
<td>( m/T )</td>
</tr>
<tr>
<td>Space-mean speed</td>
<td>( \frac{1}{n} \sum_{i=1}^{n} u_i )</td>
<td>( \left( \frac{1}{m} \sum_{i=1}^{m} \frac{1}{v_i} \right)^{-1} )</td>
</tr>
<tr>
<td>Time-mean speed</td>
<td>( \frac{\sum_{i=1}^{n} u_i^2}{\sum_{i=1}^{n} u_i} )</td>
<td>( \frac{1}{m} \sum_{i=1}^{m} v_i )</td>
</tr>
</tbody>
</table>
TMS \( (v_t) \) and SMS \( (v_s) \)

Example to demonstrate differences between speeds

**Space mean speed:**

\[
\bar{u}_s = \frac{120 + 140 + 100}{3} = 120 \text{[km/h]}
\]

**Time mean speed:**

during one hour:
- vehicle travels at 100 (km/h) completes 50 laps
- vehicle travels at 120 (km/h) completes 60 laps
- vehicle travels at 140 (km/h) completes 70 laps

\[
\bar{u}_t = \frac{50(100) + 60(120) + 70(140)}{180} = 122 \text{[km/h]}
\]
Characteristics of $v, k, q$

- A: almost zero density, free-flow speed, very low volume
- B: increased density, reduced speed, increased volume
- C: increased density, reduced speed, max volume
- D: jam density, min speed (crawling), very low volume
Some other data
A triangular FD

- However, these diagrams are not very realistic. Researchers now know that the flow-density relation is better described by a triangle than by a parabola.

- The following graph shows the Fundamental Diagram as we use it today. It contains enough information to find any of the 5 descriptors, if one is given $k$. 

![Diagram of a triangular Fundamental Diagram](image)
Input-Output Diagrams

- $Q(0) =$ number of customers in queue at time $0$
- $Q(t) =$ number of customers in queue at time $t$
- $A_n =$ time of arrival of the $n^{th}$ customer
- $D_n =$ time of departure of the $n^{th}$ customer
Input-Output vs. Time-Space
I-O curves (Example of a traffic signal)
Kinematic wave theory (Example 1)
Traffic signal example
Kinematic wave theory (Example 2)
Generalized definitions of $q$ and $k$

\[ Q = \frac{d(A)}{|A|} = \frac{VKT}{Area} \]

\[ K = \frac{t(A)}{|A|} = \frac{VHT}{Area} \]

\[ V_{SMS} = \frac{d(A)}{t(A)} = \frac{VKT}{VHT} \]
Traffic Studies & Data Collection System Monitoring and ITS
Traffic Studies

- A traffic engineer’s laboratory is the surrounding roadway system
- This system must be continually monitored, evaluated, and managed
Guiding Principles

- “If you cannot tell the system performance yesterday, you cannot hope to manage your system today.”
  -- Data Collection/Analysis

- “Data are too valuable to only use once.”
  -- Data Archive
  -- Real Time and Historical
Reasons for Traffic Studies

- Inventories
  -- Street or highway links
  -- Intersections
- Operational Parameters
  -- Volume studies
  -- Speed Studies
  -- Travel-time studies
  -- Delay Studies
  -- headway and spacing studies
- Special purpose studies
  -- Accident Studies
  -- parking studies
  -- Pedestrian studies
Traffic Studies

- Traffic demand/patterns will change over time, monitoring of system will enable necessary system changes to be identified.
- The effects of system “improvements” must be justified, e.g.,
  - Signal timing changes
  - Lane additions or reconfigurations
Traffic Studies

- Data collection is the key foundation
  - What kind of data?
  - How much data?
  - How to collect it?

- The study characteristics must be considered in answering these questions, e.g.,
  - Short-term or long-term study
  - Statistical confidence level
Temporal Variation

- Monthly (Jan. – Dec.)
- Daily (Sun. – Mon.)
- Hourly (12:00 AM – 11:59 PM)
- K values (e.g., $K_{100}$, $K_{30}$)
  - The ratio of the $X^{th}$ highest traffic volume hour of the year to the AADT
  - Historically, 30$^{th}$ has been used in rural planning, design and operations. (generally flatten out from this point)
Graphic Summary of Vehicle Movements

<table>
<thead>
<tr>
<th></th>
<th>E / W</th>
<th>N / S</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Street</td>
<td>1501</td>
<td>4772</td>
<td>6273</td>
</tr>
</tbody>
</table>

Total Entering Intersection

N = North
E = East
W = West
S = South
Traffic Counts Displayed in a Network
Types of Traffic Volume

- Average Annual Daily Traffic (AADT)
- Average Annual Weekday Traffic (AAWT)
- Average Daily Traffic (ADT)
- Peak Hour Volumes (PHV)
- Vehicle Classification (VC)
- Vehicle Miles Travel (VMT)
Peak Hour Volume (PHV)

- The max # veh passing a point on a highway over 60 consecutive minutes

Peak Hour Factor (PHF)

\[
\text{PHF} = \frac{\text{PHV}}{4 \times \text{highest 15min volume}}
\]

(0.25<PHF<1)

- Mainly used for urban:
  - Highway design (e.g., highway classification, # of lanes, signalization, etc.)
  - Traffic management (e.g., capacity analysis, parking, etc.)
Vehicle Classification (VC)

- Volume with respect to vehicle type
  - Passenger cars
  - 2 axle trucks
  - 3 axle trucks
  - Public service vehicle (PSV)
  - Emergency vehicle
  - 2 wheel vehicles

- Applications
  - Geometric design (e.g., turning radii, max. grade, lane width)
  - Capacity Analysis (e.g., PCU conversions)
  - Automated counts
  - Pavement & Structure design
Vehicle Mile Travel (VMT)

- ADT x roadway length

Applications:
- Economic evaluation
- Resource allocation (maintenance & improvement)
- Planning
Small Network Volume Study

- Amount and spatial pattern of traffic flow over a small network (e.g., CBD, airports, stadiums, etc.)
- Provide valuable information for traffic planning and control (e.g., parking requirements, special events, etc.)
- Control counts
  - Monitor volume variation patterns in the network
  - Counts are taken for the entire period
- Coverage counts
  - Locations of coverage counts
  - Counts are taken for some periods
- See board
Example (Table 6-3)

(a) Data from a one-day study

<table>
<thead>
<tr>
<th>Time (pm)</th>
<th>Count (vph)</th>
<th>Coverage Station</th>
<th>Time of Count (vph)</th>
<th>Observed Count (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-1</td>
<td>825</td>
<td>1</td>
<td>12-1</td>
<td>840</td>
</tr>
<tr>
<td>1-2</td>
<td>811</td>
<td>2</td>
<td>1-2</td>
<td>625</td>
</tr>
<tr>
<td>2-3</td>
<td>912</td>
<td>3</td>
<td>2-3</td>
<td>600</td>
</tr>
<tr>
<td>3-4</td>
<td>975</td>
<td>4</td>
<td>3-4</td>
<td>390</td>
</tr>
<tr>
<td>4-5</td>
<td>1056</td>
<td>5</td>
<td>4-5</td>
<td>1215</td>
</tr>
<tr>
<td>5-6</td>
<td>1153</td>
<td>6</td>
<td>5-6</td>
<td>1440</td>
</tr>
</tbody>
</table>

(b) Computation of hourly volume proportions from control-count data

<table>
<thead>
<tr>
<th>Time</th>
<th>Count</th>
<th>Proportion of 8-hour total</th>
<th>=825/7057</th>
<th>Largest value</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-1</td>
<td>825</td>
<td>0.117</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>1-2</td>
<td>811</td>
<td>0.115</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>2-3</td>
<td>912</td>
<td>0.129</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>3-4</td>
<td>975</td>
<td>0.138</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>4-5</td>
<td>1046</td>
<td>0.148</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>5-6</td>
<td>1153</td>
<td>0.163</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>6-7</td>
<td>938</td>
<td>0.133</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>7-8</td>
<td>397</td>
<td>0.056</td>
<td>825/7057</td>
<td>0.163</td>
</tr>
<tr>
<td>Total</td>
<td>7057</td>
<td>1</td>
<td></td>
<td>0.163</td>
</tr>
</tbody>
</table>
Example (Table 6-3)

<table>
<thead>
<tr>
<th>Location</th>
<th>Time</th>
<th>Count</th>
<th>8-hr Vol (est)</th>
<th>Peak-hr Vol (est)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12-1</td>
<td>840</td>
<td>7185</td>
<td>1174</td>
</tr>
<tr>
<td>2</td>
<td>1-2</td>
<td>625</td>
<td>5439</td>
<td>889</td>
</tr>
<tr>
<td>3</td>
<td>2-3</td>
<td>600</td>
<td>4643</td>
<td>759</td>
</tr>
<tr>
<td>4</td>
<td>4-5</td>
<td>390</td>
<td>2631</td>
<td>430</td>
</tr>
<tr>
<td>5</td>
<td>5-6</td>
<td>1215</td>
<td>7436</td>
<td>1215</td>
</tr>
<tr>
<td>6</td>
<td>6-7</td>
<td>1440</td>
<td>10834</td>
<td>1770</td>
</tr>
</tbody>
</table>

\[=840/0.117 \text{ (from (b))} \]

\[=7185 \times 0.163 \text{ (from (b))} \]
Measurement methods

- measurements at a (cross-sectional) point
- measurements along a short distance
- measurements along a length
- measurements along an arterial or small area (by e.g. moving observer method)
- other realtime large-scale monitoring methods
Measuring means

Measuring passage times, time headways, and flow

- manual counting, using a form and a stopwatch. Advantage: simple method; Disadvantage: labour costs and inaccuracies.
- Pneumatic tubes. Advantage: can accurately determine passage times and time headways; Disadvantage: relatively short time survival.
- Induction loops.
- Infrared detector.
- Instrumented vehicles (moving observer method).

Individual speeds, instantaneous, and local mean speed

- Radar speedometers at a cross-section.
- Induction loops or double pneumatic tubes.
- vehicle recognition.
- Probe vehicles.
- Remote-sensing techniques.
“Manual” counting

Manual Count Board

JAMAR Handheld Devices
Pneumatic tube
Inductance Loops

Vehicle Loops

Bike Loops
A single-loop detector can directly measure (only):

- The time \( t_{\alpha}^0 \) at which the front of vehicle \( \alpha \) passes the detector (voltage drop),
- The time \( t_{\alpha}^1 \) at which the rear end of the vehicle passes the detector (voltage rise)
From these directly measured quantities:

- **Length of each vehicle** $\alpha$: $l_\alpha = v_\alpha \cdot (t_{1\alpha} - t_{0\alpha})$
- vehicle type
- **headways**: $\Delta t_\alpha = t_{0\alpha} - t_{0\alpha-1}$
- **distances**: $d_\alpha = v_{\alpha-1} \cdot \Delta t_{\alpha}$
Inductance Loop Signatures (1)

Sport Car

Truck
Inductance Loop Signatures (2)

Pickup Truck

Trash Truck
Inductance Loop Signatures (3)

Tailgating vehicles

Vehicle with a boat
Video sensors
Infra-red sensors
Laser guns
Travel times

- Comparable for different traffic modes
- easy to be used in traffic models
- can be perceived easily

measurement sensors
- Vehicle Plate Recognition
- GPS receivers
- Cellular antenas
Vehicle Plate Recognition
Global Positioning System (GPS)

- GPS Time
- Latitude and Longitude
- Speed

Typical GPS Data

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:27:39</td>
<td>30.389885</td>
<td>-91.242426</td>
<td>40.0</td>
</tr>
<tr>
<td>16:27:40</td>
<td>30.390090</td>
<td>-91.242276</td>
<td>40.6</td>
</tr>
<tr>
<td>16:27:41</td>
<td>30.390159</td>
<td>-91.242225</td>
<td>40.7</td>
</tr>
<tr>
<td>16:27:42</td>
<td>30.390298</td>
<td>-91.242122</td>
<td>41.0</td>
</tr>
<tr>
<td>16:27:43</td>
<td>30.390507</td>
<td>-91.241966</td>
<td>41.8</td>
</tr>
</tbody>
</table>
Cellular antennas
Bluetooth sensors
Speed Data Collection

- Radar gun
- Inductance loop detectors
  - Single loop
  - Double loop
- Video imaging
Density

- Aerial photographs
- Volume / Speed
- Surrogate measure from inductance loop detectors
  - Ratio of occupied time to total observation time, expressed as a percent, is termed ‘lane occupancy’, denoted by $\phi$ (phi)
  \[
  \phi = \frac{\text{total occupied time}}{\text{total observation time}} \times 100
  \]
  - To use lane occupancy for estimation of density, we must know vehicle length, then density can be estimated by
  \[
  k = \frac{\phi}{100} \times \frac{5280}{L_e}
  \]
  $L_e$ is the effective vehicle length
Travel Time

Travel time is a popular performance measure, for several reasons:

- Can compare across different modes (e.g., bus, train, car)
- Easy to work with mathematically/statistically
- Easy to understand by traveling public
Travel Time Measurement Techniques

- Floating Car
- License plate matching
- Automatic Vehicle Location (AVL)
  - Global Positioning Systems (GPS)
  - Cellular Phones
- Automatic Vehicle Identification (AVI)
Floating Car

- Driving a vehicle in the traffic stream, trying to maintain an “average” position in the traffic stream, i.e., passing only as many vehicles as pass you
Electronic Toll Collection (AVI)
Origin-Destination (O-D) Studies

- Determining the percentage of all traffic traveling from each origin point of interest to each destination point of interest

![Diagram of O-D studies with labels for internal-internal, internal-external, external-internal, external-external, and cordon line (boundary of study area).]
O-D Measurement Techniques

- Roadside Interview
- Postcards
- License Plate Matching
- Vehicle Re-Identification Technology
## Sensor Types, Data, and Example Sensors

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th><strong>Point Data:</strong> Loop and Loop Emulators</th>
<th><strong>Point to Point:</strong> Toll Transponders and AVI</th>
<th><strong>Wireless:</strong> Cellular Phone Signatures and Beacons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notation</td>
<td><img src="image" alt="l" /></td>
<td><img src="image" alt="t" /></td>
<td><img src="image" alt="w" /></td>
</tr>
<tr>
<td>Data</td>
<td><strong>At fixed points</strong></td>
<td><strong>Between fixed points</strong></td>
<td><strong>Within range of reader</strong></td>
</tr>
<tr>
<td></td>
<td>1. Flows (Volumes)</td>
<td>1. Travel times</td>
<td>(a) Travel times</td>
</tr>
<tr>
<td></td>
<td>2. Occupancies</td>
<td>2. Lane changes</td>
<td>(b) Space mean speed</td>
</tr>
<tr>
<td></td>
<td>3. Time mean speed</td>
<td></td>
<td>(c) Many vehicles exhibit activity changes</td>
</tr>
<tr>
<td>Sensors</td>
<td>• Inductive loops</td>
<td>• Electronic toll and traffic management transponders</td>
<td>• Cellular phone positioning systems:</td>
</tr>
<tr>
<td></td>
<td>• Infrared</td>
<td>• Commercial AVI systems</td>
<td>1. Vehicle beacons (as for driver info systems)</td>
</tr>
<tr>
<td></td>
<td>• Video image processors</td>
<td></td>
<td>2. GPS probes</td>
</tr>
<tr>
<td></td>
<td>• Microwave radar</td>
<td>• Pattern matching</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Acoustic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data Fusion

- the process of combining data from multiple, heterogeneous data sources such as cross-sectional data, floating-car data, police reports, etc.
- each of these categories of data describes different aspects of the traffic situation and might even contradict each other.
- the goal of data fusion is to maximize the utility of the available information.

Data: Autobahn A5 near Frankfurt/Main, Germany (south-bound, recorded May 28, 2001).

- Figure 5.1: Color-coded visualization of the speed measured by stationary detectors and the speed field reconstructed by the adaptive smoothing method (Sect. 5.2). The data are from a section of the Autobahn A5 near Frankfurt/Main, Germany (south-bound, recorded May 28, 2001). The "active" bottlenecks causing congestions are the on-ramps of two highway junctions, and an accident at location 478 km restricting the local capacity at this location between 10:00 and 11:30 am.

- Figure 5.2: Spatiotemporal interpolation as a way of reconstructing the traffic state at location \( x \) and time \( t \) using the isotropic weighting kernel (5.2). Data: Autobahn A5 near Frankfurt/Main, Germany (south-bound, recorded May 28, 2001).

- Figure 5.8: Influence of parameter variations when applying the adaptive smoothing method on the detector data of Fig. 5.3.

- Figure 5.9: Example of heterogeneous data sources: cross-sectional detectors and floating-car data.

- Data Fusion: the process of combining data from multiple, heterogeneous data sources such as cross-sectional data, floating-car data, police reports, etc.

- each of these categories of data describes different aspects of the traffic situation and might even contradict each other.

- the goal of data fusion is to maximize the utility of the available information.
5.3 Data Fusion

Another example of diverse data sources used in the spatiotemporal reconstruction of the traffic state. The horizontal dotted lines represent two stationary detectors at locations $x_1$ and $x_2$, which send data every minute (green circles: free traffic, yellow: dense traffic, red: traffic jam). Three floating cars cross the road segment in question and also send data, though not in fixed intervals but event-based. A camera on a bridge at location $x_3$ reports trajectory data over a small road segment (black curves). An accident was reported via cell phone (call 1) but the caller was only able to give the approximate location (vertical orange line). Caller 2 was standing on a bridge and observed free traffic over some period of time. Caller 3 reported standing in a traffic jam at time 2:55 p.m. and location 435.5 km. Finally, a helicopter (flying against the driving direction) observed free traffic.

5.3.1 Model-Based Validation of a Data Fusion Procedure

The adaptive smoothing method introduced in Sect. 5.2 can be used as an algorithm for data fusion if all data sources provide spatiotemporally resolved point measurements of the local speed, i.e., data sets $\{x_i, t_i, v_i\}$. This includes stationary detector data (SDD) and floating-car data (FCD). To test and validate this application of the adaptive smoothing method, one needs congested traffic situations where (i) SDD, (ii) FCD, (iii) a sufficient approximation to the ground truth are available. To date, such test cases are rarely available. We therefore demonstrate how to validate data-fusion procedures based on models and simulations. For this purpose, we simulate traffic waves with a model of human drivers that can reproduce the waves realistically (Fig. 5.12, see Chap. 12 for a model description). As input for the adaptive smoothing method, we generate virtual SDD and FCD from the simulation (Fig. 5.11) and apply the method with the standard parameters. The prediction quality of the method is assessed by comparing the reconstructed speed fields shown in Fig. 5.12 b–d with the reference of Fig. 5.12 a. It becomes evident that both data sources contribute to the reconstruction.
(a) Ground truth
(b) Stationary detector data (SDD)
(c) Floating car data (FCD)
(d) SDD + FCD
(taken from "Traffic Flow Dynamics" book, springer 2013)