INTELLIGENT TRANSPORTATION SYSTEMS

Lecture 7:
Traffic Flow Modelling

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Why traffic flow modeling?

Population growth & Economic growth → Mobility demand growth
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Population growth & Economic growth  ➔ Mobility demand growth

What Strategies?
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Population growth & Economic growth  ➔  Mobility demand growth

What Strategies?

- Encouraging people to
  - shift to sustainable transport modes
  - use different routes
  - commute at different hours
- Optimizing road network
- Expanding road network
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For traffic management, it is needed to know

- how traffic flow will actually look
- where and when will there be congestion,
- what are the bottlenecks, and
- where is the road capacity already sufficient?
Traffic flow modelling cycle

To describe and predict traffic, real-world observations are used to build theories, models and discretized models of traffic flow. By doing simulations based on these models, the performance of roads or traffic networks can be assessed.
Applications of traffic flow models

- State estimation & short-term predictions to inform travelers.
- State estimation & short-term predictions for traffic management.
- Decision support for (semi-)autonomous vehicles.
- Long-term assessment of development plans, e.g. the (re)design of a transportation network.
- Assessment of the impact of traffic on safety and emissions.
- Design of evacuation plans.
A Useful model

- The model only has a few parameters.
- Parameters are (easily) observable and have realistic values.
- Not require more input data than what is available for calibration.
- Relevant phenomena are reproduced and predicted by the model.
- Captures the most important characteristics of the underlying system.
- The model allows fast computations for state estimation or prediction.
- Not require more time and memory than what available hardware permit.
A historical example

Relation between spacing and speed?
A simple example is the observations by Greenshields of vehicles passing his camera in the 1930s.
Plotting the distance between the vehicles (spacing) and their change in position in consecutive photographs leads to a theory that spacing and speed are related. Subsequently, this leads to a model with a linear relationship between spacing and speed.

Fig. 1.2 Greenshields making field observations and turning this into a simple traffic flow model. Pictures reproduced with permission from Greenshields (1934). (a) Making field observations. (b) Resulting photographs. (c) Plotting data: speed against spacing. (d) Determining a linear relationship between spacing and speed.
A **model** is a set of mathematical equations that tries to describe (or replicate) a physical process (ex. evolution of traffic congestion over time and space).

“**All models are wrong, but some are useful.**”

George Box

General pattern: start with a model which is simple, transparent, insightful... and also wrong. This simple model can then be improved in ways to make it more correct and useful.
Transportation Elements

Road Network  Traffic Flow  Signaling
Networks are a type of mathematical model which are very frequently used in the study of transportation: Static or Dynamic.

A network consists of links and nodes.

- A link usually represents a means of travel from one point to another: a road segment between two intersections, a bus route between two stops, and so on.
- The nodes are the endpoints of the links.

<table>
<thead>
<tr>
<th>Network type</th>
<th>Nodes</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roadway</td>
<td>Intersections</td>
<td>Street segments</td>
</tr>
<tr>
<td>Public transit</td>
<td>Bus or train stops</td>
<td>Route segments</td>
</tr>
<tr>
<td>Freight</td>
<td>Factories, warehouses, retailers</td>
<td>Shipping options</td>
</tr>
<tr>
<td>Air</td>
<td>Airports</td>
<td>Flights</td>
</tr>
<tr>
<td>Maritime</td>
<td>Ports</td>
<td>Shipping channels</td>
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</tbody>
</table>
Elements of Flow (demand)

Travels cause by people who need to perform activities at different geographic locations. Therefore highly differentiated by time of the day, day of the week, purpose, type of cargo, importance of duration of traveling, etc.

Demand is traditionally represented by aggregated “origin-destination-matrix” (OD matrix).

![Normalized OD matrix of trips between municipalities of Tartumaa.]

First step for modelling; Observation

1. **Local** (fixed position): a loop detector, camera, or other sensor that observes traffic passing at a certain point along the road.
2. **Instantaneous** (fixed in time): a camera or other sensor that captures the traffic on a longer road stretch at a certain time (e.g. a picture taken from a helicopter).
3. **Trajectory** (moving with vehicle): an in-car device or other sensor that collects data about the position of the vehicle over a certain time period.
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<tr>
<th>Type</th>
<th>Principle data</th>
<th>Derived variables</th>
</tr>
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<tbody>
<tr>
<td>Local</td>
<td>Vehicle counts</td>
<td>Time headways, flows</td>
</tr>
<tr>
<td>Instantaneous</td>
<td>Vehicle positions</td>
<td>Space headways, densities</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Location, time</td>
<td>Trajectories</td>
</tr>
<tr>
<td>Local and instantaneous</td>
<td>Counts at series of positions</td>
<td>Headways, flows, densities</td>
</tr>
</tbody>
</table>
Main model types for traffic flow

Agent-based models intuitively describe the behavior of individual travelers. Based on assumptions on human behavior. The behavior of each vehicle is modeled based on the position, velocity, and acceleration of the leading vehicle.

Continuum models consider traffic as a compressible fluid and replicate its behavior on a macroscopic level through aggregated state variables such as flow and density.

![Diagram showing traffic flow and density models](image)
Classification of Traffic Flow Models

- **Microscopic** (mainly used for simulation)
  - models car-following and lane-changing behavior.
- **Mesoscopic**
  - captures vehicles with similar characteristics in aggregated terms.
- **Macroscopic**
  - similar to fluid mechanics, variables like flow and density are used to describe the state of the network.

The precise relationship between variables such as density, headway, speed, and flow, is an important subarea of traffic flow research.

A simple human behaviour: drivers tend to choose a speed that is as high as possible, while still safe. Therefore, traffic flow models commonly use a decreasing—or at least nonincreasing—relationship between density and speed.

Thus, maximum flow (density × speed) occurs at some intermediate density and speed values.
Water versus Granular flow

**Water**: outflow equals inflow, up to a maximum.
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**Water**: outflow equals inflow, up to a maximum.

**Granular**: at low inflows, outflow equals inflow. When the inflow is too high, particles ‘get stuck’ in bottleneck, and outflow is lower than with a medium inflow.
Macroscopic Traffic Flow Models

Given a road segment, space is discretized ($dx$). We have:

- **density** $\rho(x, t)$: number of vehicles per length unit (veh/km)
- **traffic flow** $q(x, t)$: number of vehicles per time unit (veh/h)
- **mean speed** $v(x, t)$ in km/h

This is a mathematical abstraction inspired by fluid mechanics.

We assume in $dx$ space we have homogeneous conditions for density and speed.
Linear in the density-velocity plane and thus parabolic in the density-flow.

Greenshields fundamental diagram (1934)
**Fundamental Diagram; different models**

**flow = density \times speed**

Linear in the density-velocity plane and thus parabolic in the density-flow.

**Greenshields fundamental diagram (1934)**

Most widespread due to its simplicity. It is bi-linear (triangular) in the density-flow plane.

**Daganzo fundamental diagram (1994)**
Smulders fundamental diagram (1990)

Combination of the previous two: it is parabolic for low densities and linear for high densities.
Fundamental Diagram

Generic model for fundamental diagram.

$$\hat{q}(\hat{\rho}) = b + (a - b)\hat{\rho} - \phi^{-1}(\phi(a\hat{\rho}) + \phi(b(1 - \hat{\rho}))) - \phi(0))$$

If the function $\phi$ is chosen appropriately, then the generic model leads to a realistic and useful fundamental diagram.
Fundamental Diagram

The diagram represents the relationship between flow and density, showing the transition from free flow to capacity and then to congestion. Key points include:

- **Flow (q)** axis:
  - $q_{\text{cap}}$ (capacity flow)
  - $q_*$ (critical flow)

- **Density (ρ)** axis:
  - $\rho_{\text{crit}}$ (critical density)
  - $\rho_*$ (density at $q_*$)
  - $\rho_{\text{jam}}$ (jam density)

- **Flow vs. Density**:
  - Free flow region
  - Capacity region
  - Congestion region

- Key velocities:
  - $v_{\text{max}}$
  - $v_{\text{crit}}$
  - $v(\rho_*)$

This diagram illustrates the fundamental diagram of traffic flow, capturing the essential dynamics of traffic density and flow.
Microscopic Traffic Flow Models

- Based on the assumption that drivers adjust their behavior to the leading vehicle.
- **Car-following** and **lane-changing** behavior are modeled.
- We get the detailed trajectories of vehicles following each other.
- Many software are available for microscopic simulation.


Microscopic Traffic Flow Models: car-following

The earliest car-following models include a car-following rule based on the safe following distance by expressing the position of the leader as a function of the position of its follower.

\[ x_{n-1} = x_n + T v_n + s_{n,\text{jam}} \]

\[ s_{n,\text{jam}} = l_n + d \text{ the minimum rear-to-rear headway.} \]
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Timid drivers would keep a longer distance when the leader decelerates into congestion, while aggressive drivers tend to keep shorter following distances.
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We expect in a rational model:
1. If velocity increases, the vehicle accelerates less.
2. If headway increases, the vehicle accelerates more.
3. If relative velocity increases, the vehicle accelerates more.
Microscopic Traffic Flow Models: lane-changing

- **Mandatory** lane change because of their route choice, e.g. from on-ramp to main road to enter the freeway, from main road to off-ramp to leave the freeway, from one lane to the next because the first lane will end or is blocked.

- **Voluntary** lane change occurs when a driver seeks a speed advantage, this often includes overtaking.

- **Random** lane change (without apparent reason) or forced merging (when a driver creates a gap to enter a congested lane).

Lane-change models consist of three steps:

1. Decide about the necessity of lane change
2. Choose target lane
3. Decide whether to accept gap
Microscopic vs Macroscopic Modeling

- Macroscopic models are **analytical**, not just simulators. We can write down the analytical form of PDEs and use them to develop model-based control strategies.
- **Computation time**: Macroscopic models are much faster than microscopic ones. However, microscopic models contain details.
- We need to think about
  - Required **resolution**
  - Traffic control **measures**
  - Potential **accuracy vs validation** efforts
How do we validate our model?

- Logical and mathematical consistency.
- **Qualitative testing.** Does the model reproduce all the essential phenomena of the process? If I have a traffic network and some bottlenecks that create the congestion, my model should be able to reproduce this congestion and equivalently, my model should have no contradiction with the essential phenomenon of the physical process.
- **Quantitative accuracy.** Estimating the parameters and checking the sensitivity and transferability of the model.
- Computational complexity.
Software for Simulation of Traffic

- SUMO
- TRANSIMS
- PTV VISSIM
- MATSim
- aimsun
"SUMO" for short, is an open-source, microscopic, multi-modal traffic simulation. It allows to simulate how a given traffic demand which consists of single vehicles, moves through a given road network.

SUMO is developed by the German Aerospace Center and community users. It has been freely available as open-source since 2001.