1.225J (ESD 205) Transportation Flow Systems

Lecture 11
Traffic Flow Models, and
Traffic Flow Management in Road Networks

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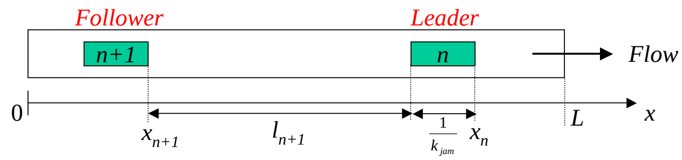
Lecture 11 Outline

- ❑ Overview of some traffic flow models:
  - Modeling of single link: Car-following models
  - Dynamic macroscopic models of highway traffic
- ❑ Dynamic traffic flow management in road networks:
  - Concepts
  - Dynamic traffic assignment
  - Combined dynamic traffic signal control-assignment
- ❑ The ACTS Group

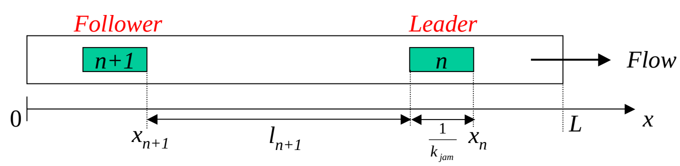
Link Travel Time Models: Car-Following Models

- Notation:



- $x_n(t) - x_{n+1}(t) = \text{spacing (space headway)} = l_{n+1}(t) + \frac{1}{k_{jam}}$
- speed of vehicle n : $\frac{dx_n(t)}{dt} = \dot{x}_n(t)$
- acceleration (deceleration) of vehicle n : $\frac{d\dot{x}_n(t)}{dt} = \frac{d^2 x_n(t)}{dt} = \ddot{x}_n(t)$
- $\dot{x}_n(t) - \dot{x}_{n+1}(t) = \dot{l}_{n+1}(t)$
- car-following regime: $l_{n+1}(t)$ is below a certain threshold

Link Travel Time Models: Car-Following Models



- Simple car-following model:

  $\ddot{x}_{n+1}(t+T) = a\dot{l}_{n+1}(t) = a(\dot{x}_n(t) - \dot{x}_{n+1}(t))$

  T : *reaction time* $(T \approx 1.5 \text{sec})$

  a : *sensitivity factor* $(a \approx 0.37 s^{-1})$

- Questions about this simple car-following model:
  - Is it realistic?
  - Does it have a relationship with macroscopic models?

From Microscopic Models To Macroscopic Models

- Simple car-following model: $\ddot{x}_{n+1}(t) = a(\dot{x}_n(t) - \dot{x}_{n+1}(t))\ \ (T = 0)$
- Fundamental diagram: $q = q_{\max}(1 - \frac{k}{k_{jam}})$
- Proof of "equivalency"

$$\ddot{x}_{n+1}(y) = a(\dot{x}_n(y) - \dot{x}_{n+1}(y))$$

$$\ddot{x}_{n+1}(y)dy = a(\dot{x}_n(y) - \dot{x}_{n+1}(y))dy = a\dot{l}_{n+1}(t)dy$$

$$\int_0^t \ddot{x}_{n+1}(y)dy = \int_0^t a\,\dot{l}_{n+1}(t)dy$$

$$u_{n+1}(t) - u_{n+1}(0) = a(l_{n+1}(t) - l_{n+1}(0))$$

$$u_{n+1}(t) = a\,l_{n+1}(t) + u_{n+1}(0) - al_{n+1}(0)$$

If $l_{n+1}(t) = 0$, then $u_{n+1}(t) = 0 \Rightarrow u_{n+1}(0) - al_{n+1}(0) = 0$

From Microscopic Model to Macroscopic Model

$$u_{n+1}(t) = al_{n+1}(t) = a(\frac{1}{k_{n+1}(t)} - \frac{1}{k_{jam}})$$

$$\Rightarrow u = a(\frac{1}{k} - \frac{1}{k_{jam}})$$

$$\Rightarrow q = uk = a(\frac{1}{k} - \frac{1}{k_{jam}})k = a(1 - \frac{k}{k_{jam}})$$

If $k = 0$, then $q = a$

Since $q = a \geq a(1 - \frac{k}{k_{jam}})$, then $a = q_{\max}$

$$\Rightarrow q = q_{\max}(1 - \frac{k}{k_{jam}})$$

- Note: if $k \to 0$, then $u \to \infty$. Does this make sense?

Non-linear Car-following Models

- $$\ddot{x}_{n+1}(t+T) = a_0 \frac{\dot{x}_n(t) - \dot{x}_{n+1}(t)}{\left(x_n(t) - x_{n+1}(t)\right)^{1.5}} = a_0 \frac{\dot{l}_{n+1}(t)}{\left(l_{n+1}(t) + \frac{1}{k_{jam}}\right)^{1.5}}$$

- If $T = 0$, the corresponding fundamental diagram is:

$$q = u_{\max} k \left[1 - \left(\frac{k}{k_{jam}}\right)^{0.5}\right]$$

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Flow Models Derived from Car-Following Models

$$\ddot{x}_{n+1}(t+T) = a_0 \dot{x}_{n+1}^m(t+T) \frac{\dot{x}_n(t) - \dot{x}_{n+1}(t)}{\left(x_n(t) - x_{n+1}(t)\right)^l}$$

l	m	Flow vs. Density
0	0	$q = q_m \left(1 - \frac{k}{k_{jam}}\right)$
1	0	$q = u_c k \ln\left(\frac{k_{jam}}{k}\right)$
1.5	0	$q = u_{\max} k \left[1 - \left(\frac{k}{k_{jam}}\right)^{0.5}\right]$
2	0	$q = u_{\max} \left(1 - \frac{k}{k_{jam}}\right)$
2	1	$q = u_{\max} k \exp\left(1 - \frac{k}{k_{jam}}\right)$
3	1	$q = u_{\max} k \exp\left[-\frac{1}{2}\left(\frac{k}{k_{jam}}\right)^2\right]$

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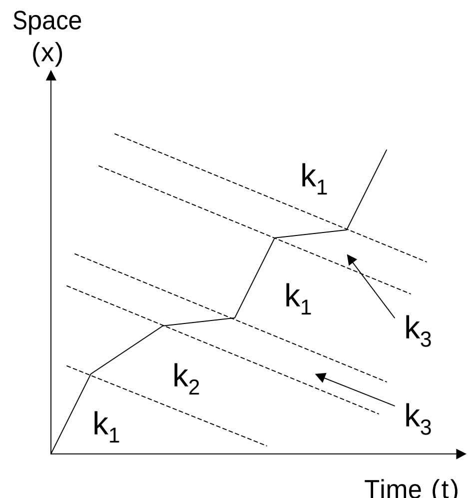
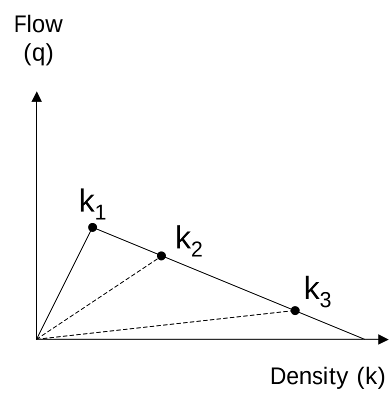
Is The Depicted Trajectory Familiar To You, and How To Predict It?

- Two facts:
  - As a vehicle travels along the roadway, its speed might change
  - The speed is lower if surrounding traffic density is higher
- A dynamic traffic model predicts speeds that vary in space and time
- A macroscopic dynamic traffic flow model:
  - Divide the highway into blocks of constant densities
  - Model speeds **within** and **between** blocks



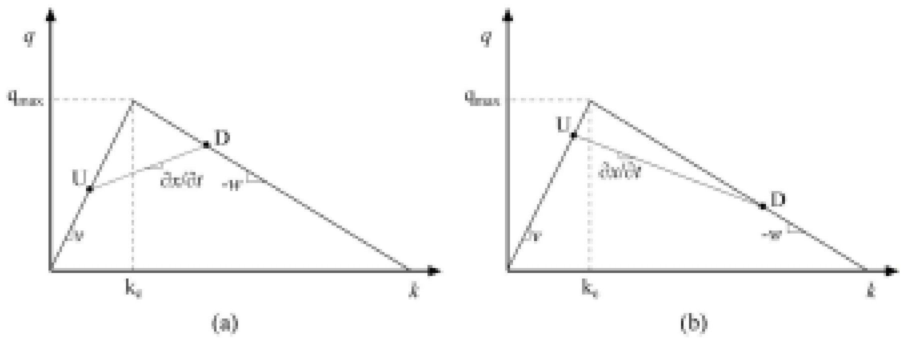
Density-Flow Relationships

- Macroscopic traffic theory shows that there is a relationship between traffic density and flow on a stretch of a highway
- This theory also predicts average vehicle speed
- Theory supported by real-world measurements
- Density-relationships:
  - A concept familiar to you by now
  - An example is depicted on the right



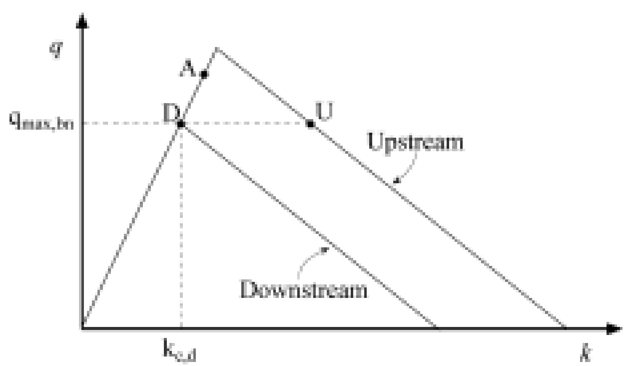
Boundary Propagation: Upstream in Free Flow, Down Stream Congested

1. Two successive density blocks:
   U: upstream block;
   D: the downstream block
2. Depending on flow on each block, there are three cases: Two are shown below



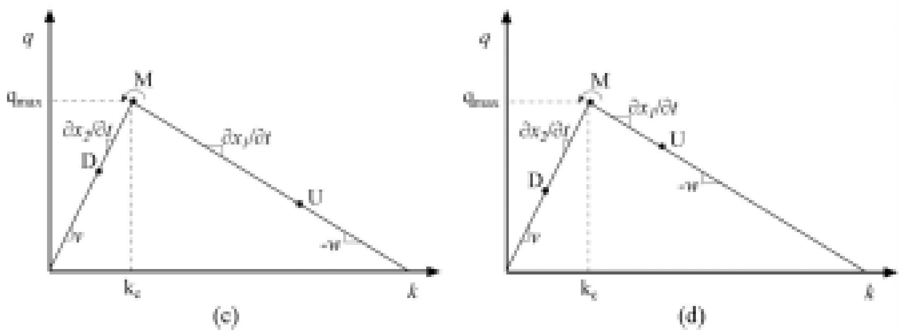
Modeling of Bottlenecks

- ❑ Change in density-flow diagram to reflect change in capacity



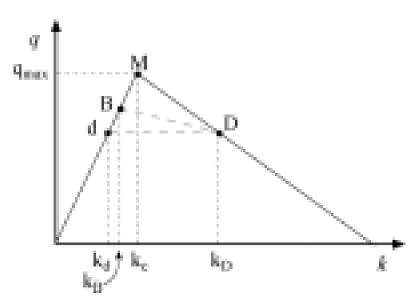
Downstream in Free Flow and Upstream Congested

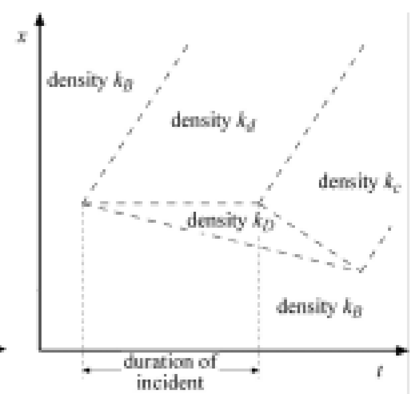
A block with maximum flow (critical density) is created in between U and D blocks



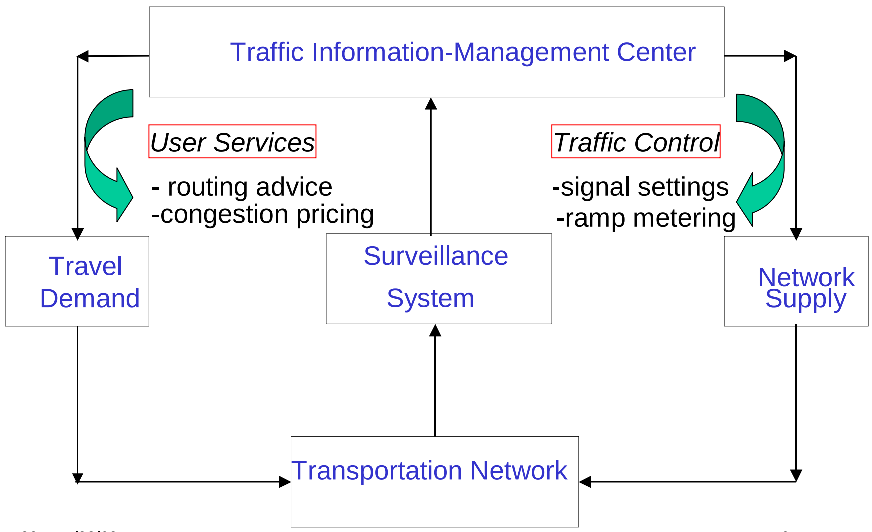
Modeling of Incidents

- Before incident, traffic flow represented by point B.
- An incident acts like a temporary bottleneck if $k_d<k_B<k_D$. Incident reduces flow to a maximum flow given by points d and D
- Following the clearing of the incident, a new block with density k_c is created





Information Technology and Transportation Network Operations



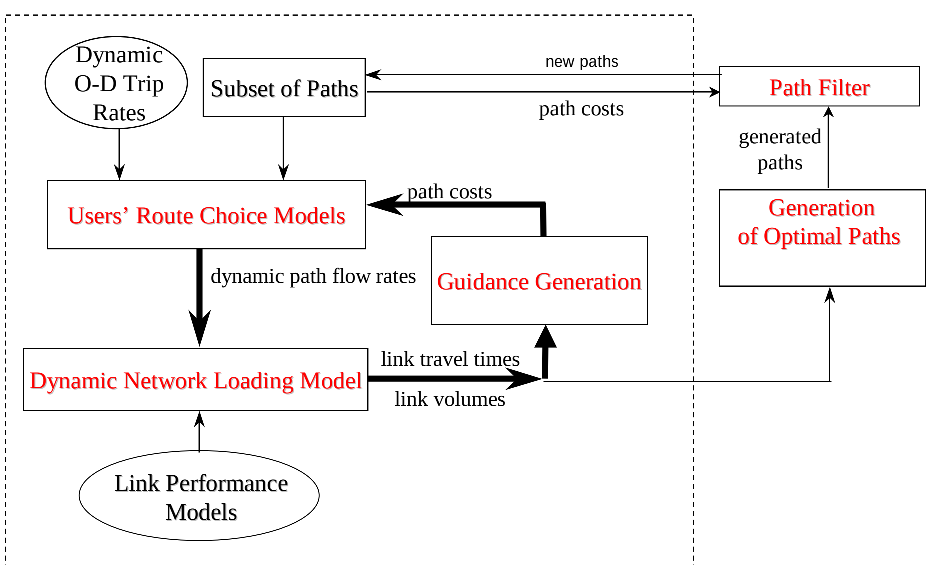
Traffic Information-Management Systems (TIMS): Properties and Methods

- TIMS should be
  - responsive to:
    - "future" demand
    - potential adjustments in travel patterns due to information provision and changes in supply network
  - based on "projected" traffic conditions to:
    - anticipate downstream traffic conditions, and
    - improve credibility
- Predictions methods:
  - Statistical: valid for short intervals only
  - Dynamic traffic assignment methods (models and algorithms)

Dynamic Traffic Flow Methods

- Traffic assignment models:
  - require time-dependent O-D flows
  - incorporate driver behavior, and information provision
  - require link network performance models
  - **have high computational requirements**
- Three modeling/algorithmic components:
  - Travelers route-choice
  - Prediction of travel times when vehicle paths are known
  - Route-guidance provision
- Two algorithmic components:
  - Path-generation
  - Dynamic traffic assignment

Framework for Dynamic Traffic Assignment Methods



Types of DTA Models

- Microscopic traffic models (MITSIM):
  - Traffic is represented at the vehicle level
  - Vehicles are moved using car-following and lane changing models
- Mesoscopic traffic models (MesoTS/DynaMIT):
  - Traffic is represented at the vehicle level
  - Speed is obtained using models that relate macroscopic traffic flow variables
- Macroscopic (or flow-based) traffic models:
  - Traffic is represented as continuous variables
  - Speed is obtained using models that relate macroscopic traffic flow variables
- Analytical (flow-based) traffic models: macroscopic models with a good mix of lot of math, computer science and traffic flow understanding

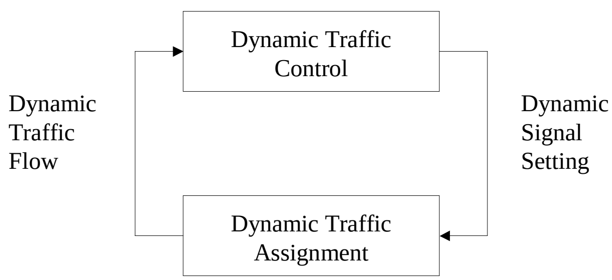
A Small Real-Word Network Model: Amsterdam Beltway Network

- 196 nodes, 310 links, 1134 O-D pairs and 1443 paths
- Morning peak: 2 hours and 20 minutes
- Discretization intervals: 2357 (3.50 sec each)
- Various types of users:
  - Fixed routes
  - Minimum perceived cost routes
  - Minimum experienced cost routes

Computer Resources Used in Analytical Model

- Link variables: 25 Mbytes
- Path variables: 34 Mbytes
- Average time for one loading: about 3 minutes
- Saving ratio compared to known analytical methods: 1000
- Results are encouraging for real-time deployment
- Analytical approach: 45 times faster than real time

Interdependence of Control and Assignment



- Consequences of the conventional approach:
  - Sub-optimal signal settings;
  - Inconsistent traffic flow predictions.

A Case Study (cont.)

- Controls
  - current existing pre-timed control
  - Webster equal-saturation control
  - Smith P_0 Control
  - One-level Cournot control
  - Bi-level Stackelberg control
  - System-optimal Monopoly control
- Route Choices
  - A set of pre-determined paths (4 paths) for each O-D pair
  - Total of 400 paths
  - Demand is model using C-Logit

Results from Back Bay Case Study

Controls	Total Travel Time (mins)	Gap from System-Optimum (%)
Existing	11784	14.12
Webster	11781	14.1
Smith P_0	11566	12.02
Cournot	10642	3.07
Stackelberg	10504	1.73
Monopoly	10325	0

Current Research Interests of ACTS Group

- **Algorithms and Computation in Transportation Systems (ACTS) Group:**
  - A group formed by Prof. Ismail Chabini and his graduate advisees
  - Has been around for 5 years now
- **Field of Interest**:
  - Design and computer implementation of models and algorithms for transportation network analysis and operations
  - Modeling and real-time management of traffic flows on road networks
  - Applications to solve increasingly important societal problems such as congestion, air quality, energy, safety, and emergency
- **Critical Characteristics of Problems**:
  - Real-time operation
  - Dynamics
  - Large networks
  - Intelligence and subsystems integration
  - Complex interactions involving humans

Related Ongoing Research Projects

- **NSF CAREER (and NSF ETI)**: "High Performance Computing and Network Optimization Methods with Applications to Intelligent Transportation Systems" (~ $350k)
- **NSF-NYSDOT**: "Deployment of ITS technologies" (~ $350k)
- **US DOT**: "Design and Implementation of Computer Models and Algorithms for Dynamic Network Flow Problems" (~$300k)
- **Ford Motor Company**: "Emissions Modeling and Control", and "Parallel Traffic Models and Applications to Safety" (~ $330k)
- **CMI (with colleagues from MIT and Cambridge University): "**The Sentient Vehicle" (~ $400k)

Some Research Contributions of the ACTS Group:
Routing Problems in Time-Dependent Networks

- Developed the fastest known algorithms for a variety of routing problems in time-dependent networks
- Algorithms are based on the Decreasing-Order-of-Time (DOT) algorithm, described in paper 2.2, which finds all-to-one shortest paths for all times
- Algorithm DOT has been a breakthrough in this area, and was shown to be a degree of magnitude faster than previously known algorithms
- Implementations of algorithm DOT exploiting high performance computing platforms and hierarchical structures of transportation networks resulted in further gains in computational speed
- The developed algorithms are essential building blocks of real-time traffic management methods, and have significantly expanded the boundary of network sizes for which these methods are deployable
- It is now computationally possible to deploy real-time traffic management methods to medium-size networks, which are a degree of magnitude larger

Some Research Contributions of the ACTS Group:
Methods and Tools for Traffic Flow Modeling and Management

- Developed new models, faster algorithms and computer implementations to solve a class of traffic flow modeling and management problems
- They are the fastest known tools in the literature, and run much faster than real-time on medium-size real-life networks
- Developed new traffic management algorithms, which have the potential to significantly improve travel-times through effective real-time dynamic adjustment of traffic signals and provision of route guidance strategies
- The developed models, algorithms and software tools contribute to creating a knowledge and computational base needed to build and deploy real-time traffic management systems to alleviate congestion
- The algorithms and software systems have unique capabilities, and have been sought by industry. Some are the subject of patent applications
- In projects sponsored by CMI and Ford-MIT initiatives, the developed methods are being used to design new solutions to problems related to air pollution, energy consumption, and safety

Lecture 11 Summary

- Overview of some traffic flow models:
  - Modeling of single link: Car-following models
  - Dynamic macroscopic models of highway traffic
- Dynamic traffic flow management in road networks:
  - Concepts
  - Dynamic traffic assignment
  - Combined dynamic traffic signal control-assignment
- The ACTS Group