Active Traffic Management using Aurora Road Network Modeler

Alex Kurzhanskiy

University of California, Berkeley

RESS Seminar
December 8, 2009
TOPL Research Group

Güneş Dervisoglu
Ajith Muralidharan
René Sánchez
Dongyan Su

Graduate Students

Andy Chow
Alex Kurzhanskiy

Postdocs

Roberto Horowitz
Pravin Varaiya

Faculty

Gabriel Gomes

PATH Researcher
**Motivation**

- **2007 USA traffic congestion caused:**
  - 4.2 billion hours of additional travel time
  - 2.9 billion gallons of additional fuel

- **Congestion delay in California:**
  - 500,000 vehicle-hours per day
  - Will double by 2025

I-880 South near San Mateo Bridge
10% increase in demand (VMT) causes 400% increase in mainline delay (8000VH per day = $1M per week); productivity loss (25LMH = 1 freeway lane in peak hours)

Efficient system operates in green region
Active Freeway Management

- Implement
- Plan
- Control
- Measure

Management
PLANNING
**Modeling Approaches**

- **Microscopic**: models individual vehicles as their drivers respond to surrounding conditions by adjusting speeds and changing lanes.
Micro-Simulation Look & Feel

Paramics

TransModeler

Vissim

Aimsun
Modeling Approaches

- **Macroscopic**: represents traffic as compressible fluid in terms of flow, density and speed
Terminology and Notation

- **Flow (vph),** $f$ - number of vehicles passing through given point during given time unit

- **Density (vpm),** $\rho$ - number of vehicles occupying given length of road

- **Speed (mph),** \[ V = \frac{f}{\rho} \]

- **Free flow speed (mph),** $\nu$ - average traffic speed measured under low volume traffic conditions

- **Capacity (vph),** $F$ - maximum flow allowed through given point

- **Bottleneck** - road spot where flow exceeds capacity
Off-ramp flows are specified by split ratios:

\[ s_i(t) = \beta_i [f_i(t) + s_i(t)] = \beta_i \beta_i^{-1} f_i(t), \quad (\beta_i = 1 - \beta_i) \]
Cell’s fundamental diagram is characterized by:

- $F_i$ - capacity
- $v_i$ - free flow speed
- $w_i$ - congestion wave speed
- $\rho_i^c$ - critical density
- $\bar{\rho}_i$ - jam density

Triangle implies:

$$F_i = v_i \rho_i^c = w_i (\bar{\rho}_i - \rho_i^c)$$
CTM: Flow between Cells

- **Demand:**  \( f_i(t) \leq v_i \rho_i(t) - s_i(t) \)

- **Capacity:**  \( f_i(t) \leq F_{i+1} \)

- **Supply:**  \( f_i(t) \leq w_{i+1}[\rho_{i+1}^j - \rho_{i+1}(t)] \)

\[
f_i(t) = \min \{ v_i \rho_i(t) - s_i(t), w_{i+1}[\rho_{i+1}^j - \rho_{i+1}(t)], F_{i+1} \}
\]
Traffic Modeling Workflow

1. **GIS**
   - OpenJUMP filtering

2. **PeMS**
   - traffic and geometric data

3. **Google Maps**
   - GIS Importer
   - manual inspection

4. **Aurora Configurator**
   - Calibration of model parameters
   - Imputation of missing ramp flows

5. **Aurora Simulator**
   - Aurora XML

6. **Report Generator**

**Scenarios**
- HOV lanes
- ramp metering
- VSL
- incidents
- special events
- etc.
Model Calibration

- Calibration: fitting fundamental diagram to density/flow data

- For each vehicle detector station estimate:
  - Free flow speed $\nu$
  - Capacity $F$
  - Congestion wave speed $\omega$
Motivation

- On-ramp and off-ramp flows are essential for simulation
- But ramps often lack functioning detector station

Approach

- Inverse problem: find ramp flows $r_i(t), s_i(t)$ from CTM and mainline measurements $\hat{\rho}_i(t), \hat{f}_i(t)$
- Ill-posed problem: non-uniqueness of solution
- Minimize $\|\rho(t) - \hat{\rho}(t)\|$ and $\|f(t) - \hat{f}(t)\|$
Building Aurora Network

- Initial cropping of GIS information in OpenJUMP

- Aurora GIS Importer
  - Filter by road type and name
  - Simplify the resulting graph
  - Save road network in Aurora XML format
GIS Importer Summary

Full Road Network

XML output:

```
<link class="aurora.hwc.LinkFR" id="30001" lanes="1" length="0.18939">
  <begin id="2"/>
  <dynamics class="aurora.hwc.DynamicsCTH"/>
  <density>0</density>
  <demand knob="1" tp="300">0</demand>
  <qmax>2100</qmax>
  <Fd densityCritical="32" densityJam="163" flowMax="2100"/>
  <position>
    <point x="-117.7118" y="-34.1216" z="23"/>
    <point x="-117.7118" y="-34.1216" z="23"/>
  </position>
</link>
```
Aurora Network
Aurora Network
Links

- **Ordinary link**
  - begin node
  - end node

- **Source link**
  - demand, queue
  - end node

- **Destination link**
  - begin node
  - free flow downstream, or boundary condition
Links

- Ordinary link
  - begin node
  - end node

- Source link
  - demand, queue
  - end node

- Destination link
  - begin node
  - end node

Conservation law implementation

Time varying boundary conditions

Free flow downstream, or boundary condition
Nodes

- Simple node
  - in-links
  - simple node
  - out-links

- Complex node is network
Controller Hierarchy

- **Local** controller operates on single input link (e.g. local ramp meter)
  - ALINEA, traffic responsive, time of day

- **Node** controller operates on all input links in a node through local controllers (e.g. signal intersection)
  - Signal control - pre-timed, actuated, coordinated

- **Complex** controller operates on input links in multiple nodes through node or local controllers (e.g. coordinated ramp or intersection control)
  - SWARM, HERO (coordinated ALINEA)
Monitors

- **Zipper Monitor** - stitches two sub-networks together into one complex network

- **Control Monitor** - monitors links, nodes or other monitors for the purpose of coordinated control

- **Event Monitor** - monitors road network and generates events if observed data meet certain thresholds
Assigns new boundary conditions for two networks by redirecting output of one into input of the other and vice versa
Complex Configuration

Freeway sub-network

Arterial sub-network

Complex network
Control Monitor

- Provides feedback for complex hierarchical controller that performs coordinated control
Coordinated Ramp Metering

Zone 1

Zone 2

Zone 3

Bottleneck 1

Bottleneck 2

Bottleneck 3

Zone 1 Controller

Zone 2 Controller

Zone 3 Controller

Main Controller
Events

At given time, switch

- Fundamental diagram
- Demand
- Queue limit
- Split ratio matrix
- Controller

occur in links

occur in source links

occurs in nodes

occurs in nodes and monitors
Event Monitor

- Generates event at current simulation time if the state of monitored network element(s) crosses given threshold

- Implements hybrid system behavior
Scenarios in Planning

- Scenarios describe incidents, diversions, changes in demand patterns, improvement plans, etc.

Example:
- changes in % traffic in HOV lane on I-80 East
Variation in % HOV traffic: Speed

20% HOV traffic

25% HOV traffic

HOV

Mainline
Variation in % HOV traffic: Total Delay

- Larger delay on HOV, smaller total delay in 25% HOV vs. 20% shows importance of managing all lanes.
DECISION SUPPORT
Traffic Management Center

- Traffic state estimation and prediction
- SCADA
- Road network
- Control center
- Scenario database
- Trusted, fast corridor simulator
- Alarm for recurrent congestion, non-recurrent congestion, productivity loss, and security assessment
## Aurora Virtual Sensors

<table>
<thead>
<tr>
<th>Static</th>
<th>Moving</th>
<th>Spatial</th>
</tr>
</thead>
</table>

- Virtual sensors are Aurora classes that simulate behavior of real sensors.
Density from Flow & Speed

- Flow measurement
  \[ y_{fi} = f_i + \omega_i, \quad \omega_i \in [-\omega_i^0, \omega_i^0] \]

- Speed measurement
  \[ y_{Vi} = V_i + \zeta_i, \quad \zeta_i \in [-\zeta_i^0, \zeta_i^0] \]

- Density bounds
  \[ \hat{\rho}_i^- = \frac{y_{fi} - \omega_i^0}{\beta_i(y_{Vi} + \zeta_i^0)} \quad \text{lower} \]
  \[ \hat{\rho}_i^+ = \frac{y_{fi} + \omega_i^0}{\beta_i(y_{Vi} - \zeta_i^0)} \quad \text{upper} \]
Real-Time State Estimation

Model prediction: $[\rho^-(t), \rho^+(t)]$

Measurement correction: $[\hat{\rho}^-(t), \hat{\rho}^+(t)]$

Flow

$F^+_i, F^-_i$

Density

$\rho^c_i, \rho^d_i$

Actual

$\rho_i^-, \rho_i^+$

Lower bound

$\rho_i^-(t) \leq \rho_i(t) \leq \rho_i^+(t)$

Upper bound

$t_0, t_1, t_k, T$

Uncertainty

Measurements

Interval Size (vpm)

5 am 11 am

Data from Image 1: $\rho^c_i, \rho^d_i$ represent the model prediction bounds, while $\rho_i^-(t), \rho_i^+(t)$ represent the actual density bounds. The diagram illustrates the application of model predictions and measurements to correct the uncertainty in traffic density estimation.
I-210 West on July 15, 2009

- Simulated time: 4 - 8 AM
  - 4 - 6 AM is past (measurement and estimation)
  - 6 AM - current time
  - 6 - 8 AM is future (prediction)

- Uncertainty in demand only: +/- 2% of nominal

- Fundamental diagrams are fixed and off-ramps do not get congested: this condition allows to use CTM monotonicity
I-210 West on July 15, 2009

Aggregate data per 1 minute

- **VMT**
  - Time (AM)
  - Measurement + Estimation
  - Prediction from 6 to 8 AM

- **VHT**
  - Time (AM)
  - Measurement + Estimation
  - Prediction from 6 to 8 AM

- **Productivity loss [lmh]**

- **Network delay [vh]**
  - Time (AM)
Predictive Analysis of Density

Density [vpm]

Temporal cut between Huntington and Santa Anita (pm 31)

Spatial cut at 7.30 AM

[Graphs showing density plots and time series data]
Predictive Analysis of Speed

Speed [mph]

Temporal cut between Huntington and Santa Anita (pm 31)

Spatial cut at 7.30 AM
Predicted Impact of ALINEA Control

Aggregate data per 1 minute

VMT

VHT

Productivity loss [lmh]

Network delay [vh]

Measurement + Estimation

Prediction from 6 to 8 AM

freeway only

freeway + on-ramps

Time (AM)
Impact of ALINEA: Density

Density [vpm]

Temporal cut between Huntington and Santa Anita (pm 31)

Spatial cut at 7.30 AM
Impact of ALINEA: Speed

Spatial cut at 7.30 AM

Temporal cut between Huntington and Santa Anita (pm 31)

measured
lower bound
upper bound

Speed [mph]
Scenario: Accident near Baldwin

- 6.15 AM: freeway capacity is reduced by 50%
- 6.30 AM: road cleared, capacity is back to normal

Worst case
Strategy 1: ALINEA Control

[Map showing the area with an accident marker and a line indicating traffic flow.]

[Graph showing time vs. delay per minute with a curve rising from 0 to 50 minutes.]

[Heat map showing speed distribution with postmiles on the x-axis and speed in mph on the y-axis.]
Strategy 2: ALINEA + VSL Control

VSL: 50-60 mph

accident

Time (AM)

Delay per 1 minute [veh]

Postmile

Speed (mph)
Strategy 3: ALINEA + VMS Control

Delay per 1 minute [vh]

Speed (mph)

Postmile

Time (AM)
Strategy 4: ALINEA with Meter at I-605

Accident

ALINEA

Delay per 1 minute [vh]

Postmile

Speed (mph)

Time (AM)

06:00 06:14 06:28 06:43 06:57 07:12 07:26 07:40 07:55

06:00 06:14 06:28 06:43 06:57 07:12 07:26 07:40 07:55
IMPLEMENTATION
7:50pm: start of incident
- Lasting 15 minutes
- Reduction to 75% of the pre-existing capacity
- Blue diamond is the incident
Aurora RNM as A Service

8:00pm
Aurora RNM as A Service
Aurora RNM as A Service
Active Traffic Management

- 9 miles of M42 near Birmingham
- Detectors placed every 330 ft, in critical areas - every 100 ft
- Cost: $ 200 million
Real-Time Aurora Operation

Real-time model

short-term scenario

short-term projection

control actions

sensor data

freeway

arterial

corridor database

Aurora RNM

performance analysis

proposed improvements

scenarios

Operations Planning

Operations Implementation
ALINEA Control: $r_{AC}(t) = r_{AC}(t - 1) + G_{AC} (\rho^c - \hat{\rho}(t))$

Queue Control: $r_{QC}(t) = d(t) + G_{QC} (\hat{q}(t) - \bar{q})$

$r(t) = \max \{ r_{AC}(t), r_{QC}(t) \}$
Real-Time Controller Deployment

```xml
<controller class="aurora.hwc.control.ControllerALINEA" type="0.08833">
  <limits clin="10.0" cmax="1600.0"/>
  <parameter name="upstream" value="false"/>
  <parameter name="gain" value="68.0"/>
  <qcontroller class="aurora.hwc.control.QOverride">
    <parameter name="delta" value="120.0"/>
  </qcontroller>
</controller>
```

2070 Controller

Queue Presence Signal Pass Entrance
Infrastructure Intelligence and Predictive Analytics

- Modeling based on reliable measurements
- Consistent imputation of missing data
- Accurate estimation of uncertainty in parameters and inputs
- Long-term planning
  - Scenario simulations; control strategies evaluation; performance analysis
- Short-term prediction
  - Real-time traffic density estimation; evaluation of short-term scenarios and short-term projection; traveler information update and real-time controller deployment
References

- TOPL Project: [http://path.berkeley.edu/topl](http://path.berkeley.edu/topl)
- Aurora RNM: [http://code.google.com/p/aurorarnm](http://code.google.com/p/aurorarnm)