Planning and Scheduling for Traffic Control

Scott Sanner

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Outline

• Motivation
• History
• Fundamentals
• Simulation
• Control
  – Single Intersection
  – Multiple Intersection
• Future
Motivation
More Motivation
Traffic Impacts Everyone

• Not a problem I have to motivate
  – Economically, impact of better control is in billions of $$ for large cities!

• Real & unsolved problem
  – Multidimensional state (integer / continuous)
  – Multidimensional concurrent actions
  – Stochastic
  – Building a high fidelity model is difficult
Theory vs. Practice

- **Theory**
  - Idealized
  - Models major phenomena
  - Good analytical techniques

- **Practice**
  - Every case is different
  - Control is principled
    - but over-constrained
  - Manually tuned

Need a stronger connection!
Integrating into the Food-chain

• Important to understand what exists theoretically
  – Entire field devoted to transportation research

• And how your research can integrate practically
  – Billions of $$$ in legacy infrastructure
  – Hardware is limited (e.g., 1970’s era)
    • But still more integrated than you think
  – Systems are safety verified
    • Difficult and expensive to replace
    • Figure out where to fit in for lowest cost
Tutorial Objectives

• Main tutorial objective
  – Understand major areas of traffic research
  – Understand basic theory and practice

• At the end of this tutorial you should know….
  – The *fundamental diagram of traffic flow*
  – How to dissipate shockwaves in your arteries
  – The importance of platoons
  – Main differences between SCOOT and SCATS
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Traffic Control: History

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Minimalist Research Timeline

Transport Research starts to split from Operations Research

Road Research Lab (RRL) Est. in UK (now TRL)

Journal of Transportation Research Part A Begins

6000+ Transport Funded Projects in EU Alone!

1933 1950’s 1966 2010
Signalized Control Timeline

- **Timed Control**: Late 1920’s
- **Analog Control (Denver)**: 1952
- **Digital Control (Toronto)**: 1960
- **Regional Coordination, Metering, VSL, Priority**: Late 1970’s
- **SCATS, SCOOT: Adaptive Control**: 2000+
SCATS

- Sydney Coordinated Adaptive Traffic System

- Stopline detectors

- Coordinated decentralized control

Car Detected!
SCOOT

• Split, Cycle, & Offset Optimization Technique

• Centralized controller

• Some predictive feedforward control
  – Loops after intersection
    • No need to predict turn probabilities
    • Optimize lights before they arrive

Car Detected!
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Traffic Control: Fundamentals

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Flow $q$: cars/s
Density $k$: cars/m
Velocity $v$: m/s

$q = kv$
$v = q/k$
Terminology

- Signal, e.g., 🚪
- Signal Group
- Phase
- Turns
  - Protected Turn
  - Filter Turn
    - unprotected
Terminology Illustration: Azalient Commuter
Each intersection has one or more phase plans
- Time percentage of cycle time is phase split
- Some absolute or variable times
  - Intergreen period
  - Walk signals
  - Turns

Typically four plans per intersection
- Heavy inbound / outbound, balanced, & light

Now just choose a plan and cycle time for one intersection!
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Traffic Control: Simulation

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Types of Simulation

• Macrosimulation
  – Model aggregate properties of traffic
  – Average flow, density, velocity of cells

• Microsimulation
  – Model individual cars
  – Typically cellular automata

• Nanosimulation
  – Model people (inside & outside of cars)
Human Factors in Microsimulation

- Microsimulation often involves driver choice:
  - Filter turns
  - Turns into flowing traffic
  - Lane merges
  - Lane changes

- Theories such as gap acceptance theory
  - Attempt to explain driver choices
  - e.g., gap size willing to accept on filter turn $\propto 1$/time

- See Ch. 3 of Traffic-Flow Theory, Henry Lieu
Microsimulation Turn Models

Two ways to model turns:

1. Turn probabilities at each intersection

2. Frequencies in origin-destination (OD) matrix (routes predetermined for each OD pair)

Which is better? Car may go in loops for 1, more realistic to choose 2!
Microsimulation

• Nagle-Schreckenberg
  – Cellular Automata Model
    • nominally each cell is 7.5m in length

  – Simplest model that reproduces realistic traffic behavior

Image and description from: http://www.thp.uni-koeln.de/~as/Mypage/traffic.html
Car Following in Microsimulation

- Nagel-Schreckenberg
- 4 Rules
  - Acceleration:
    \[ v_i := \min(v_i + 1, v_{\text{max}}) \]
  - Safety Distance:
    \[ v_i := \min(v_i, d) \]
  - Randomization:
    \[ \text{prob } p: v_i := v_i - 1 \]
  - Driving:
    \[ x_i' = x_i + v_i \]

Image and description from: http://www.thp.uni-koeln.de/~as/Mypage/traffic.html
Car Following Microsimulation

• Continuous traffic flow example:
  – Upper plot is space/time diagram
  – Lower plot is actual traffic

Image and description from: [http://www.thp.uni-koeln.de/~as/Mypage/simulation.html](http://www.thp.uni-koeln.de/~as/Mypage/simulation.html)
An Even Better Microsimulator

Traffic Jam without Bottleneck

Experimental evidence for the physical mechanism of forming a jam

Yuki Sugiyama, Minoru Fukui, Macoto Kikuchi, Katsuya Hasebe, Akihiro Nakayama, Katsuhiro Nishinari, Shin-ichi Tadaki and Satoshi Yukawa

Movie 1

The Mathematical Society of Traffic Flow

http://news.sciencemag.org/sciencenow/2008/03/28-01.html
Shockwaves

- Low density traffic meets high density traffic...

\[ K_d = 0.1 \text{ cars/m}, \quad v_d = 15 \text{ m/s} \]

\[ K_u = 0.05 \text{ cars/m}, \quad v_u = 30 \text{ m/s} \]

- Shockwave (density wave)

Shockwave velocity \( u = -5 \text{ m/s} \)
Calculation of Shockwave Speed

• Law of conservation of cars:
  – “Cars can neither be created nor destroyed”

• Traffic flows in/out of shockwave at rate:

\[
q_{\text{enter}} = k_u(v_u - u)
\]
\[
q_{\text{exit}} = k_d(v_d - u)
\]
\[
q_{\text{exit}} = q_{\text{exit}} \Rightarrow u = \frac{k_d v_d - k_u v_u}{k_d - k_u} = \frac{q_d - q_u}{k_d - k_u} = \frac{\Delta q}{\Delta k}
\]
Theory of Shockwaves

Determine shockwave speed $u$ from diagram:
Theory of Shockwaves

Determine shockwave speed $u$ from diagram:

$$u = \frac{q_d - q_u}{k_d - k_u} = \frac{\Delta q}{\Delta k}$$

$u < 0$ causes shockwave to propagate back.
Theory of Shockwaves

Determine shockwave speed $u$ from diagram:

$$u = \frac{q_d - q_u}{k_d - k_u} = \frac{\Delta q}{\Delta k}$$

$u > 0$ dissipates shockwaves!
Macro Simulation

• Cell Transition Model
  – Model **aggregate properties** of traffic
  – Average flow, density, velocity over **segments**

<table>
<thead>
<tr>
<th>100m</th>
<th>100m</th>
<th>100m</th>
</tr>
</thead>
<tbody>
<tr>
<td>K=.02 car/m, V=30 m/s</td>
<td>K=.05 car/m, V=20 m/s</td>
<td>K=.07 car/m, V=10 m/s</td>
</tr>
</tbody>
</table>

– Nonlinear difference equation transition model
– **Recreates shockwave phenomena**

Simulation Software

• **Quadstone Paramics (microsimulation)**
  – Largest market share
  – Industrial strength
  – Expensive

• **Azalient Commuter (micro- and nano-simulation)**
  – Relatively recent startup
  – Intuitive 3D GUI
  – Java API for external control and evaluation
  – More economical for academia
Azalient Commuter
Traffic Control:
Single & Multi-intersection
Optimization Objective

• Can minimize
  – Delays,
  – Stops,
  – Fuel consumption,
  – Emission of pollutants,
  – Accidents

• Here we focus on delays in car-seconds
  (and implicitly stops, fuel, emissions)
Coordinated Control

• Unconstrained policy space (state → action) is large / ∞!

• **One intersection:** multidimensional state and action
  – Changing demand observations & predictions
  – Demand-based protected turns & walk signals
  – Min/max cycle, phase, & intergreen times

• **Coordinated Intersections:** multidimensional action
  – 10x10 grid = 100 intersections
  – Simplest model: 2 decisions per intersection (NS or EW)
  ⇒ $2^{100}$ decisions
Delay vs. Optimal Cycle Times

- Use maximum best cycle time of any phase

Best cycle time \( \approx \max \text{ of best cycle times per phase} \)
Optimal Cycle Times vs. Flow

• **Light traffic**
  – Short cycle times
  – Minimize delay for individual cars

• **Heavy traffic**
  – Long cycle times
  – Maximize steady-state flow
Single Intersection Control

• Given cycle time, what is best phase split?
  – Webster’s theory…

\[
y_i = \frac{q_i \leftarrow \text{inflow}}{s_i \leftarrow \text{max outflow}}
\]

  – Worst case?

  any \( y_i > 1 \)

  – Solution

  \[
  \text{phase time } i \propto \frac{y_i}{\sum_i y_i}
  \]
Problems with Local Control

• **Upstream or downstream intersections**
  – Downstream queue saturated \( s_i \) decreases
  – In-flow of cars \( q_i \) is **not uniformly distributed**!

• **Platoons**
  – Cars tend to “clump” into platoons
    • Due to discharge from upstream queues
  – Best throughput with good platoon management
    • Careful timing needed

AI papers tend to ignore
Multi-intersection Control

• Optimize phase offsets for platoon throughput:

![Graph showing time vs. space with light phases and delays optimized for platoons.](image)
Master/Slave Offset Control

- Fix timing offsets from critical intersections
  - Allows platoons to pass in dominant flow direction

Married intersections should share cycle times (or 2x)!

Critical intersection

Offset Green = 25s

Offset Green = 40s

Offset Green = 30s
Multi-intersection Control in Practice

• **Split, Cycle, Offset Optimization (SCOOT, SCATS)**
  – Decide on married intersections
  – Decide on intersection offsets
    • Based on dominant flow direction
  – Decide on phase splits
    • w.r.t. offset constraints

• Practical, but highly constrained
  – Room for more fine-grained optimization
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Traffic Control: Future

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The Future of Traffic Control

- Priority (bus) control
  - Change objective to minimize delay in person-seconds

- Ramp metering & variable speed limits
  - Shockwave / density control

- Real-time selfish routing

- Better sensors
  - Cameras

- Better road topology…
Topology and Traffic I: Braess’s Paradox

- Adding network capacity can reduce flow if
  - Local route choices based on observed flow

http://en.wikipedia.org/wiki/Braess%27s_paradox#How_rare_is_Braess.27s_paradox.3F
Topology and Traffic II

- Turbo Roundabouts

http://en.wikipedia.org/wiki/Roundabout_intersection#Turbo_roundabouts
Topology and Traffic III

• Magic Roundabouts

http://en.wikipedia.org/wiki/Magic_Roundabout_Swindon
Traffic Control: Conclusions

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Advice

• Room for improvement in Traffic Control
  – State-of-the-art is principled, but ad-hoc
  – Could use better planning & scheduling

• If your traffic work draws on traditional AI P&S
  – Publish in ICAPS, AAAI, IJCAI, …

• If you really think you’re onto something
  – Go for a journal visible to traffic field…

Transportation Research is a journal-oriented field
Publish in a Journal (bold top-rated)

- **Transportation Research (TR)**
  - TR Part A: Policy and Practice
  - TR Part B: Methodological
  - TR Part C: Emerging Technologies
  - TR Part D: Transport and Environment
  - TR Part E: Logistics and Transportation Review
  - TR Part F: Traffic Psychology and Behaviour

- **Transportation Science**
- **Journal of Transport Economics and Policy**
- **Environment and Planning**
- **Transportation**
Find a Research Collaborator

- Transport Research Laboratory (TRL)
  - Independent consultancy (500+ employees)
- University College London (UCL)
  - Center for Transport Studies
- UC Berkeley
  - Institute of Transportation Studies
- University of Minnesota
  - Center for Transportation Studies
- University of Texas, Austin
  - Center for Transportation Research
- University of Michigan
  - Transportation Research Institute
- National ICT Australia (NICTA)
  - STaR Project

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Thank you!

Questions?