Planning and Scheduling Approaches for Urban Traffic Control

Stephen F. Smith, Mauro Vallati, Scott Sanner
Outline

- Introduction to Urban Traffic Control
- Related Works and landscape
- State of the art of P&S Approaches to UTC
  - QTM
  - SURTRAC
  - SimplifAI
- Future directions of the area & Conclusions
Introduction to Urban Traffic Control
What is UTC about?

In a nutshell: Urban Traffic Control is about dealing with traffic congestion, with the overall goal of *minimising delay*.

- Recurrent congestion
- Unexpected disruption / accidents
Do we have a problem?

Traffic congestion is increasing worldwide.

The city immigration trend is consistently predicted to continue for decades. City population is growing by 1% per annum.

By 2025 there will be 2bn more vehicles on the road.
Do we have a problem? (a UK focus - 1 year)

- Drivers spend 32 hours per annum in traffic jams
- Congestion costs 30 bn to the economy

- **Health**.
  - Traffic pollution contributes to (at least) 40,000 premature deaths
  - Traffic accidents contributes to 2,000 premature deaths.
Is the problem going to last?

Two elements are re-shaping the transport area:

- **Mobility-as-a-service**: a shift away from personally-owned modes of transportation and towards mobility solutions that are consumed as a service.
- **Connected Autonomous Vehicles**.
Future: optimism or pessimism?

Will MaaS & CAVs relief congestion in the long term?

- CAVs have the potential to improve the throughput of roads by more than 100%
- Improved safety, better service, faster transport

But..

- Travel demand is expected to increase as a consequence of making road travel cheaper, more comfortable, more efficient and accessible
- Increase of number of vehicles (shared and owned) between 30-90%
- Reduction in multi-modal journeys, and reduction in the use of train / flights.

(Analysis made in the C2ART project)
We do have a problem now.

and there will be the same problem in the future, despite (or even worsen by) new technologies and the paradigm shift.
Traditional approaches for traffic control

- Optimise Traffic Signal Phases
- Variable Message Signs
- Variable Speed Limits
- Lanes Reduction

...but in Urban Traffic Control...

- Optimise Traffic Signal Phases
- Variable Message Signs
- Variable Speed Limits
- Lanes Reduction
And it can lead to unpleasant surprises

Technically, this is a gridlock. (A quite unusual one, though).
UTC: what is deployed?

- A large number of junctions are usually controlled using **fixed-time** traffic light phases.
  - No information on actual traffic.

- A few junctions are controlled using reactive methods, such as **SCOOT** or **SCATS**.
  - Fast, but can control small areas of the network.

- **Model Predictive Controls** have been engineered to control signals for larger regions.
  - not widespread in application for “real-time” decisions. (computationally expensive and usually slow to converge)
How traffic authorities operate?

**Network Monitoring Officer**

- Are journey times as expected?
- What all are saying on social media?
- What’s happening on the streets?

**Mental Models**

- Is it an incident?
- Is it blackout?
- What’s happening on google maps?
- What’s the junction name? What drawings do I need to check?
- Has it happened before?
- Can we do something about it?
- What are the possible interventional?
- If it is an incident, is there historical data?
- What is causing the issue? Will it can scale? How does it affect traffic flow?
- What is the potential impact of intervening or not?

**Journey**

**METHOS**

- CCTV
- Google Maps
- Twitter
- Email
- In person

**INVESTIGATE**

- Did Highways England send anything?
- What’s happening on google maps?
- Should we do a site visit? Is there anyone available?
- What is the local context? Are there any hospital? Schools?
- What is the possible intervention?
- What is causing the issue? Will it can scale? How does it affect traffic flow?
- What is the potential impact of intervening or not?

**INFORM**

- Did bus drivers send anything?
- Is there anyone available?
- Do we have CCTV coverage in this area?
- Do I need to investigate it further?
- What alternatives can be offered?
- What information should I pass over?
- What is causing the issue? Will it can scale? How does it affect traffic flow?
- What is the potential impact of intervening or not?

**VIBRIPY**

- Is it a recurrent issue?
- What are the short-term impact?
- What is the junction name? What drawings do I need to check?
- What systematic operate in this area? What cause do we have available?
- Has it happened before?
- Can we do something about it?
- What are the possible interventional?
- What is the potential impact of intervening or not?

**EVALUATE**

- Do I need to investigate it further?
- What alternatives can be offered?
- What information should I pass over?
- What is causing the issue? Will it can scale? How does it affect traffic flow?
- What is the potential impact of intervening or not?

**IMPLEMENT**

- How is the IT performing?
- Do I have to make any new change to improve traffic?
- Did changes reduce congestion?
- How has the journey time after changes?

**REPORT**

- CCTV
- Google Maps
- Twitter
- Email
- In person

**SYSTEMS AND COMMUNICATION TOOLS**

- Google Maps
- Twitter
- Email
How traffic authorities operate? (1)
How traffic authorities operate? (2)
Landscape of related works in AI
**Traffic Signal Plans**

**Movement Phases:**

- Conventional signal systems use pre-programmed timing plans, sometimes with simple actuation.
- Adaptive signal systems sense approaching traffic flows and dynamically adjust timing plans in real-time.
Centralized systems that adjust timing plan parameters have had the most success (SCOOT, SCATS, ACLITE)

- Can be limiting with respect to real-time response

Online intersection planning approaches focus on the real-time problem and extend naturally to network level (OPAC, RHODES)

- But computational requirements restrict planning horizon and/or timing plan precision, which can limit effectiveness

If single dominant flow, then use of shared global timing plan can be effective (IN-SYNC)
AI-Based Traffic Research

- Reservation-based intersection control approaches – [Stone et. al]
- Real-time schedule-driven traffic control [Smith et. al. 2013]
- MILP-based network optimization – [Guilliard et al. 2015]
- PDDL-based planning of signal timings for congestion response – [Valeti et. al. 2016]
- Periodic, data-driven timing plan optimization [DiDi]
P&S Approaches: Queue Transmission Model (QTM)
A Non-homogenous Time Mixed Integer LP Formulation for Traffic Signal Control (TRR-16)

Iain Guilliard, Scott Sanner, Felipe Trevizan
Traffic Signal Control as Optimization

• Encode a **macroscopic model of traffic flow**
  – Often a piecewise linear, discrete time model
  – Let the traffic signals be variables to optimize

• Define an objective (e.g., minimum delay) and starting state

• Use optimization tools (e.g., MILP solvers) to find best signal control over a time horizon
Overview

• Traffic Signal Control via Optimization
  – Existing models & optimization methods
    • CTM: Large models, hard to scale
    • LTM: Model is compact, but fidelity less than CTM
Cell Transmission Model (CTM)

- **CTM setup** (Daganzo 1994):
  - **Variables**: flow rate, density
  - **Constants**: max capacity, peak and jam densities
  - Piecewise linear difference equation transition model
  - Provides realistic traffic flow models including shockwaves

<table>
<thead>
<tr>
<th>20m</th>
<th>20m</th>
<th>20m</th>
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</thead>
<tbody>
<tr>
<td>$K=.1$ car/m, $Q=1.1$ car/s</td>
<td>$K=.1$ car/m, $Q=2.1$ car/s</td>
<td>$K=.25$ car/m, $Q=0.5$ m/s</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\frac{k_j}{v + l} & = q_{max} \\
\end{align*}
\]
But the CTM requires a lot of cells…

Is there a more compact macrosimulation model?
Link Transmission Model (LTM)

- Link is a traffic queue vertically stacked at stopline

- **Limitations** (Gartner 2002, Han et al 2012)
  - Some versions poorly model delay
  - Single traffic boundary (single platoon)
Overview

• Traffic Signal Control via Optimization
  – Existing models & optimization methods
    • **CTM**: Large models, hard to scale
    • **LTM**: Model is compact, but fidelity less than CTM
  
  – **QTM**: Queue Transmission Model (Guilliard et al, 2016)
    • Compact, moderate fidelity MILP-based model
Each link is a FIFO queue of traffic
Vertically stacked at stop line
Explicitly model link delays (travel time between intersections)
Non-Homogenous Link Flow LP

- Constraints:

\[
\begin{align*}
\text{in}^n_j \leq Q^\text{IN}_j \\
q^n_{j,\text{in}} = \text{in}^n_j \Delta t^n + \sum_{i=1}^{Q} f^n_{i,j} \Delta t^n \\
\text{out}^n_j \leq Q^\text{OUT}_j \\
q^n_{j,\text{out}} = \text{out}^n_j \Delta t^n + \sum_{i=1}^{Q} f^n_{i,j} \Delta t^n \\
f^n_{j,i} = F^{\text{PROB}}_{j,i} \sum_{k=1}^{Q} f^n_{j,k} \\
q^n_{j,\text{out}} \leq q^n_{j,-1} \\
q^n_j \leq Q^{\text{MAX}}_j \\
q^n_{j,\text{in}} = q^n_{j,-1} - q^n_{j,\text{out}} \\
q^n_{j,\text{in}} + \sum_{k=n-b+2}^{n-1} q^n_{k,\text{in}} \leq q^{\text{MAX}}_j - q^{n-1}_j \\
\end{align*}
\]

Non-homogenous allows exact modeling of link delays + compact models with fewer time steps

q1-q7 delay  q7-q9 delay
What to Optimize?

• Minimize delay
  - i.e. area between arrival & departure curves
  - equal to car-seconds of delay

• Formally: \[
  \left( \sum_{n=1}^{N} \sum_{j=1}^{Q} (T^{MAX} - t^n + 1)q_{j,\text{out}}^n + \sum_{n=1}^{N} \sum_{j=1}^{Q} (T^{MAX} - t^n + 1)i n_j^n \right)
\]
Define the MILP and Solve!

- Determine $\Delta t$’s, instantiate variables
- $p$ – binary phase, $q$ – queue volumes, $f$ – flows
Fixed Time vs. QTM Optimized Control

- Peak queue build up:
  - Fixed: 7 min 20 sec
  - Optimized QTM: 6 min 40 sec ⇒ 40 sec less delay

Time to clear network:

- **Fixed**: 7 min 20 sec
- **Optimized QTM**: 6 min 40 sec ⇒ 40 sec less delay
Quantitative Comparison of Fixed Time vs. QTM

Time to clear network:

- **Fixed (solid):** 7 min 20 sec
- **Optimized QTM (dashed):** 6 min 40 sec $\Rightarrow$ 40 sec less delay

Note: **CTM** could not scale to this domain, **LTM** model not accurate enough
QTM Summary

• QTM is a compact macroscopic model of traffic flow

• QTM + MILP solver = optimal signal control
  – If there is a complex, optimal pattern, MILP finds it

• Moderate scalability up to ~10 intersections
  – Not clear how to optimally scale to large cities
P&S Approaches: SURTRAC
INTERSECTIONS ARE DUMB

Unnecessarily disrupt traffic flows
- Congestion costs US Cities $160B annually in time and fuel
- Drivers spend 40% of their time on surface streets idling

Programmed for *average* conditions
- Actual conditions vary greatly and change over time

Only use sensors in mundane ways
- Traffic signal control intelligence has not advanced in 40 years
**Goal:** Real-time optimization of urban road networks

**Technical Approach:**

- Collaborative Online Planning
- **Decentralized control**
- **Coordinated Action**
How Does Surtrac Work?

1. Observe Traffic

2. Compute phase schedule and begin executing

3. Communicate schedule to down-stream neighbors

4. Repeat cycle every few seconds
Key Technical Ideas

• Treat intersection control problem as a *single machine* scheduling problem
  – Aggregate representation of traffic flows to identify *input jobs*

• Communicate planned outflows to downstream neighbors to give visibility of future *input jobs*
Aggregate Flow Representation

Clusters (jobs): height = flow rate, width = duration, area = number of vehicles

1. **Threshold-based clustering**: merge clusters with small gaps

2. **Anticipated queue**: Anticipate the number of vehicles that are either presently in the queue or will join it before it clears (Lämmer & Helbing, 2008)

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**Startup lost time**
A **Schedule** = a sequence of all clusters (indivisible jobs)

Schedule → **Planned Signal Timing Plan** (for traffic light)
Problem: Minimize the cumulative delay of all jobs, subject to:

- timing constraints for safety (yellow time) and fairness ($G_i^{\text{min}}$ and $G_i^{\text{max}}$ for each phase)
Scheduling Strategy

• Forward dynamic programming search
  – New job added to at each decision stage
  – Eliminate dominated solutions at each stage (same current phase, same jobs, *different orders*)
  – Only keep the state with minimum delay for each extension (greedy)

  – Time complexity: $|\text{phases}|^2 \prod (|\text{clusters}_i|+1)$
Setup in the Field
Surtrac in East Liberty

Penn Circle Test Site (Jun 2012):

<table>
<thead>
<tr>
<th></th>
<th>% Improv.</th>
<th>Travel Time</th>
<th># of Stops</th>
<th>Wait Time</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM rush</td>
<td>30%</td>
<td>29%</td>
<td>48%</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>Mid Day</td>
<td>33%</td>
<td>53%</td>
<td>50%</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>PM rush</td>
<td>23%</td>
<td>9%</td>
<td>36%</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>Evening</td>
<td>18%</td>
<td>35%</td>
<td>28%</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>26%</td>
<td>31%</td>
<td>41%</td>
<td>21%</td>
<td></td>
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</tbody>
</table>

Bakery Square Expansion (Nov 2013):

<table>
<thead>
<tr>
<th></th>
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<th>Wait Time</th>
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</tr>
</thead>
<tbody>
<tr>
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<td>17%</td>
<td>34%</td>
<td>33%</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>Mid Day</td>
<td>21%</td>
<td>37%</td>
<td>38%</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>PM rush</td>
<td>29%</td>
<td>45%</td>
<td>46%</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>24%</td>
<td>40%</td>
<td>42%</td>
<td>21%</td>
<td></td>
</tr>
</tbody>
</table>
150 More Intersections are on the way.
Accounting for Network Pressure

**[Hu & Smith IJCAI 2017]**

**Issue:** As road network becomes saturated, coordination between intersections deteriorates

**Approach:**
- Define and measure “network pressure”
- Weight intersection clusters to bias optimization toward queue management

**Neighbor Pressure:**
\[
\begin{align*}
Q &= Q_{up} + Q_{local} - Q_{down} \\
Q' &= Q'_{up} + Q'_{local} - Q'_{down} \\
\Delta Q &= Q - Q' \\
\Delta Q' &= Q' - Q
\end{align*}
\]

where
\[
Q_{up} = \sum_k \alpha_k Q^{(k)}_{up} \\
Q_{down} = \sum_k \alpha_k Q^{(k)}_{down}
\]

\(\alpha_k = \) turning prop. of route \(k\)

**Local Pressure:**
\[
\begin{align*}
\Delta F &= \text{InFlow}_{NS} - \text{InFlow}_{EW} \\
\Delta F' &= \text{InFlow}_{EW} - \text{InFlow}_{NS}
\end{align*}
\]
Performance at Different Demand Levels

- Simulation results using Baum-Centre corridor model

**Observations:**
- Negligible effect at low, medium traffic levels
- Substantial improvement in heavy traffic conditions
Expressive Real-Time Intersection Scheduling
[Goldstein & Smith AAAI 2018]

- Expand precision of intersection control scheduling to lane-based flow models
- Cope with extended search space through use of A*
- 5-10% improvement in delay over Surtrac in simulation
Advantages:

– Optimizes signals for the actual traffic on the road right now
– Coordination for networks, not just arterials
– Optimizes for multiple travel modes
– Scalable, incremental deployment
P&S Approaches: SimplifAI
Introduction to SimplifAI

SimplifAI exploits planning for dealing with unexpected traffic conditions in a large urban area.

Initially involving BT, Transport for Greater Manchester, 2 SMEs, and the University of Huddersfield

- **Overall aims**: To use traffic, air quality and environmental data to automatically produce signal strategies for regions of a city centre in order to address unforeseen events.
SimplifAI evolution

- 2014: Work begins with University of Huddersfield on concept design for Simplifai (innovation voucher)
- 2015: Collaborative research, supported by Innovate UK to prove Simplifai concept
- 2016: 'First of a Kind' business case development
- 2017: 'First of a Kind' live prototype with Transport for Greater Manchester
- 2018: TUSForge and Pitch@Palace (finalists) accelerator programmes

KAM Futures Limited
Simplifai Systems Limited
The PDDL+ Approach of SimplifAI

PDDL+ is an expressive planning language that allows to describe Mixed discrete-continuous problems (modelling durations and continuous changes).

- Processes have been used for describing flows of vehicles and modelling green times.
- Events control limits
- The planner can control traffic phases using actions.

Scalability is not an issue (up to 11k vehicles problems solved in few seconds)!
Required Information

- For each junction, minimum and maximum time of phases
- Description of the network
- Current occupancy of links in the network
- Description of the (expected) amount of vehicles entering the network

Different kind of goals can be specified
Example of the Model: Information

(= (queue R10) 5.0)
(= (max_queue R10) 35.0)

(= (flowvalue s1 R10 R7) 0.7)
(= (flowvalue s1 R10 R9) 0.5)

(= (greentime s1) 0)
(= (mingreentime s1) 5)
(= (mingreentime s0) 5)
(= (maxgreentime s1) 40)
(= (maxgreentime s0) 20)
(active s0)
(contains J2 s0)
(next s0 s1)
(next s1 s0)
Part of the Domain Model

(:action `switchPhase`
  :parameters (?p - phase ?i - intersection)
  :precondition (and
    (controllable ?i)
    (active ?p) (contains ?i ?p)
    (> (greentime ?i) (mingreentime ?p))
  )
  :effect (and
    (trigger ?i)
  ))
How Traffic Moves?

(:process flowrun_green
 :parameters (?p - phase ?r1 ?r2 - road)
 :precondition (and
   (active ?p)
   (> (queue ?r1) 0.0)
   (> (flowvalue ?p ?r1 ?r2) 0.0)
   (< (queue ?r2) (max_queue ?r2))
 )
 :effect (and
   (increase (queue ?r2) (* #t (flowvalue ?p ?r1 ?r2)))
   (decrease (queue ?r1) (* #t (flowvalue ?p ?r1 ?r2)))
 ))
How Does a Plan Look Like?

05.0: (switchphase l1867_4574 l1349_1867 s1867_s0 n1867) [0.000]
65.0: (switchphase l6013_5840 l1202_6013 s6013_s0 n6013) [0.000]
65.0: (switchphase l6014_6013 l6159_6014 s6014_s1 n6014) [0.000]
65.0: (switchphase outside l1349_1353 s1353_s1 n1353) [0.000]
65.0: (switchphase l1202_6013 l1349_1202 s1202_s2 n1202) [0.000]
65.0: (switchphase l1349_3621 l1202_1349 s1349_s0 n1349) [0.000]
70.0: (switchphase outside l1352_1353 s1353_s2 n1353) [0.000]
70.0: (switchphase l1349_3621 l1202_1349 s1349_s1 n1349) [0.000]
70.0: (switchphase l1202_6013 l1349_1202 s1202_s3 n1202) [0.000]
70.0: (switchphase l6013_5840 l6014_6013 s6013_s1 n6013) [0.000]
Deployment Architecture

Domain Engineers

Persistent Knowledge
e.g. Effectors / domain topology + physics

DOMAIN MODEL

Current State

Goals / Tasks

Status Knowledge

Planner

Real Time Generation Of Deterministic Plans

Domain Experts

Monitor + Trigger

Real Time Updates

Simulated World

Physical World (Simulated by REAL HISTORICAL DATA)
Evaluation with Transport for Greater Manchester
High Complexity of Junctions

STAGE 1: flows L3966_1202 to L1202_1349 = 0.64522; L3966_1202 to L1202_6013 = 0.71739; L6013_1202 to outside = 0.41067

INTERGREEN 0 seconds

STAGE 2: Etc etc

STAGE 7: flows L6013_1202 to outside = 0.41067; L6013_1202 to outside = 0.41067; L6013_1202 to L1202_1349 = 0.165

INTERGREEN 5 seconds
(ORIGINAL 5)
Test Cases

Set 1 Clear saturated road link asap
Set 2 Clear several saturated road links asap
Set 3 Clear region asap
Set 4 Clear saturated road link with nearby road works

*Overall: Investigate Tailpipe Emission Savings*

Tests and Evaluation done using ENHSP and UPMUrphi, extended with a domain-specific heuristic.
Generated plans tested by **Visual inspection**

- Human experts checked for “common sense” strategy: maximise green time to light stages allowing vehicles to leave goal links, minimise others. In case where goals are concurrent, a balance among green light stages is expected.

- **Result:** *All strategies had recognisable common sense parts*
Results (2)

Generated plans tested by Traffic Simulators

- SUMO and AINSUM
- Compared against fixed-time manually optimised strategies which would be in place in the case of exceptional event

**Result:** generated strategies cleared links better than manually optimised timings, typically by 25%
SimplifAI: In a Nutshell

- Project’s “AI planning” work demonstrated the effectiveness of the auto-generation of goal-directed strategies within an area of Manchester.

- Strategies of 5–30 minutes are produced in real-time using the ENHSP planner and domain-specific heuristics.

- In terms of emissions, a 5% reduction has been observed on average.
SimplifAI: And Now?

- Working on a specifically-designed planning engine
- Real-world collaborations and exploitation are ongoing
- We are looking to merge and reason upon information gained from other traffic means and authorities (e.g., highways)
- Connected vehicles...
AI4ME: EPSRC Funded Project

- Vehicles approaching a urban region communicate to the traffic control centre their destination, and preferences / requirements for the route
- The AI controller, on the basis of the current network situation and provided metrics to maximise, calculates a route for the vehicle
Future Directions
Smart Infrastructure for Future Urban Mobility

• Opportunities and Research Directions
  – Connected and Autonomous Vehicles
  – Ubiquitous Sensing
  – Multi-modal trip planning
  – Integrated municipal services (traffic signals, snow removal, emergency vehicles, etc.)
  – Sustainable infrastructure
  – … (What are some other suggestions here)
Integration of Signal Control with Connected Vehicle Technology

- Better sensing
- Use of mode, route information
- Incident detection and real-time re-routing
Enhanced Mobility

Real-time Bus Information
- Equip Port Authority buses with DSRC
- Signal system uses info. to better predict bus arrivals and provide smart transit priority

Sharing Vehicle Routes
- Connected Vehicle (CV) shares its route with the network
- Intersections incorporate this info. into local optimization
Safe Intersection Crossing for Pedestrians with Disabilities

Concept: A smartphone app that allows pedestrians to interact directly with a smart signal control system

Capabilities:
- Personalized crossing time
- Active monitoring and dynamic extension
- Anticipation of arrival time to streamline crossing
PHAENON Sensor Networks

• Measure real-time traffic conditions for:
  – Incident detection
  – Congestion due to cruising for parking
  – ...

Low-cost automatic vehicle identification (AVI) sensors

Dense, ubiquitous sensor network deployments

Reconstructed vehicle routes
Real-Time Vehicle (Re-)Routing

Concept: *Exploit network-level schedule to provide real-time routing guidance*

Approach

- Distributed computation of shortest path using most recently generated plans at each intersection
- Fall back on historical delay information when planning horizon is exceeded
Broader Vision

• As X2I communication proliferates, the signal network will become the gateway for real-time information

• Self-driving cars in urban environments will depend just as heavily on this information

• Connectivity and smart signals can also enhance sustainability

• Smart infrastructure is key to future urban mobility