Online auction Designs for Traffic Intersection Operations

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Main idea

• Transportation systems normally work on a FIFO rule.
• FIFO is *the fairest rule* but may not the most efficient (efficient = maximum satisfaction from users)
• There may be an efficiency loss due to lack of use of information.
• Smartphones: elicit this private information from drivers on real time and change this FIFO rule.
• New challenges: efficiency, fairness and the role of regulation.
• Two examples: vehicle position in highway and traffic lights.
Mechanism Design

• Mechanism definition: a mechanism is a game form that induces a Bayesian game on a set of agents.

• Purpose: elicit private information from agents to reach a particular goal: efficiency or optimality.
  – Efficient mechanism: total welfare is maximized.
  – Optimal mechanism: revenue extracted from agents is maximized.

• A direct mechanism $D = (k, p)$
  – Allocation function $k: \Theta \rightarrow K$
  – Payment function $p: \Theta \rightarrow \mathbb{R}$
  – $\Theta$ is the space of players’ types (private information)
Mechanism Design: Incentive Compatibility constraints

- **Incentive compatibility (IC):** truth-telling is an equilibrium of the induced game, condition on other agents telling the truth as well.
  - Dominant Strategy Incentive Compatibility (DSIC)
  - Bayesian Incentive Compatibility (BIC)

<table>
<thead>
<tr>
<th>Use of priors</th>
<th>Economists</th>
<th>CS/Engineers</th>
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<tr>
<td>Use of priors</td>
<td>They prefer them (BIC)</td>
<td>Real implementability (DSIC)</td>
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<tr>
<td>Approach</td>
<td>Calculus based</td>
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<tr>
<td>Comp. Efficiency</td>
<td>No primary goal</td>
<td>Primary goal</td>
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Mechanism Design: IR constraints and environments

• Individual rationality (IR): each agent, despite other agents’ reports, is better off to tell the truth than stay out.

\[ u_i(k(\theta_i, \theta_{-i}), \theta_i) \geq \bar{u}_i(\theta_i) \ \forall (\theta_i, \theta_{-i}) \in \Theta \]

• We’ll work on quasi-linear environments:

\[ u_i(k(\theta), \theta_i) = v_i(k(\theta), \theta_i) - p_i(\theta) \]
The Vickrey-Clarke-Groves Mechanism

The VCG mechanism is:

\[ k^*(\theta) = \arg\max_k \sum_i v_i(k(\theta), \theta_i) \]

\[ p_i(\theta) = \sum_{j \neq i} v_j(k_{-i}^*(\theta), \theta_j) - \sum_{j \neq i} v_j(k^*(\theta), \theta_j) \]

The VCG is DSIC, ex-post IR. But problems…

1. Collusion
2. Not budget balanced
3. Shill bidding vulnerable
Introduction of current research

Problem:
• Current traffic light systems do not account for VoT heterogeneity.
• There is an efficiency loss.
• Smartphones can allow us to elicit this private information from drivers on real time.

Proposed solution:
• Value exchange traffic light system.
• Aiming to improve the efficiency of urban traffic networks, not to extract revenue from agents.
Literature review

• Mostly based on reservation systems for self-driving vehicles (Dresner and Stone, 2004) (Carlino et al., 2013)

• Simulation on large cities, or intersection scale simulation without clear theoretical-based Car Following model.

• They don’t address the microeconomic aspects of intersections.

• Desired mechanism properties not thoroughly checked.

• Some research groups focused on AI protocols (Schepperle and Böhm, 2008)
Problem configuration

• Mechanism modelling of a single isolated intersection.
• Cycle-free traffic light.
• VCG mechanism.
• Allocations are phases (winning approach + phase duration).
• Coded on MATLAB.
Problem configuration (I)

- 2 phase one-way intersection
- The mechanism knows about players after being close than $d = 500\text{ ft}$. Approaching speed = 40mph.
- Intersection has a width $w = 120\text{ ft}$.
- There is a $t_{lost}$ at every start of GREEN.
- Vehicle trajectories modelled through Newell’s CFM.
- The bidding agents are the two approaches
Problem configuration (II)

• First step: decide winning approach \( k^* \)
  \[ k^* = \arg\min \{ c_1^{\text{win}} + c_2^{\text{lose}}, c_1^{\text{lose}} + c_2^{\text{win}} \} \]
  \[ c_l^{\text{win}} = \sum_{i \in I} \theta_itime_i^{(l \text{ wins})} \]
  \[ c_l^{\text{lose}} = \sum_{i \in I} \theta_itime_i^{(l \text{ loses})} \]
  \[ \text{Next phase and prices are decided at the end of the current phase.} \]
  \[ \text{Length of next outcome: time required for the winning approach cars to safely cross the intersection.} \]
  \[ p_l(\theta) = \sum_{j \neq l} v_j(k^*_l(\theta)) - \sum_{j \neq l} v_j(k^*_j(\theta)) \]
  \[ \text{Then the price per approach is divided by the number of drivers in that approach.} \]

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Results

- Two different types of arrivals will be tested:
  - Uniform
  - Poisson
- Sensitivity analysis based on arrival flow, ratio of values of time per approach.
- Arrivals are symmetric (perfect conflict, worst case analysis): when flows are the same at both approaches.
- Computation of prices and agents’ utilities
- Proposed system is compared to an optimal fixed-cycle traffic light

\[ C = \frac{2*t_{lost}}{v_c} \left( 1 - \frac{PHF}{v/c} \right) \left( 1 - \frac{h_{sat}}{3600} \right) \]

\[ t_{lost} = 3s \quad PHF = 1 \quad v/c = 1 \quad h_{sat} = 2.3s \]

- If calculated \( C \) is < 30, \( C \) will be set to 30s.
Results: Poisson case. Trajectories (ft & s) $\theta_2 = 20, q = 720 \text{ veh/h.}$
Results: Poisson case. Travel times and valuations ($cost_i = \theta_i v_i$) $\theta_2 = 20$, $q = 720$ veh/h.
Results: Poisson case. Travel times and valuations

\[(\text{cost}_i = \theta_i \nu_i) \theta_2 = 20, q = 720 \text{ veh/h.}\]
Results: Poisson case, prices and u’s.

Prices per approach

- Price, approach lane 1 in $
- Price, approach 2 in $

Prices per car per approach

- Price per car, approach 1 in $
- Price per car, approach 2 in $

Utility per car approach 1

- Utility per car, approach 1 in $

Utility per car approach 2

- Utility per car, approach 2 in $

Total average utility

- Total average utility ($/car)

Liberty Approach 1
- Fixed-cycle Approach 1

Proposed system Ap.1

- Proposed system Ap.2
- Fixed-Cycle Approach 2

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Results: Poisson case. Sensitivity analysis over $q \ (\text{veh/h})$ and $\theta_2 \ ($/h).

- **Av. Cost Approach 1** Proposed system
- **Av. Cost Approach 1** Proposed system over Fixed-Cycle
- **Av. Cost Approach 2** Proposed system
- **Av. Cost Total Cost**
- **Av. Benefit Approach 1** Proposed system over Fixed-Cycle
- **Av. Benefit Approach 2** Proposed system over Fixed-Cycle
- **Av. Total Benefit** Proposed system over Fixed-Cycle

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Comments about results

- As it is by now, mechanism considers only future costs and not past ones.
- This can produce very long phases when there is a high difference in values of time.
- Need to refine the allocation rule.
- The outcome is shared by all the agents in the approach. How does this affect IC, IR and collusion?

Further research

1. Signal coordination. Adaptive control system on network
2. 8 phase signal. Budget balancing assessment.
3. Simulation on Irvine Triangle in Paramics (Yang, 2011)