Coordinated Platoon Routing in a Metropolitan Network

Jeffrey Larson Todd Munson Vadim Sokolov

Argonne National Laboratory

October 10, 2016

Computationally Enhanced Mobility

- Developing high-fidelity simulation tools to estimate the energy impact of Connected and Automated Vehicles.
- Developing algorithms for optimally routing vehicles with platooning capabilities.

Computationally Enhanced Mobility

- Developing high-fidelity simulation tools to estimate the energy impact of Connected and Automated Vehicles.
- Developing algorithms for optimally routing vehicles with platooning capabilities.

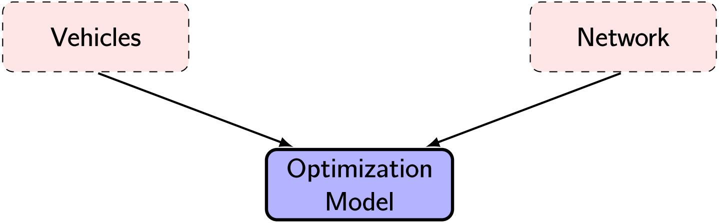
▸ POLARIS

Workflow

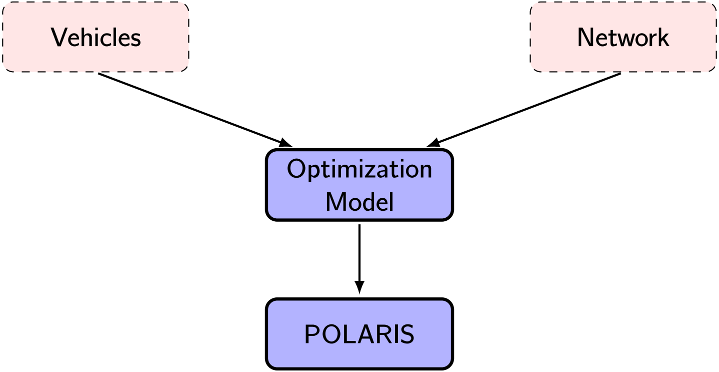
Vehicles

Network

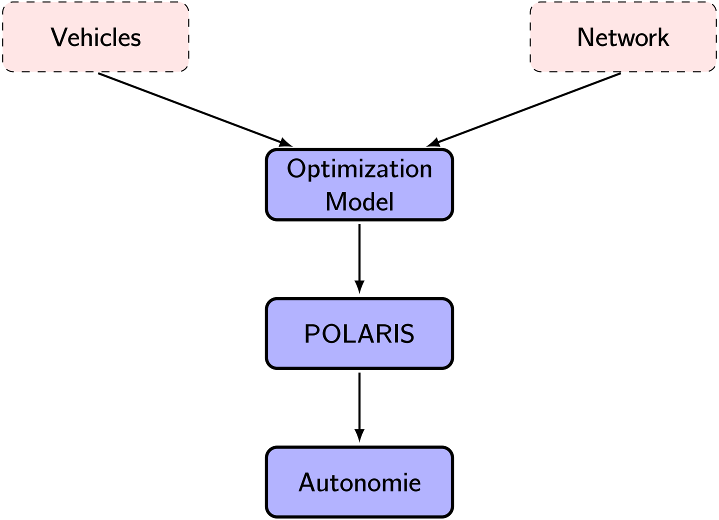
Workflow



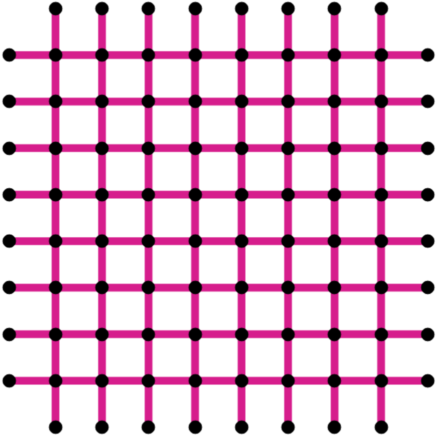
Workflow



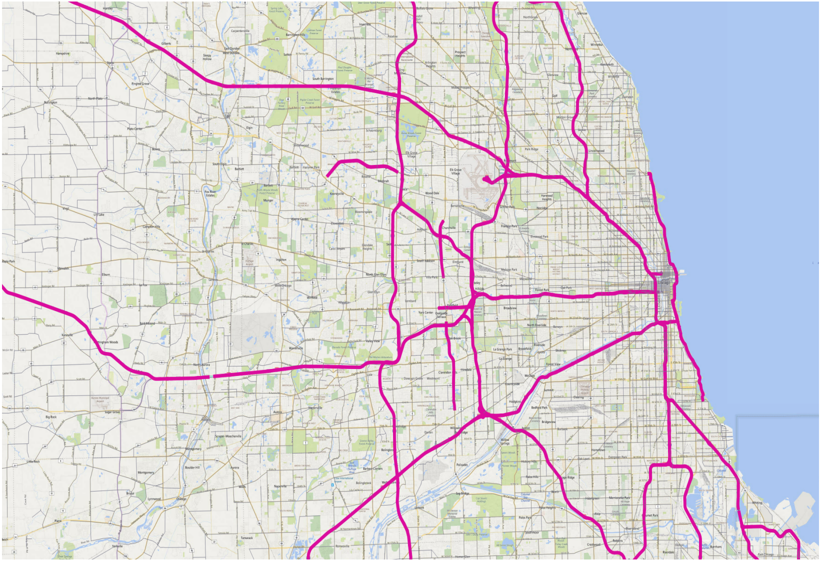
Workflow



Networks



Networks



Animation

Grid

Chicago

Optimization Model - Model Parameters

Set	Meaning
V	Vehicles to route
I	Network nodes
$E \subseteq I \times I$	Network edges

Optimization Model - Model Parameters

Set	Meaning
V	Vehicles to route
I	Network nodes
$E \subseteq I \times I$	Network edges

Parameter	Meaning
O_v	$v \in V$ origin node
D_v	$v \in V$ destination node
T_v^O	$v \in V$ origin time
T_v^D	$v \in V$ destination time
C_v^W	waiting cost for $v \in V$
$C_{i,j}$	cost for taking $(i, j) \in E$

Optimization Model - Model Variables

Variable	Meaning
$f_{v,i,j}$	1 if v travels on (i,j)
$q_{v,w,i,j}$	1 if v follows w on (i,j)
$e_{v,i,j}$	Time v enters (i,j)
$w_{v,i}$	Time v waits at i

Optimization Model - Model Constraints

Node outflows must equal inflows.

When platooning, enter times are equal.

Platooning requires at least two vehicles.

Only one vehicle can follow.

T_v^O plus waiting time is the origin enter time.

T_v^D is the final enter time plus the time required to travel the final edge plus waiting at the end.

Intermediate enter times are equal plus the travel and waiting times.

Can't have nonzero enter time if there is no flow.

Can't have nonzero wait time if there is no flow.

Platoon requires flow for the leader.

Platoon requires flow for the followers.

Optimization Model - Example Constraints

Can't have nonzero enter time if there is no flow.

$$e_{v,i,j} \leq M f_{v,i,j}; \quad \forall v \in V,\ (i,j) \in E$$

Optimization Model - Example Constraints

Can't have nonzero enter time if there is no flow.

$$e_{v,i,j} \leq Mf_{v,i,j}; \quad \forall v \in V, \ (i,j) \in E$$

Enter times are equal when platooning.

$$-M(1 - q_{v,w,i,j}) \leq e_{v,i,j} - e_{w,i,j} \leq M(1 - q_{v,w,i,j})$$

Optimization Model - Example Constraints

Can't have nonzero enter time if there is no flow.

$$e_{v,i,j} \leq M f_{v,i,j}; \quad \forall v \in V,\ (i,j) \in E$$

Enter times are equal when platooning.

$$-M(1 - q_{v,w,i,j}) \leq e_{v,i,j} - e_{w,i,j} \leq M(1 - q_{v,w,i,j})$$

Objective:

$$\text{minimize} \quad \sum_{v,i,j} C_{i,j} \left(f_{v,i,j} - \eta \sum_{w} q_{v,w,i,j} \right) + \sum_{v,i} C_v^W w_{v,i}$$

Helping the MIP solver

Helping the MIP solver

Consider v and w platooning on edge (i, j) only if

$$\max\left\{T_v^O + M_{O_v,i},\, T_w^O + M_{O_w,i}\right\} + T_{i,j} \leq \min\left\{T_v^D - M_{D_v,j},\, T_w^D - M_{D_w,j}\right\}$$

where $M_{a,b}$ is the minimum time required to reach b from a.

Helping the MIP solver

Consider v and w platooning on edge (i, j) only if

$$\max\left\{T_v^O + M_{O_v,i},\, T_w^O + M_{O_w,i}\right\} + T_{i,j} \leq \min\left\{T_v^D - M_{D_v,j},\, T_w^D - M_{D_w,j}\right\}$$

where $M_{a,b}$ is the minimum time required to reach b from a.

Lemma

If vehicles use a fraction η less fuel when trailing in a platooning and t_s is the shortest time for a vehicle to travel from its origin to destination, it will never travel a path longer than $\frac{1}{1-\eta} t_s$.

Helping the MIP solver

Consider v and w platooning on edge (i, j) only if

$$\max\left\{T_v^O + M_{O_v,i},\, T_w^O + M_{O_w,i}\right\} + T_{i,j} \leq \min\left\{T_v^D - M_{D_v,j},\, T_w^D - M_{D_w,j}\right\}$$

where $M_{a,b}$ is the minimum time required to reach b from a.

Lemma

If vehicles use a fraction η less fuel when trailing in a platooning and t_s is the shortest time for a vehicle to travel from its origin to destination, it will never travel a path longer than $\frac{1}{1-\eta} t_s$.

Lemma

There exists an optimal platoon routing in which no two vehicles split and then merge together.

Problem Setup

- Vehicles all travel at free-flow speeds

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes
- Start times drawn uniformly from [0,100]

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes
- Start times drawn uniformly from [0,100]
- Destination times

$$T_D^v = T_O^v + M_{O_v, D_v} + p,$$

for some time $p \geq 0$

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes
- Start times drawn uniformly from [0,100]
- Destination times

$$T_D^v = T_O^v + M_{O_v,D_v} + p,$$

  for some time $p \geq 0$
- No cost for waiting

Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes
- Start times drawn uniformly from [0,100]
- Destination times

$$T_D^v = T_O^v + M_{O_v,D_v} + p,$$

  for some time $p \geq 0$
- No cost for waiting
- 10 replications

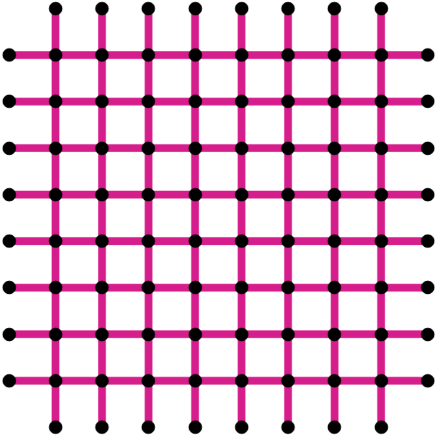
Problem Setup

- Vehicles all travel at free-flow speeds
- 10% savings for platooning
- 25 vehicles
  - Grid: random origin/destination pairs
  - Chicago: origin/destination pairs drawn from the most common morning commutes
- Start times drawn uniformly from [0,100]
- Destination times

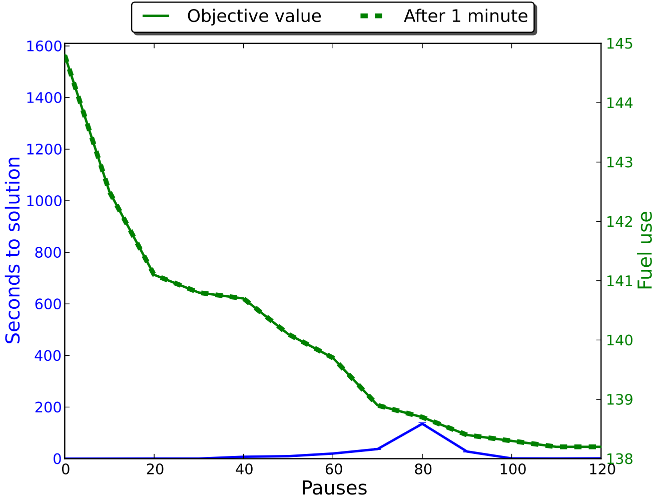
  $$T_D^v = T_O^v + M_{O_v,D_v} + p,$$

  for some time $p \geq 0$
- No cost for waiting
- 10 replications
- Running Gurobi until its optimality gap is less than 1e-8

Example solution times

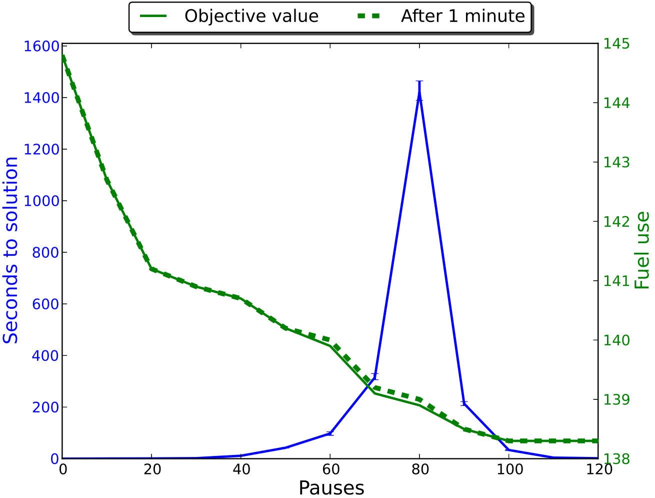


Example solution times



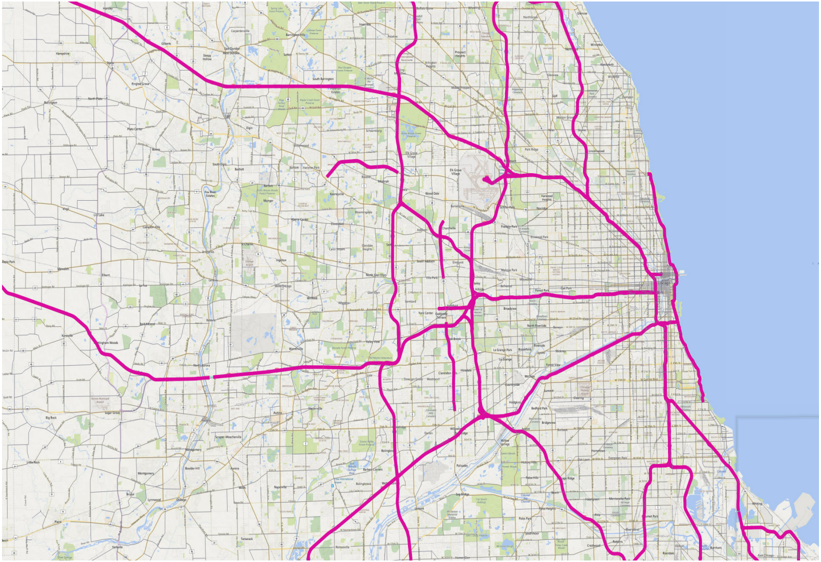
Grid, waiting allowed at intermediate nodes

Example solution times

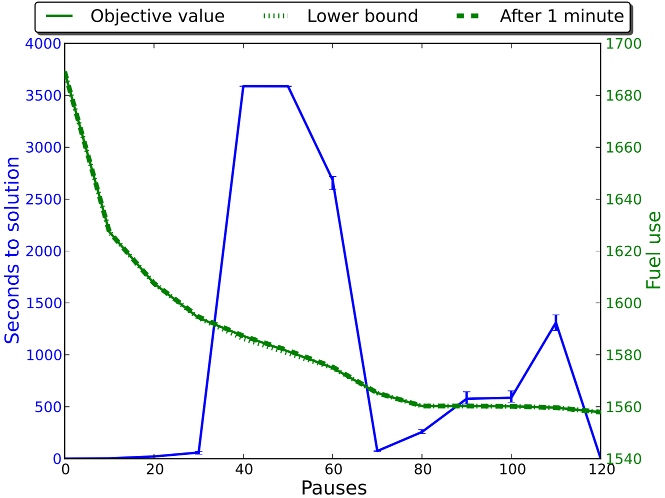


Grid, no waiting allowed at intermediate nodes

Example solution times

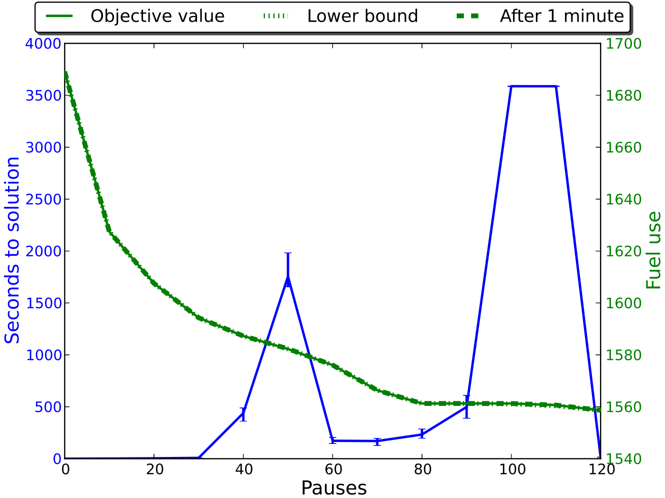


Example solution times



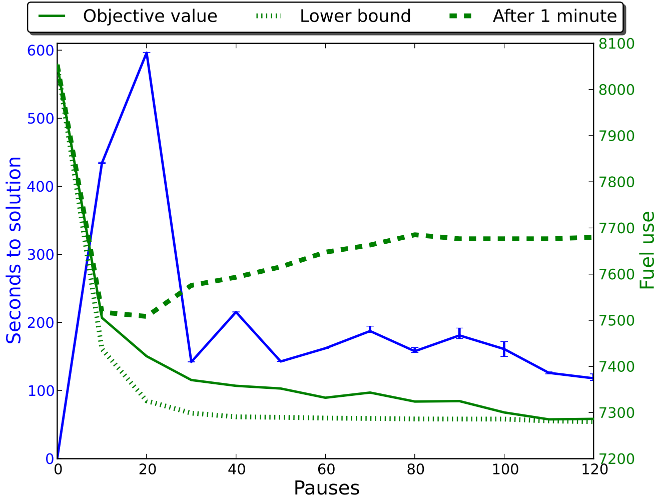
Chicago, waiting allowed at intermediate nodes

Example solution times



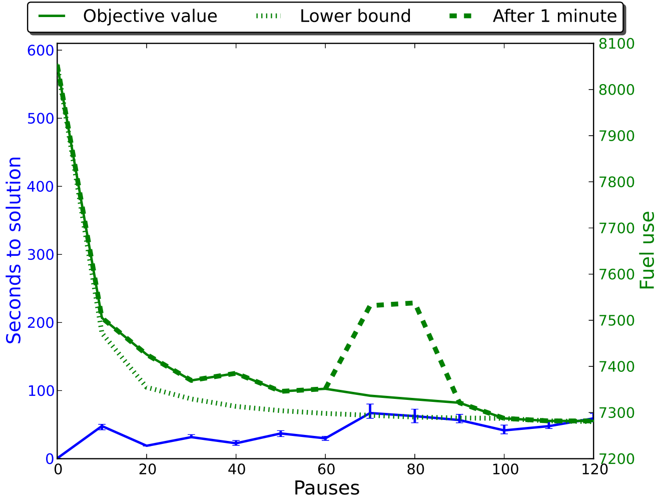
Chicago, no waiting allowed at intermediate nodes

Example solution times



Chicago, 100 vehicles, (20 from each of the 5 most common origin/destination pairs), stopping at 1% optimality gap

Example solution times



Chicago, 100 vehicles, (20 from each of the 5 most common origin/destination pairs), stopping at 1% optimality gap, using lemmas

Lemma

$$\max\left\{T_v^O, T_w^O\right\} + M_{O_v,D_v} \leq \min\left\{T_v^D, T_w^O\right\}. \tag{1}$$

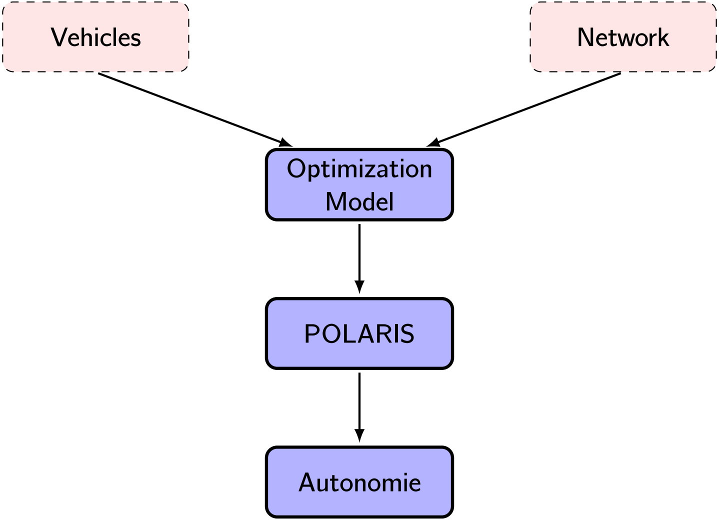
Lemma

Let $v, w \in V$ satisfying $O_v = O_w$, $D_v = D_w$, and (1). Then if an optimal solution has $q_{v,w,i,j} = 0$ for any edge $(i,j) \in E$, there exists an optimal solution with $q_{v,w',i,j} = 0$ for all (i,j) all w' arriving later than w.

Current work

- Non-free-flow speeds
- Graph-reduction techniques
- Larger problems
- http://www.mcs.anl.gov/~jlarson/Platooning/

Workflow



Workflow