Deployment and Testing of Optimized Autonomous and Connected Vehicle Trajectories at a Closed-Course Signalized Intersection

Clark Letter*, Lily Elefteriadou, Mahmoud Pourmehrab, Aschkan Omidvar
Civil & Coastal Engineering

Sanjay Ranka, Patrick Emami
Computer & Information Science & Engineering

Carl Crane, Patrick Neal
Mechanical & Aerospace Engineering
Problem Description

Given: the arrival information of automated vehicles and conventional vehicles
Goal: to optimize the average delay by advising automated vehicles and controlling signal phase and timing
Involves Sensing technologies
- Dedicated Short Range Communication
- Radar
- (Camera, Lidar)

Autonomous Vehicle Technology
- Navigation and Localization algorithms

Optimization Algorithm
- Vehicle Path Optimizer
- Signal Status Optimizer
Intelligent Intersection Control System

1. Intelligent Intersection Control Algorithm
   - Arrival information: (Lane, Speed, Location, Length, Max acceleration, Max deceleration, Destination)
   - Vehicle Arrivals

2. Conventional Vehicles
3. Device to collect and fuse vehicle arrivals information
   - Arrival information: (Lane, Speed, Location)

4. Optimal Signal Decision

5. Optimized Trajectories

6. Signal Controller
   - Signal Heads

Camera/Radar to obtain conventional vehicle arrivals
Goal: Classify and track all traffic participants up to ~600 feet away from the intersection

Challenging Multisensor-Multitarget problem
- Occlusion is common in medium-heavy traffic
- Need to synchronize and associate sensor data in real-time
- Need accurate models of uncertainty in sensor measurements and vehicle dynamics
Traditional Traffic Sensors + V2I

- Dedicated Short Range Communication (DSRC) for Vehicle-to-Infrastructure (V2I) (range ~900 ft)
- Doppler-based advanced detection traffic radar (range ~600 ft)
- Video Camera (range ~300 ft)
V2I Communication Infrastructure

Vehicles are equipped with On-Board Units (OBUs) containing a DSRC radio.

In the image:
2. Cohda Wireless Mk5 DSRC radio
3. Small computer for developing OBU software
4. GPS antenna
A Cohda Wireless Mk5 is used as our Road-Side Unit (RSU), and is connected to a server running our sensor fusion and optimization algorithms at the intersection. Can receive Basic Safety Messages from multiple instrumented vehicles simultaneously over the 5 Ghz band.
Demonstration of Fusing DSRC and Radar

Tested proof of concept DSRC and radar sensor fusion system at isolated intersection

One Smartmicro radar and Five Cohda Wireless DSRC units

Demonstrated ability to classify and track connected and conventional vehicles in isolated, low-traffic scenario

Uncertainty in GPS from off-the-shelf DSRC

Fusing data from DSRC with traffic radar and video camera data requires careful time synchronization and a probabilistic model for the uncertainty in the reported vehicle position.

Need sub-meter precision to ensure safety of traffic participants.

GPS can be affected by tall buildings, trees, and poor satellite coverage due to, e.g., cloudy skies.
DSRC GPS compared with high-precision GPS

The DSRC GPS error is biased when vehicle is in motion (partly due to small clock synchronization error between GPS sensors).

Overall, measurement error appears to be non-Gaussian, and the bias (offset from 0) proves to be difficult to estimate and remove.
Optimization Algorithm

Objective: Minimize the Average Travel Time Delay experienced at the intersection

Approach: Mathematical Programming

Description:
- Automated Vehicles Shall receive a trajectory at the time they enter the detection range
- The Trajectories Shall comply with signal status and have no conflict with other vehicles
- The joint decision on Trajectories and Signal Phase and Timing yields the minimum average travel time delay
Adaptive Signal Control with Trajectory Optimization

With information about trajectories, green intervals can be allocated to serve phases. The lag time accounts for the distance vehicles must travel to arrive at the stop bar. This image shows how green and yellow times that are assigned to each phase can cover arrivals (the ones with delta t) on a continuous basis.
Three-stage Trajectory for Lead AV

\[ d_{n_1}(t) = \begin{cases} 
  d_{n_1}^1(t) & \text{for } [t_{n_1}^0, t_{n_1}^1] \\
  d_{n_1}^2(t) & \text{for } [t_{n_1}^1, t_{n_1}^2] \\
  d_{n_1}^3(t) & \text{for } [t_{n_1}^2, t_{n_1}^3] 
\end{cases} \]
Trajectory of a Follower Vehicle

Diagram showing the distance-time relationship for a follower vehicle, with key points and stages labeled.
Automated Vehicle Trajectory Optimization

Depending on vehicle class and position:

- **Lead automated vehicle Trajectory Optimization (LTO)**
- **Follower automated vehicle Trajectory Optimization (FTO)**
- **Lead conventional vehicle Trajectory Estimation (LTE)**
- **Follower conventional vehicle Trajectory Estimation (FTE)**

Recursive equation for Automated vehicle Trajectory Optimization (ATO):

\[
d_{n_l}(t) = \begin{cases} 
  \text{LTO}(s(t), V_{m}^{\text{max}}, V_{m}^{\text{cross}}, a_{n_l}^{\text{acc}}, a_{n_l}^{\text{dec}}) & \text{for } n_l = 1, \ \forall \ l \in L, \ c_{n_l} = \text{AV} \\
  \text{FTO}(d_{(n_l-1)}(t), s(t), V_{m}^{\text{max}}, V_{m}^{\text{cross}}, a_{n_l}^{\text{dec}}, a_{(n_l-1)}^{\text{dec}}) & \text{for } n_l = 2, \ldots, N_l, \ \forall \ l \in L, \ c_{n_l} = \text{AV} \\
  \text{LTE}(s(t), v_{n_l}(t_{n_l})) & \text{for } n_l = 1, \ \forall \ l \in L, \ c_{n_l} = \text{CV} \\
  \text{FTE}(d_{(n_l-1)}(t), s(t), V_{m}^{\text{des}}, a_{n_l}^{\text{acc}}, a_{n_l}^{\text{dec}}) & \text{for } n_l = 2, \ldots, N_l, \ \forall \ l \in L, \ c_{n_l} = \text{CV} 
\end{cases}
\]
Lead vehicle Trajectory Optimization

\[
(LTO) \; \text{del}^*_{n_l} = \min_{v_{n_l}(t_{n_l}^1), v_{n_l}(t_{n_l}^3), a_{n_l}^1, a_{n_l}^3} \sum_{i=1}^{3} (t_{n_l}^i - t_{n_l}^{i-1}) - \frac{d_{n_l}(t_{n_l}^0)}{V_{n_l}^{des}}
\]

subject to

\[
t^s_{\phi}(t) \leq \eta_{\phi_l} \times (t_{n_l}^3 - t_{n_l}^0) \leq t^s_{\phi}(t) + G_{\phi}(t) + Y_{\phi}(t) \quad \forall \; \phi \in \Phi
\]

\[
0 \leq v_{n_l}(t_{n_l}^1) \leq V_{m}^{max}
\]

\[
0 \leq v_{n_l}(t_{n_l}^3) \leq V_{m}^{cross}
\]

\[
a_{n_l}^{dec} \leq a_{n_l}^1 \leq a_{n_l}^{acc}
\]

\[
a_{n_l}^{dec} \leq a_{n_l}^3 \leq a_{n_l}^{acc}
\]

The objective function: Travel Time Delay of vehicle \( n \) in lane \( l \)

The summation is over the travel time of all stages (which is equivalent to the total travel time of lead AV)

The fraction is the base travel time assuming vehicle would maintain its desired speed

Therefor, the travel time minus base travel time shows travel time delay (extra time vehicle spent to travel the detection distance)
We showed the optimal solution to LTO is on the boundary of its feasible region (constrains on previous slide).

Under the for loop we move on edges and search for optimal answer. It’s done by setting all variables fix except one of them which is free to change between its bounds.

**Algorithm 1 AV Lead vehicle Trajectory Optimizer**

**Require:** signal control status, vehicle arrival information, vehicle attributes, and speed limits

**Ensure:** valid trajectory with minimal delay for the lead AV

1: procedure LTO_EXACT_SOLVER($s(t), V^\text{max}_m, V^\text{cross}_m, a^\text{acc}_m, a^\text{dec}_m$)
2: \hspace{1em} $\text{det}_m^* \leftarrow M$ \hspace{1em} $\triangleright$ M to be a relatively large value
3: \hspace{1em} $\text{flag} \leftarrow 0$
4: \hspace{1em} $A \leftarrow \{v_n(t^1_n), v_n(t^2_n), a^1_n, a^2_n\}$
5:  \hspace{1em} for counter = 1:4 do
6: \hspace{2em} Select a new variable $x$ from $A$
7: \hspace{2em} Set variables in $A \setminus x$ to limit(s) using Eqs. (12-15)
8: \hspace{2em} Correct the bounds based on Eq. (11)
9: \hspace{2em} Obtain the range of variable $x$
10: \hspace{2em} Solve the remaining single-variable constrained problem over $x$
11: \hspace{2em} $\text{det}_m \leftarrow$ travel time delay at given the obtained solution
12: \hspace{2em} if $\text{det}_m < \text{det}_m^*$ then $\triangleright$ current solution can be improved
13: \hspace{3em} $\text{det}_m^* \leftarrow \text{det}_m$
14: \hspace{3em} $\text{flag} \leftarrow 1$
15: \hspace{2em} end if
16: \hspace{2em} end for
17: \hspace{2em} if $\text{flag} = 1$ then
18: \hspace{3em} return $\text{det}_m^*$ $\triangleright$ the global optimal solution found
19: \hspace{2em} else
20: \hspace{3em} return LTO problem is infeasible
21: \hspace{2em} end if
The hypothetical trajectory is the earliest imaginary path that a vehicle can cross the stop bar right after the vehicle ahead of it. However, the vehicle may not be able to catch up with the hypoth trajectory all the times. The for loop looks for acceleration/deceleration to transition the vehicle to hypoth trajectory.

If found, it constructs the trajectory, otherwise we solve LTO for this vehicle.
This shows the result of previous slide’s algorithm.

1. Hypothetical trajectory is ideal because it makes vehicle discharge at saturation headway.

2. The for loop in previous page searches for the transition stage to get the vehicle on hypothetical trajectory. This figure shows when such a transition is feasible.

3. The final trajectory will be the solid transition part followed by the dashed line on the hypothetical curve.
Follower Conventional Vehicle Trajectory Estimator (Gipps Model)

**Algorithm 3 Conventional Follower vehicle Trajectory Estimator**

**Require:** trajectory of lead vehicle, lead and follower's attributes, follower vehicle arrival information

**Ensure:** trajectory of conventional follower

1. **procedure** FTE SOLVER($d_{(n-1)}(t)$, $s(t)$, $V_{n_i}^{des}$, $a_{n_i}^{acc}$, $a_{n_i}^{dec}$)
2. $t \leftarrow t^0$
3. **while** $d_{n_i}(t) > 0$ **do**
4. **Compute** $v_{n_i}(t)$ **using** Eq. (17)
5. $a_{n_i}(\tau) \leftarrow \frac{v_{n_i}(t+\Delta t) - v_{n_i}(t)}{\Delta t}$ **for** $\tau \in [t, t + \Delta t]$
6. $d_{n_i}(\tau) \leftarrow d_{n_i}(t) - v_{n_i}(t) \times (\tau - t) - \frac{a_{n_i}(\tau)}{2} \times (\tau - t)^2$ **for** $\tau \in [t, t + \Delta t]$
7. $t \leftarrow t + \Delta t$
8. **end while**
9. **return** $d_{n_i}(t)$

**end procedure**

$$v_{n_i}(t + \Delta t) = \min\{v_{n_i}(t) + 2.5a_{n_i}^{acc} \times \Delta t(1 - \frac{v_{n_i}(t)}{V_{n_i}^{des}}) \times \sqrt{0.025 + \frac{v_{n_i}(t)}{V_{n_i}^{des}}},$$

$$a_{n_i}^{dec} \times \Delta t + \sqrt{a_{n_i}^{dec} \times (2(d_{(n-1)}(t) + L_{n_i} - d_{n_i}(t)) + \Delta t \times (a_{n_i}^{dec} \times \Delta t + v_{n_i}(t)) + \frac{v_{(n-1)}(t)^2}{a_{n_i}^{dec}})} \}$$

where:

- $\Delta t$ is the time steps to compute trajectory points
- $v_{n_i}(t + \Delta t)$ is the speed of follower vehicle $\Delta t$ seconds after $t$
- $L_{n_i}$ is the length of nth vehicle in lane $i$

The dashed part is the part vehicle does not have any trajectory because the algorithm is not done computing.

The higher the delay, or the higher the initial speed, the bigger portion of detection distance is lost with no control.
The minimum detection range based on vehicle arrival information, deceleration capability, maximum crossing speed, and algorithms computation time.

Observations:
1. For lower communication range with higher speed arrival of vehicles, the algorithm should perform faster.
2. For a given delay (service time) in trajectory computation and initial vehicle’s speed, a minimum detection range should be provided.
Overall Algorithm

1. Start
2. Initialize Intersection Parameters (Movements, Lanes, Phases, Speed limits, Detection ranges)
3. Generate Random Arrivals at Detection Ranges
4. Yes
   - Ongoing green phase serves all vehicles?
      - No
         - Do all new vehicles belong to lanes in green phase?
            - No
               - Provide enough green (and at least minimum green) to the earliest arriving vehicle.
            - Yes
               - Extend the green to serve new vehicles
5. No
   - Update Vehicle Location Using Received Message Timestamp
6. Calculate Trajectories for New Vehicles (solve ATO given updated signal decision)
7. Yes
   - All new vehicles processed?
      - No
         - Update the signal decision with the new phase and tuning
      - Yes
         - Complete
Field Test of the System
15-minute Simulation Result (per lane)
Sensitivity Analysis Results

**Measures:** average travel time (vertical axis of first row), average travel time delay (vertical axis of the second row), average effective green (the vertical axis of the third row)

**Dimensions:** AV ratio (size), average flow (color), saturation headway at the stop bar (columns)

**Observations:**

Average travel time delay increases with flow

Average travel time delay decrease with detection distance

Shorter green intervals are assigned for higher flows (sensitive to flow fluctuation)

Flow threshold of 450 vehicles/hour/lane cause a surge in average travel time delay (indicating the congested situation)
State of the art control for current isolate intersections is actuated control logic (Used as a baseline for comparison to IICS algorithm).

Loop detectors are placed in the pavement within a short distance from the stop bar. Every time a vehicle occupies the space inside the loop detector a call is sent to the signal controller to assign green. Two major cases may happen:

A phase being gap-out: a minimum green is assigned, however since no more vehicles showed up, the green is terminated and given to another phase.

A phase being maxed-out: vehicles keep coming in the ongoing phase, however to prevent excessive delay on other phases the a maximum green duration is set. In this case the green keeps being extended up to the threshold and then becomes maxed-out.)
Average Effective Green Comparison

Saturation Headway = 2.0 sec

Higher Flow leads to more frequent switches in the right-of-way
Comparison with Actuated Control (Average travel time per mile)

IICS strategy leads to lower average travel times per mile compared to fully actuated control with all conventional vehicles.

The rate of improvement increases as the saturation headway decreases, AV penetration rate increases, or average flow increases,
Next Steps and Continued Research

**Inclusion of Bicycles/Peds/Scooters:**
Expand the algorithm for multimodal traffic

**Additional Sensor Fusion:**
Fusion of different sensors may prove beneficial for different scenarios

**Field Deployment in Gainesville:**
Deploy the system at an isolated intersection on campus

clarklet@ufl.edu
http://avian.essie.ufl.edu/

http://www.transportation.institute.ufl.edu/research-2/istreet/