Abstract
Traffic congestion results in increasing delay in daily commutes and unreliable transportation services. Signal phasing and time control on arterial corridors attracts strong research and implementation attention due to its advancement on direct traffic management and coordination for congestion mitigation. With increasing penetration rates of connected vehicles, signals are able to interact with real-time traffic conditions and to be operated more proactively with traffic prediction models to mitigate road congestions, to improve road capacities, and to enhance transportation network efficiency. This paper develops a proactive signal control system based on connected vehicles to minimize vehicle delay at multiple intersections. The system utilizes connected vehicles to accurately predict the volumes entering the intersection through different movements. The optimal signal timing plan is estimated based on a short-term prediction of total vehicle delay at the intersection. The macroscopic simulations at isolated and multiple intersections illustrate the effectiveness of the proactive signal control system on reducing vehicle delays. Compared with pre-timed signal control, the proactive system can reduce the average trip delay as high as 77%. The study also verifies that the proactive control has better performance than the Nash-Bargaining (NB) control. In addition, a real-world road with multiple intersections is simulated with a microscopic traffic simulator – INTEGRATION, to validate the proposed system. The result obtained under the proactive control system is compared to a well-tuned fully actuated control. Applying the proactive control system, the total vehicle delay can be reduced by up to 89%, the vehicle stops by 31%, and the fuel consumption by 24%.

Motivation
- Operating arterial traffic relies significantly on signal phasing and timing (SPaT) plans and signal coordination systems;
- The connected vehicles can monitor real-time traffic conditions for traffic signals to design optimal control strategies;
- Most studies of signal control on arterial corridors attempt to minimize vehicle delay at intersections with only conventional detection technologies;
- Current advanced signal control systems with coordination are generally very complex.

Our Work
- Develop a proactive signal control system to mitigate road congestions at signalized intersections;
- Enable connected vehicles to communicate with traffic signals to predict road traffic conditions as well as to improve the Nash-Bargaining (NB) signal control system;
- Illustrate the effectiveness of the proposed system with both macroscopic and microscopic traffic simulations;
- Apply the system for multiple intersections to verify its benefit on coordinating signals.

Signal Control at Intersection

Objective function for signal control
\[
\min_{\nu(t)} \sum_{i=1}^{n} D_i(T_0);
\]
\[\text{s.t.}
N_{i}(t) = N_{i}(t-1) + f_{i}(t);
\]
\[N_{i}(t) = \begin{cases} N_{i0}(t-1) + f_{i}(t-\frac{4}{3}) & m_0(t) = 0 \\
N_{i0}(t-1) + f_{i}(t) + Q_{i} & m_0(t) = 1, N_{i0}(t-1) + Q_{i} > N_{i0}(t-1) + f_{i}(t) \\
N_{i0}(t-1) + Q_{i} & m_0(t) = 1, N_{i0}(t-1) + Q_{i} \leq N_{i0}(t-1) + f_{i}(t) \\
0 & \text{otherwise}
\end{cases}
\]
\[D_i(T_0) = \sum_{t=0}^{T_0} (N_{i}(t) - N_{i0}(t) - f_{i}(t))
\]

- \(N_{i}(t)\): Cumulative inflow of the movements \(i\) at time \(t\);
- \(N_{i0}(t)\): Cumulative outflow of the movements \(i\) at time \(t\);
- \(m_0(t)\): Permission of the movement \(i\) at time \(t\);
- \(D_i(T_0)\): Total delay of all vehicles from the movement \(i\) at time \(t\);
- \(p_{ij}(t)\): Activation index of the green phase \(j\) at time \(t\);
- \(L_{ij}\): The length of the control region for the movement \(i\);
- \(v_{ij}\): The free-flow speed of the movement \(i\).

Proactive Signal Control: Model Development

1. Update signal timing phase at every time interval (predefined).
2. Estimate the in- and out-flow rates of each movement based on connected vehicle information at time step \(n\).
3. Predict total delay by activating green phase \(k\) at the next time step \(n+1\)
   \[d_k(t_{n+1}) = \sum_{i=1}^{n} \left( D_i(t_n) + \sum_{t=0}^{t_n} \left( N_{i0}(t) - N_{i0}(t) - f_{i}(t) \right) \right)
   \]
   \[N_{i0}(t) - N_{i0}(t-1) = \begin{cases} Q_{i} & i \in \mathcal{A_k} \\
0 & \text{otherwise}
\end{cases}
\]
   \[N_{i0}(t) - N_{i0}(t-1) = \begin{cases} Q_{i} & i \in \mathcal{A_k}, N_{i0}(t) - Q_{i} > N_{i0}(t-1) - Q_{i} \\
N_{i0}(t-1) - Q_{i} & i \in \mathcal{A_k}, N_{i0}(t) - Q_{i} \leq N_{i0}(t-1) - Q_{i} \\
0 & \text{otherwise}
\end{cases}
\]
4. Select the optimal green phase to minimize the total delay of the intersection
   \[k^* = \arg \min_{k} d_k(t_{n+1})
   \]
Compared with the pre-timed plan, the proactive signal control reduced total vehicle delay by about 77% for a two-phase isolated intersection, and 62% for two consecutive intersections. Among these three control systems, the proactive control always resulted in the best performance, and the pre-timed plan exhibited the worst performance.

The proactive signal control system always performed better than the NB control. For one two-phase intersection, the proactive control reduced the delay by about 40%, and 45% for two intersections. The extra benefits of the proactive control came from the accurate prediction of the severe traffic oscillations at intersections.

The implementation on FM 1964 indicated that the system was able to reduce the average vehicle stop delay by up to 89%, vehicle stops 31%, and fuel consumption 24%. The daily monetary savings from the tested road could be as high as $2,400 in a weekday and $3,270 in a weekend.