Traffic flow optimization at sags by controlling the acceleration of some vehicles

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Characteristics of the freeway section and the traffic stream

$n$ vehicles

Constant-gradient downhill section

$G = G_d < 0$

Beginning of control section

Non-controlled vehicles

Controlled vehicles

End of control section

Constant-gradient uphill section

$G = G_u > 0$

$r_0^c$

$r_d$

$r_u$

$r_f^c$

1 lane
Optimization objective

Minimize Total Travel Time of all vehicles (TTT)

$n$ vehicles

Constant-gradient downhill section

Sag vertical curve

Constant-gradient uphill section

End of control section

Beginning of control section

Arrival point (travel times)

Non-controlled vehicles

Controlled vehicles

1 lane
Traffic state dynamics

- Vehicle positions: \[ r(t+1) = r(t) + v(t) \cdot T_s + \frac{a(t)}{2} \cdot T_s^2 \]
- Vehicle speeds: \[ v(t+1) = v(t) + a(t) \cdot T_s \]
- Vehicle accelerations:
  - Non-controlled vehicles
  - Controlled vehicles

\( a(t) = a_{\text{CF}(t)} \)
\( a(t) = \min (\text{control input } (k), a_{\text{CF}(t)}) \)

\( t \): simulation step index
\( T_s \): simulation step length
\( k \): control time step index
Optimal control problem

Find \( u^*(0), u^*(1), \ldots, u^*(\frac{T}{T_c}) \)

that minimize \( J(x(0), x(1), \ldots, x(\frac{T}{T_c}), u(0), u(1), \ldots, u(\frac{T}{T_c})) \)

subject to:

\[
\begin{align*}
x(0) &= x_0 \\
u(\kappa) &\in \mathcal{U}, \text{ for } \kappa = 0, 1, 2, \ldots, \frac{T}{T_c} \\
x(\tau + 1) &= f(x(\tau), u(\kappa)), \text{ for } \tau = 0, 1, 2, \ldots, \frac{T}{T_c}
\end{align*}
\]

where \( \kappa \) is such that \( \tau \cdot T_c \in [\kappa \cdot T_c, (\kappa + 1) \cdot T_c] \)

- Max. acceleration (of all controlled vehicles at all control time steps)
- Total travel time
- Initial traffic state
- Admissible control region
- Traffic state dynamics

- Characteristics:
  - Non-linear
  - Non-convex

- Solution method:
  - Sequential quadratic programming
Optimization experiments

Objectives:

To determine:
1. Optimal acceleration behavior of the controlled vehicles
2. Main effects on traffic flow
3. Reasons why total travel time decreases

In scenarios with:
• Nearly-saturated traffic conditions
• Low penetration rates (≤ 1%)
Experimental setup

- Total number of vehicles: 300
- Controlled vehicles
  - Number: 0, 1, 2 or 3
  - Positions: 75, 150 and/or 225
- Network parameters
- Initial traffic state
  - Speed: Desired speed (120 km/h)
  - Position vehicle 1: $r^c_0$
  - Headway: Desired headway
- Simulation period = 800 s
- Time step length
  - Simulation step: 0.5 s
  - Control step: 8 s
- Admissible control set: [-0.5, 1.4] m/s²

**Network parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_d$ (%)</td>
<td>-0.5</td>
</tr>
<tr>
<td>$G_u$ (%)</td>
<td>+2.5</td>
</tr>
<tr>
<td>$r_d$ (m)</td>
<td>1000</td>
</tr>
<tr>
<td>$r_u$ (m)</td>
<td>1600</td>
</tr>
<tr>
<td>$R$ (m)</td>
<td>5000</td>
</tr>
<tr>
<td>$r^c_0$ (m)</td>
<td>-2000</td>
</tr>
<tr>
<td>$r^c_f$ (m)</td>
<td>7000</td>
</tr>
</tbody>
</table>
The optimal acceleration behavior of controlled vehicles is defined by two main strategies:

1. **Primary strategy:**
   - DADA maneuver in the sag area
   - Applied in all cases
   - Maneuver with well defined general characteristics

2. **Supporting strategy:**
   - DA maneuvers upstream of the sag
   - Applied in some cases
   - Maneuvers with case-specific characteristics

\[ M = \{150\} \]
Primary strategy

- DADA maneuver in the sag area

\[ M = \{75\} \]
Primary strategy

- Effects on traffic flow

\[ \Delta AVD = -2.9 \text{ s} \]

\[ M = \{75\} \]
Primary strategy

- Effects on traffic flow

$ΔAVD = -2.9 \text{ s}$

$M = \{75\}$
Supporting strategy

• Effects on traffic flow

\[ M = \{150\} \]

\[ \Delta AVD = -2.4 \text{ s} \]

Primary strategy

Primary strategy

Supporting strategy

Primary strategy

Primary strategy (supporting strategy excluded)

\[ \Delta AVD = -2.1 \text{ s} \]
Supporting strategy

- Effects on traffic flow

\[ M = \{150\} \]
Results

- Reduction in AVD in comparison with no control: 1.2 - 6.3 s
- The primary strategy is the one that contributes the most to reduce AVD
- More controlled vehicles and closer to 1\textsuperscript{st} vehicle $\rightarrow$ Greater reduction in AVD [assuming low penetration rates]
Conclusions

- Our optimization method is effective (and transferable)

- The optimal acceleration behavior of controlled vehicles primarily involves performing a DADA maneuver in the sag
  - Main effects on traffic:
    - Temporary limitation of inflow to the sag
    - Temporary increase in traffic speed and flow at the bottleneck
  - Significant reduction in AVD, at low penetration rates (up to 6s with 1% controlled vehicles)

- Further research:
  - Development of traffic control measures based on this principle
  - Traffic flow optimization in scenarios with:
    - Multi-lane freeway section
    - Higher penetration rates of controlled vehicles
Questions?

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In-car systems

- Cooperative ACC systems
- In-vehicle advisory systems
- Others

Influence on longitudinal vehicle acceleration
Car-following model

\[
a_{\text{CF},i}(\tau) = \alpha_i \cdot \min \left[ 1 - \left( \frac{v_i(\tau)}{v_{\text{des},i}} \right)^4, 1 - \left( \frac{s_{\text{des},i}(v_i(\tau), \Delta v_i(\tau))}{s_i(\tau)} \right)^2 \right] - \theta_i \cdot (G(r_i(\tau)) - G_{\text{com},i}(\tau))
\]

\[
s_{\text{des},i}(v_i(\tau), \Delta v_i(\tau)) = s_s,i + v_i(\tau) \cdot H_i + \frac{v_i(\tau) \cdot \Delta v_i(\tau)}{2 \cdot \sqrt{\alpha_i \beta_i}}
\]

\[
G_{\text{com},i}(\tau + 1) = \begin{cases} 
G(r_i(\tau + 1)) & \text{if } G(r_i(\tau + 1)) \leq G_{\text{com},i}(\tau) + \lambda_i \cdot T_s \\
G_{\text{com},i}(\tau) + \lambda_i \cdot T_s & \text{if } G(r_i(\tau + 1)) > G_{\text{com},i}(\tau) + \lambda_i \cdot T_s 
\end{cases}
\]
Primary strategy

• Effects on traffic flow (2 controlled vehicles)  \( \Delta \text{ATT} = -3.5 \text{ s} \)  
  \[ M = \{75, 225\} \]
Maximum distance headways

- **Primary strategy**: narrow range, not too long
- **Supporting strategy**: wide range, longer