Safety Aware Platooning of Automated Electric Transport Vehicles

Master of Science Thesis Defense

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   - Monte Carlo Analysis of the Unsafe Headway Zone

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4 Emergency Braking of a Full Platoon
   - Additional Models for Vehicle Interactions
   - Controllers
   - Controller Performance

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Highway Automation

- Computers drive for you
- Economic benefits - fewer wrecks, fewer delays, fewer lanes
- Many groups are researching
- Platoons - linear groups of consecutive vehicles acting in unison and traveling in close-following formation

Two platoons. L indicates lead vehicle of the platoon, F a follower.
Automated Electric Transport (AET)

- Electric vehicles - nicer plants than combustion vehicles
- Small batteries through wireless power transfer
- Safety is key factor in design
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Definition and Significance of Emergency Brake Scenario

Emergency Brake Scenario
Situation requiring a platoon to stop as quickly as possible

- Considered conservative design point
- Used to determine safe maneuvers and headways
Model Abstraction of a Platoon

```
\begin{align*}
\text{Leader} & : a_{\text{min}l}, \tau_l, d_l, v_{0l}, \text{brake signal} \\
\text{Delay} & : T \\
\text{Follower} & : a_{\text{min}f}, \tau_f, d_f, v_{0f}, v_f, x_f, H(t), \Delta v(t)
\end{align*}
```

Block diagram of first order model
Difference in Velocity Curves
As a Function of Initial Headway

$H - \Delta v$ curves for different $a_{\text{minf}}$
Threshold of Safety for Difference in Velocity

- $\Delta v$ proportional to risk of injury
- $\Delta v_{\text{safe}}$ small enough no risk
- Region in $H-\Delta v$ curve is therefore unsafe headway zone (UHZ)
Unsafe Headway Zone Sensitivity

Unsafe headway zones for varying parameters with:

\[ a_{\text{min}} = -9.5 \text{m/s}^2 \]
Probability of Unsafe Collision

Monte Carlo analysis results

- Minimum acceleration assigned 2 distributions: "strict" & "loose"
- Delay assigned 2 values: "short" & "long"
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A More Detailed Model

- Greater insight to influence of physical parameters
- Easier to add other vehicle interactions (scalability)

Block diagram of physical vehicle model
Vehicle Subsystem Models

- PID - physical layer control
- DC motor model - first-order actuator
- LuGre model - dynamic tire/road interaction
- Quarter-vehicle model - rotational, longitudinal dynamics
Minimum Acceleration Sensitivity

- Tire condition ($\theta$), battery charge ($V_{max}$), vehicle mass ($m$), aerodynamic drag, and tire radius varied
- Vehicle minimum acceleration ($a_{min}$) made equal to strict and loose distributions
- Mass considered most likely cause of variance in $a_{min}$

Values used to achieve $a_{min}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>$-10$</th>
<th>$-9.5$</th>
<th>$-9$</th>
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<th>$-5.5$</th>
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</thead>
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<td>$\theta$</td>
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<td>-</td>
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<td>2.65</td>
<td>11.52</td>
<td>-</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>V</td>
<td>263.5</td>
<td>248.7</td>
<td>233.9</td>
<td>196.9</td>
<td>130.8</td>
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<tr>
<td>$m$</td>
<td>kg</td>
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<td>1710</td>
<td>1810</td>
<td>2119</td>
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</tbody>
</table>
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   ■ Controllers
   ■ Controller Performance

5 Conclusions
Communication, Sensing, and Collisions

- Vehicle interaction models allow modeling an entire platoon
  - Communication - constant delay
  - Sensing - no dynamics
  - Collisions - impulse-momentum based model

- Entire emergency scenarios can be simulated
- More sophisticated models can be added for future work
Regulation Layer Controller

- Sensed and communicated information combined to determine best acceleration behavior
- Rajamani controller used for simplicity and frequency in publications
- Leader and preceding vehicle acceleration and velocity required
- Design parameters provided for weighting leader information, controller bandwidth, and damping

Controller hierarchy

\[ a^* \rightarrow \text{Physical Controller} \rightarrow V \rightarrow \text{Motor} \rightarrow T \rightarrow \text{Vehicle Dynamics} \rightarrow a \]
Emergency Controllers

- Rajamani - no change from steady state operation
- Choi - Rajamani with leader information weight zero
- Preceding acceleration - match preceding vehicle
- Preceding acceleration with headway - match preceding vehicle acceleration while maintaining target headway
- Uncoordinated - only sensor data used to maintain target headway
Platoon of 5 vehicles assembled with masses from a normal distribution

Vehicles travel 1 second, emergency brake to complete stop

Masses arranged in random, heaviest-in-rear, and heaviest-as-lead order

Metrics
  - Peak collision force
  - Vehicle acceleration and jerk
  - Platoon total time to stop
  - $\Delta v$
Performance with Five Vehicles

Results of heaviest-in-rear platoon in emergency brake scenario using Rajamani controller

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Safety Aware Platooning of AET Vehicles
Performance with Five Vehicles

Results of heaviest-in-rear platoon in emergency brake scenario using Rajamani controller

Spencer Scott Jackson  Safety Aware Platooning of AET Vehicles
Performance of All Five Controllers with Heaviest in Rear

$\Delta v$ of impacts in heaviest-in-rear platoon under different control strategies

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Rajamani</th>
<th>Choi</th>
<th>Prec. Acc.</th>
<th>PAH</th>
<th>Uncoord.</th>
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<tr>
<td>2-1</td>
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<td>0.7</td>
<td>1.3</td>
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<tr>
<td>4-3</td>
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<td>0.6</td>
<td>2.9</td>
<td>-</td>
</tr>
<tr>
<td>5-4</td>
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<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
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</tbody>
</table>
## Performance of All Five Controllers with Heaviest as Lead

$\Delta v$ of impacts in heaviest-as-lead platoon under different control strategies

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Rajamani</th>
<th>Choi</th>
<th>Prec. Acc.</th>
<th>PAH</th>
<th>Uncoord.</th>
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<td>0.5</td>
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<tr>
<td>4-3</td>
<td>-</td>
<td>-</td>
<td>0.6 0.3</td>
<td>1.2</td>
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<td>5-4</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
## Performance with More Vehicles

\[ \Delta v \text{ of collisions in 20 vehicle platoon} \]

<table>
<thead>
<tr>
<th>Vehicles</th>
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<th>Choi</th>
<th>Uncoord.</th>
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<tbody>
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<td>6-5</td>
<td>0.8456</td>
<td>0.8566</td>
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<td>9-8</td>
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</tr>
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<td>19-18</td>
<td>-</td>
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<tr>
<td>20-19</td>
<td>-</td>
<td>1.0791</td>
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</table>
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Conclusions

- Variation in braking ability compromises safety
- Vehicle and system design should consider unsafe headway zone
- More information in control improves performance
- Most massive vehicle as lead improves safety
Acknowledgements

- Committee
- AET Project
- DOE Grant
The End
Appendix Slides
Simplified First Order Model
For Monte Carlo Simulations

Reduced block diagram of model as used in Monte Carlo analysis
Other Groups Researching Highway Automation

- PATH - Gave real platooning demo in 1997 (NAHSC ’98)
- SARTRE - Currently developing road trains with manually driven lorries as leaders (Davila ’10)
- KONVOI - Researching automated platoons of cargo trucks (Wille ’07)
Electric Vehicle vs. Internal Combustion

- Primary time constant of electric motor one tenth to one hundreth that of internal combustion engine (ICE) (Hori ’04)
- ICE rate limits effectively increases delay between vehicles
Highway Safety

- Over 90% of incidents are due to human error (Hitchcock ’92)
- Nearly 34,000 deaths occurred in 2009 due to automobile accidents (NHTSA ’10)
- An AET system must improve upon this to be supported and implemented
- Hal says: removing human error will greatly improve safety
Emergency Brake Scenario as a Design Point

- PATH designed platoon spacing and lane change maneuvers based on emergency brake scenario (i.e. Kanaris '01)
- This is the worst case scenario in platooning as it requires strongest braking and thus generates largest $\Delta v$
- More work is required to really assess the probability and causes of emergency brake scenarios
### Values used for $H$-$\Delta v$ curves

<table>
<thead>
<tr>
<th></th>
<th>$v_0$ (m/s)</th>
<th>$a_{min}$ (m/s)</th>
<th>$T$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader</td>
<td>30</td>
<td>$-10$</td>
<td>n/a</td>
</tr>
<tr>
<td>Follower</td>
<td>30</td>
<td>$-9.5$, $-10$, $-10.5$</td>
<td>200</td>
</tr>
</tbody>
</table>
California incident data was found to have a threshold at 3.3 m/s where no injuries were recorded (Hitchcock ’95).

Similar results are in Krafft ’02 and Kullgren ’03.

In this work 2.5 m/s is used as $\Delta v_{safe}$. 
### Values Used for UHZ Sensitivity Analysis

Nominal values and variation for sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Nominal</th>
<th>Sweep Range</th>
<th>Sweep Range (%)</th>
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<td>$-10$</td>
<td>$-10$</td>
<td>$100$</td>
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<tr>
<td>$\tau_l$</td>
<td>ms</td>
<td>$10$</td>
<td>$10$</td>
<td>$100$</td>
</tr>
<tr>
<td>$d_l$</td>
<td>ms</td>
<td>$5$</td>
<td>$5$</td>
<td>$100$</td>
</tr>
<tr>
<td>$v_{0l}$</td>
<td>m/s</td>
<td>$30$</td>
<td>$30$</td>
<td>$100$</td>
</tr>
<tr>
<td>$a_{minf}$</td>
<td>m/s²</td>
<td>$-10$</td>
<td>$(-15, -5)$</td>
<td>$(150, 50)$</td>
</tr>
<tr>
<td>$\tau_l$</td>
<td>ms</td>
<td>$10$</td>
<td>$(1, 100)$</td>
<td>$(10, 1000)$</td>
</tr>
<tr>
<td>$d_l$</td>
<td>ms</td>
<td>$5$</td>
<td>$(0, 100)$</td>
<td>$(0, 2000)$</td>
</tr>
<tr>
<td>$v_{0f}$</td>
<td>m/s</td>
<td>$30$</td>
<td>$(25, 35)$</td>
<td>$(83, 117)$</td>
</tr>
<tr>
<td>$T$</td>
<td>ms</td>
<td>$20$</td>
<td>$(2, 200)$</td>
<td>$(10, 1000)$</td>
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Monte Carlo Analysis Values

Case values for Monte Carlo simulations

<table>
<thead>
<tr>
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<th>Units</th>
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<th>SL</th>
<th>LS</th>
<th>LL</th>
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<tbody>
<tr>
<td>$T$</td>
<td>ms</td>
<td>20</td>
<td>200</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>$\mu$</td>
<td>m/s$^2$</td>
<td>9.5</td>
<td>9.5</td>
<td>7.75</td>
<td>7.75</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>m/s$^2$</td>
<td>0.25</td>
<td>0.25</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Upper Bound</td>
<td>m/s$^2$</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Lower Bound</td>
<td>m/s$^2$</td>
<td>9</td>
<td>9</td>
<td>5.5</td>
<td>5.5</td>
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</tbody>
</table>

PID Control

PID controller equation

\[ V_m = k_p e + k_i \int e \, dt + k_d \frac{de}{dt} \quad (1) \]

\[ e = a^* - a \quad (2) \]

- Common controller is robust to variation
- Here \( k_d = 0 \) making a slower response
- Actual gains vary drastically with different plants
- Primary time constant is \( \approx 30 \text{ms} \) without overshoot
DC Motor

DC motor model

\[ \dot{T} = K_t \frac{V_m - K_e \omega - RL}{L} \]  

- Input voltage \( V_m \) limited to represent battery
- Same model used by Walterman '96 for hybrid vehicle
- Values used from solar-powered direct drive vehicle’s motors (Lovat '97)
LuGre Model

\[ g(v_r) = \mu_c + (\mu_{st} - \mu_c) e^{-\sqrt{\frac{v_r}{v_s}}} \]  \hspace{1cm} (4)

\[ \dot{z} = v_r - \theta \frac{\sigma_0 |v_r|}{g(v_r)} z \]  \hspace{1cm} (5)

\[ \mu = \sigma_0 \dot{z} + \sigma_1 z + \sigma_2 v_r \]  \hspace{1cm} (6)

- Dynamic model adds 1 state for integration but represents many phenomena of friction
- Values used from Buick LeSabres used by PATH (Yi ’02)
Quarter vehicle model

\[ a = \frac{4\mu F_n - C_d v^2}{M} \]  
\[ \dot{\omega} = \frac{T_m - h \ast \mu F_n - B\omega}{J} \]

- Only one wheel represented, result multiplied by 4
- Values used from Buick LeSabres used by PATH (Yi ’02)
Collision impact force

Brach collision model

\[ F_{Ci} = \begin{cases} 
c_{dmp} \dot{\epsilon}_i^b (\epsilon_i - l_{i-1})^c + k(\epsilon_i)^a, & \epsilon_i \leq l_i \\
0, & \epsilon_i > l_i
\end{cases} \]

(9)

\[ \epsilon_i = x_i - x_{i-1} \]

(10)

\[ c_{dmp} = \begin{cases} 
c'_d, & t \leq t_p \\
c_{dmp} \left( \frac{t}{t_p} \right)^d, & t > t_p
\end{cases} \]

(11)

- Based on measured data from low-\(\Delta v\) collisions (Brach '03)
- Values used based on example from Brach
Rajamani Regulation Layer Control

Rajamani controller

\[ a_i^* = (1 - C_1)\ddot{x}_{i-1} + C_1\ddot{x}_l - \left(2\zeta - C_1 \left(\zeta + \sqrt{\zeta^2 - 1}\right)\right)\omega_n\dot{\epsilon}_i \tag{12} \]
\[ - C_1 \left(\zeta + \sqrt{\zeta^2 - 1}\right)\omega_n(\dot{x}_i - \dot{x}_l) - \omega_n^2\epsilon_i, \tag{13} \]
\[ \epsilon_i = x_{i-1} - x_i - l_{i-1} + H^* \tag{14} \]

- Leader and preceding vehicle acceleration and velocity required (Rajamani ’00)
- Design parameters provided for weighting leader information, controller bandwidth, and damping
- Referenced over 50 times on IEEEXplore
Choi Regulation Layer Control

Choi controller

\[ a^*_i = \ddot{x}_{i-1} - 2\zeta \omega_n \dot{\epsilon}_i - \omega_n^2 \epsilon_i, \quad (15) \]
\[ \epsilon_i = x_{i-1} - x_i - l_{i-1} + H^* \quad (16) \]

- Controller inspired by stochastic analysis of emergency brake scenario (Choi '01)
- Leader information less useful if other vehicles are in brake saturation ahead
- Implemented by setting leader information weight zero
- Proper implementation breaks into “subplatoons”
Preceding Acceleration Regulation Layer Control

Preceding acceleration controller

\[ a_i^* = \ddot{x}_{i-1} \]  (17)

- Also inspired by Choi ’01
- Only uses preceding vehicle acceleration
- Very susceptible to communication errors ×
Preceding Acceleration with Headway Regulation Layer Control

Preceding acceleration with headway (PAH) controller

\[ a_i^* = \ddot{x}_{i-1} + \epsilon, \quad (18) \]
\[ \epsilon_i = x_{i-1} - x_i - l_{i-1} + H^* \quad (19) \]

- A variant of the preceding acceleration controller
Uncoordinated Regulation Layer Control

Uncoordinated controller

\[ a_i^* = a_{\text{emergency}} + \epsilon, \quad (20) \]
\[ \epsilon_i = x_{i-1} - x_i - l_{i-1} + H^* \quad (21) \]

- Each vehicle tries to maintain previously determined acceleration and separation
- No inter-vehicle communication after emergency initiated (headway from sensor)
Masses for Full Platoon

- Mean 1707kg, standard deviation 80kg
- Standard deviation corresponds to distribution between “strict” and “loose” distributions

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Random (kg)</th>
<th>Heavy Rear (kg)</th>
<th>Heavy Lead (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1750.0</td>
<td>1750.0</td>
<td>1853.7</td>
</tr>
<tr>
<td>2</td>
<td>1853.7</td>
<td>1526.3</td>
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<td>4</td>
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<td>5</td>
<td>1732.5</td>
<td>1853.7</td>
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Results of heaviest-in-rear platoon in emergency brake scenario using PAH controller
Performance with Five Vehicles

Results of heaviest-in-rear platoon in emergency brake scenario using PAH controller