Safe highways platooning with minimized inter-vehicle distances of the time headway policy

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Content of presentation

Introduction

Modeling

Control

Results

Conclusion
**Platoon**

**Why platooning?**

- Increases traffic density
- Increases safety:
  - Collision (Small relative velocity)
  - No human factor
  - Reaction time is smaller
- Decreases fuel consumption
- Decreases driver tiredness
Platooning projects on Highways

- Platooning in the cadre PATH project (1997)
  - 8 automated cars (Velocity up to 105 Km/h)
  - Fix distance between the vehicles (6.5 m)
  - Information from the precedent car and leader

- Chauffeur II project (2003)
  - The leader is human driver
  - Information from the precedent car and leader

- SARTRE project
  - Began in 2009 and finished at 2012
  - The leader is expert driver (V up to 90 km/h)
  - Information from the precedent car and leader

Introduction

Modeling

Control

Results

Conclusion

Platoon (examples)
Platoon

- Vehicles following each other
- The leader
  - Real or virtual
  - Driven manually or automatically
- Other vehicles
  - Following each other and moving at the same speed
  - Keeping desired distance
Motivation: Inner-cities congestion

- Waste of time/activities
- Waste of energy (fuel, gas, ...)
- Atmospheric pollution
- Noise pollution

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Motivation: Urban Transportation Systems Concept

Their attractiveness depends mainly on their flexibility "they have to answer to various public needs"

Car sharing concept appears as a suitable answer in specific areas (inner-cities pedestrian zones, airport terminals, ...)

Such systems have been developed since the mid-90's: Praxitèle in France, CarLink in USA, Crayon in Japan...
Motivation: Autonomous navigation

Car sharing concept demands for automatic guidance capabilities

- To transport passengers in an entire automatic way
- To bring back empty vehicles to stations for refilling and reuse
- To deliver free vehicles for customer use

Autonomous vehicle

Platoon capability

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Control

• Global Control and Local Control
  ➢ Data (at least from leader, adjacent vehicles)
  ➢ Sophisticated sensors (required, Not required)
  ➢ Adaptation of the environment (Maybe, Not required)
  ➢ Communication system (need very reliable, not required)
  ➢ Trajectory tracking and inter distance keeping (accurate, 
    Not very accurate)
  ➢ The car is totally autonomous (No, Yes)
**Inter-distance**

- **Constants inter-vehicle distances**
  - ✔ High traffic density
  - ✔ The communication between vehicles is mandatory

  ![Fixed Inter-distance Diagram]

  \[ \Delta X = L \]

- **Variable inter-vehicle distances** (according to vehicle’s dynamic)
  - ✔ Distances are proportional to velocity in Constant Time Headway (CTH)
  - ✔ Low traffic density
  - ✔ Stable without communication
  - ✔ The cars can work autonomously

  ![Variable Inter-distance Diagram]

  \[ \Delta X = L + h v_i \]
Content of presentation

Introduction

Modeling

Control

Results

Conclusion

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Dynamic Longitudinal Model of the vehicle

Using Newton’s law:

\[ m \ddot{x} = F + F_a + F_{\text{aero}} + F_{\text{drag}} \]

\[ m \ddot{x} = F - mg \sin(\theta) - \frac{\rho A C_d}{2} \dot{x}^2 \text{sgn}(\dot{x}) - d_m \]

- \( \theta \): Angle between the road surface and the horizontal plane.
- \( \rho \): Specific mass of air.
- \( A, C_d \): Cross-sectional area and drag coefficient of the vehicle.
- \( d_m \): The amplitude of the mechanical drag force.

The engine of the vehicle is modeled as a first order system

\[ \dot{F} = -\tau F + u \]
**Dynamic Longitudinal Model of the vehicle**

\[ m \ddot{x} = F - mg \sin(\theta) - \frac{\rho A C_d}{2} \dot{x}^2 \text{sgn}(\dot{x}) - d_m \]
\[ \dot{F} = -\tau F + u \]

By derivation and substitution

\[ m x^{(3)} = -\tau F - mg \cos(\theta) \dot{\theta} - \rho A C_d \dot{x} \ddot{x} + u \]

Introducing an auxiliary control command \( w \) (exact linearization)

\[ u = m w + \tau F + mg \cos(\theta) \dot{\theta} + \rho A C_d \dot{x} \ddot{x} \]

\[ x^{(3)} = w \]
**Dynamic Longitudinal Model of the platoon**

- $\Delta X_i = x_{i-1} - x_i$: real spacing between car number $i$ and its predecessor, car number $i-1$.
- $x_i$: position of $i$-th vehicle.
- $L$: desired inter-vehicle distance

\[
e_i = \Delta X_i - L
\]

**Constant**

\[
\delta_i = e_i - h v_i = \Delta X_i - L - h v_i
\]

**Adaptive**

\[
\dot{e}_i = \dot{x}_{i-1} - \dot{x}_i = v_{i-1} - v_i
\]

**New model [ICINCO13]**

\[
\delta_i = e_i - h (v_i - V) = \Delta X_i - L - h (v_i - V)
\]

$V$ is a common velocity shared by the platoon.
Content of presentation

Introduction

Modeling

Control

Results

Conclusion

Safe highways platooning with minimized inter-vehicle distances of the time headway policy
Main control objectives

The main objectives of the control law are to:
1) Keep the inter-vehicle distance equal to \( L \), and make all vehicles move at the same speed so \( \dot{e}_i = 0 \).
2) Assure the string stability of the platoon (the spacing error does not increase as it propagates through the platoon).
3) Increase the traffic density.
4) Keep the system stable in case of total loss of communication.
Control Law

The new spacing error

\[
\delta_i = e_i - h (v_i - V) = \Delta X_i - L - h (v_i - V)
\]

Control Law

\[
w_i = -k_a \ddot{x}_i + k_v \dot{e}_i + k_p \delta_i
\]

Control scheme of the \(i^{th}\) vehicle

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**String stability**

String Stability for a platoon means that the spacing error must decrease as it propagates through the platoon

\[ \| e_{s_i} \|_\infty \leq \| e_{s_{i-1}} \|_\infty \]

Spacing error propagation transfer function

\[ G_i(s) = \frac{e_i(s)}{e_{i-1}(s)} \]

A sufficient condition for string stability is given by

\[ \| G_i(s) \|_\infty \leq 1 \quad \text{and} \quad g_i(t) > 0 \quad i = 1, 2, \ldots N \]

Where \( g_i(t) \) is error propagation impulse response of the \( i^{th} \) vehicle.
String stability

\[ G_i(s) = \frac{k_v s + k_p}{s^3 + k_a s^2 + (k_v + h k_p) s + k_p} \]

\[ \|G_i(\omega)\| = \sqrt{\frac{k_p^2 + k_v^2 \omega^2}{(k_p - k_a \omega^2)^2 + ((k_v + k_p h) \omega - \omega^3)^2}} \]

\[ \omega^6 + (k_a^2 - 2(k_v + k_p h)) \omega^4 + (k_p^2 h^2 + 2 k_p (k_v h - k_a)) \omega^2 \geq 0 \]

One simplification with: \( k_v = k_a / h \)
error between the leader and the first vehicle

If $V_s = v_{leader}$ then

$$G_1(s) = \frac{\epsilon_1(s)}{w_{leader}(s)} = \frac{1}{s^3 + k_\alpha s^2 + (k_v + h k_p) s + k_p}$$

$$||G_1(\omega)|| = \frac{1}{\sqrt{(k_p - k_\alpha \omega^2)^2 + ((k_v + k_p h) \omega + \omega^3)^2}}$$

If the platoon is stable and by choosing $k_p > 1$

$$||G_1|| < ||G_2|| \leq 1$$

$$||\epsilon_1|| < ||w_{leader}||$$

So the maximum error in the platoon is bounded by the maximum control value of the leader (the jerk of the leader).

As the maximum of jerk must be < 0.5 to 0.6 m/m3 (for comfort)

The maximum error will be < 1m
Content of presentation

Introduction

Modeling

Control

Results

Conclusion

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Safe highways platooning with minimized inter-vehicle distances of the time headway policy
Simulation

- Matlab and TORCS.
- TORCS (The Open Racing Car Simulator) is:
  - Racing game.
  - Advanced simulator used for academic purposes.
  - Sophisticated physics engine (aerodynamics fuel consumption, traction...).
  - 3D graphics engine for the visualization of the race.
- We used 10 identical vehicles.
- The trajectory is almost straight.
- \( L = 1 \) meter
- Parameter setting: \( h=3, k_v=1/3, k_p=5, k_a=1 \)

Leader velocity profile

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Simulation

• Classical time headway policy  \( L + h \cdot v_i \)

![Simulation Diagram](image_url)
Simulation

- Modified time headway policy

\[ L + h(v_i - V_s) \]
Comparison
✓ String stability
✓ Inter-vehicles distances
✓ Collisions
✓ Communication
✓ Stability without communication
✓ Simplicity and type of required data

Supervision of parameter $V$
✓ Increase safety

\[ V = \min(v_{\text{Leader}}, v_1, v_2, ..., v_N) \]

\[ h_i(v_i - V) > 0 \]

\[ \Delta X_i = L + h_i(v_i - V) > L \]

✓ Updating rate

Discussion

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Content of presentation

Introduction

Modeling

Control

Results

Conclusion

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• Control law for platoons (on highways)
• A modification of the CTH control law with the following benefits:
  ➢ Minimize the distance between vehicles (1m there)
  ➢ Increase the stability and the robustness of the control
  ➢ No high speed communications needed
  ➢ Stability even with total losing of communications
  ➢ Simplicity