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Enhanced Flatbed Tow Truck Model
Stable and Safe Platooning in the Presence of Lags, Communication and Sensing Delays

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GTAA 04/06/2015
Nantes, France
Problematic

- Traffic congestion

**Buses:**
- Not Flexible (destination).
- No privacy.
- Need wide roads.
- **Reduce congestion.**
- Cheap.

**Private cars:**
- Flexible (destination).
- Full privacy.
- Small unit size.
- **Increase congestion.**
- Expansive.

**Solution**
- Flexible (destination, size).
- No need for wide roads.
- Increases road density.
- Reduces congestion.
- Safer (human factor, speed)
- Reduces fuel consumption

Moving in compact way (Platoon)
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  ◦ Vehicle,
  ◦ Platoon
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I. Introduction

- **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.
I. Introduction

- **Why platooning:**
  - Increases traffic density,
  - Increases safety:
    - Weak collision (Small relative velocity),
    - No human factor,
    - Small reaction time,
  - decreases fuel consumption,
  - decreases driver tiredness,
I. Introduction

• Global Control and Local Control:
  ◦ **Data** (at least from leader, adjacent vehicles)
  ◦ **Sophisticated sensors** (needed, Not needed).
  ◦ **Environment adaptation** (Maybe, Not needed)
  ◦ **Communication system** (need very reliable, no)
  ◦ **Trajectory tracking** and inter distance keeping (accurate, Not very accurate)
  ◦ **Autonomous (No, Yes).**
I. Introduction

• **Variable inter-vehicle distances:**
  - The distance is not fix (e.g. proportional to velocity in (CTH) Constant Time Headway policy)
  - Low traffic density.
  - Stable without communication.
  - The cars can work autonomously.

\[
\Delta X = L + h v_i
\]

• **Constants inter-vehicle distances:**
  - High traffic density.
  - The communication between vehicles is mandatory.

\[
\Delta X = L
\]
Platooning

Constant spacing and Variable spacing

\[ \Delta X = L \]

High mandatory

traffic density

Communication

low Not important

- Our proposition \([3]\):
  - High traffic density with low Communication rate

\[ \Delta X = L + h v_i \]

\[ \Delta X = L + h (v_i - V) \]
I. Introduction

- **The proposed model and law:**
  - We proposed in [3] the flatbed tow truck model,
  - Inter-vehicle distances become proportional to relative velocities instead of absolute velocities.
  - The inter-vehicle distances decrease **largely**,
  - Low communication rate is needed (transmit $V$),

\[
\Delta X = L + h (v_i - V)
\]
I. Introduction

- The proposed model and law:
  - Actuators lags, sensing and communication delays may cause instability.
Objective:

- Robustness of the control law:
  - In the literatures, communication delays make platoons unstable [],
  - We study the effects of lags and delays on stability and safety of homogeneous platoons,
I. Introduction

- **State of the art:**
  - Platoon with actuators **lags** and **sensing delays:**
    - Stability can be assured [8,9,14,17].
    - The time headway policy is more robust than the constant spacing policy.
  - Platoon with **communication** delays:
    - Platoon stability can be obtained in presence of the same communication delay for all the vehicles [8].
    - **No** stability in presence of **propagation** delay in the leader information [7].
    - **Practically,** previous result represents an over constrained condition (i.e. instability is only caused by applying non-eliminating positive (or negative) acceleration),
  - We proved the stability in presence of all previous delays.

II. Modeling (vehicle)

- Newton’s law,

- Applying the exact linearization system,

\[ \ddot{x} = W \]
II. Modeling (Platoon)

- **Definitions:**
  - $L$: desired inter distance,
  - $V$: shared velocity,
  - $x_i, v_i$: Position and speed of the $i$-th vehicle
  - $e_i = x_{i-1} - x_i - L$: the $i$-th spacing error,
  - $X_V$: the position of the virtual truck,

- **Flatbed tow truck model:**
  - Unidirectional spring-damper model,
  - With virtual truck running at a speed $V$. 
III. Control

• Control Objectives:
  ◦ Keep a desired distance between the vehicles,
  ◦ Make the vehicles move at the same speed,
  ◦ Ensure vehicles and platoon stability [1-3],
  ◦ Control on highways [1,3] and in urban areas [2,5],
  ◦ Ensure vehicles and platoon safety [3,4,5,6],
  ◦ Increase traffic density,
  ◦ Ensure the stability and safety even in case of:
    ❖ Entire communication loss between vehicles [4],
    ❖ **Existence of actuating lags, sensing and communication delays** [6, current work].
  ◦ Study non-homogenous platoons [6],
III. Control

- **Control law (classical CTH):**

  \[
  W_i(t) = \frac{\dot{e} + \lambda \delta_i}{h}
  \]

  \[
  \delta_i = e_i - \lambda h v_i
  \]

  \(\lambda, h\) Control parameters

- **Proposed control law (enhanced CTH):**

  \[
  W_i(t) = \frac{\dot{e}_i + \lambda \delta_i + \lambda_1 e_V}{h}
  \]

  \[
  \delta_i = e_i - \lambda h (v_i - V)
  \]

  \[
  e_V = X_V - x_i - L_V
  \]
III. Control

- **Control law without delays:**

\[ W_i(t) = \ddot{x}_i(t) = \frac{\dot{e}_i(t) + \lambda \delta_i + \lambda_1 e_V(t)}{h} \]

\[ \delta_i(t) = e_i(t) - \lambda h (v_i(t) - V(t)) \]
III. Control

- Control law with delays (homogenous):

\[
\tau \ddot{x}(t) + \dot{x}(t) = \frac{\dot{e}(t - \Delta) + \lambda \delta_i(t, \tau_{c_i}, \Delta) + \lambda_1 e_V(t, \tau_{c_i}, \Delta)}{\lambda h}
\]

\[
\delta_i(t, \tau_{c_i}, \Delta_i) = e_i(t - \Delta) - h [v_i(t - \Delta) - V(t - (\Delta + \tau_{c_i}))]
\]

\[
e_V(t, \tau_{c_i}, \Delta) = X_V(t - (\Delta + \tau_{c_i})) - x_i(t - (t - \Delta)) - L_V
\]
IV. Stability

- **Platoon stability (string stability):**
  - The platoon is stable when all the spacing errors are bounded if the initial states are bounded.
  - We find Laplace function of the i-th error $E_i(s)$:
    $$E_i(s) = G_e(s) E_{i-1}(s) + G_V(s) e^{-\tau_{ci} s} V(s)$$
  - $G_x(s)$ are transfer functions,
  - The first error is given by:
    $$E_1(s) = F_e(s) V_0(s) + F_V(s) V(s)$$
  - $V_0(s), V(s)$ the Laplace function of leader and truck speed,
  - We want to make the error is limited so that
    $$\|e_i\|_\infty < \alpha, \text{where} \quad \alpha < \infty, \quad i = 1...N$$
IV. Stability

- We find $E_i(s)$ as a function of the first error:
  $$E_i(s) = G_{e}^{i-1}(s) \ E_1(s) + G_{m}(s) \ V(s)$$

- For any positive function $g(t)$, if $G(s)$ is its Laplace function then we have:
  $$\left\| G(\omega) \right\|_{\infty} = \left\| g(t) \right\|_{1}$$

- For any linear system $Y(s) = G(s) \ U(s)$ we always have:
  $$\left\| y(t) \right\|_{\infty} \leq \left\| g(t) \right\|_{1} \left\| u(t) \right\|_{\infty}$$

- So for the first error we get:
  $$\left\| e_1(t) \right\|_{\infty} \leq \left\| F_{e}(\omega) \right\|_{\infty} \left\| V_0(t) \right\|_{\infty} + \left\| F_{V}(\omega) \right\|_{\infty} \left\| V(t) \right\|_{\infty}$$

- Practically $\left\| V_0(t) \right\|_{\infty}, \left\| V(t) \right\|_{\infty}$ are limited, so to make $e_1(t)$ limited it is sufficient to make $\left\| F_{e}(\omega) \right\|_{\infty}, \left\| F_{V}(\omega) \right\|_{\infty}$ limited
IV. Stability

• For the i-th error we get:

\[ \|e_i(t)\|_\infty \leq \|G_e(\omega)\|_\infty^{i-1}\|e_1(t)\|_\infty + \|G_m(\omega)\|_\infty \|V(t)\|_\infty \]

• We already made e1 limited, and \(\|V(t)\|_\infty\) is practically limited, so to prove that the i-th error is limited it is sufficient to prove that \(\|G_m(\omega)\|_\infty\) is limited and \(\|G_e(\omega)\|_\infty \leq 1\).

• This give us **stability conditions** of the platoon in presence of actuation lags, sensing and communication delays.

• This mean that we can get stable platoon even with propagation delays (contrary to the results in [7])
V. Safety

- The inter-vehicle distances must be always bigger than zero. This can be ensured by limiting the maximum error:
  \[ \| e_i(t) \|_\infty \leq L \quad i = 1, ..., N \]

- \( e_1 \) and \( e_i \) are given by:
  \[ E_1(s) = K_V(s) \ A_V(s) + G_V(s) \ V(s) \]
  \[ E_i(s) = G_V(s) \ E_{i-1}(s) + G_V(s) \ V(s) \]
V. Safety

- So we apply safety condition on $e_1$ and $e_i$:

$$\|e_1(t)\|_\infty = \|K_V(s)\|_\infty \|a_V(t)\|_\infty + \|G_V(s)\|_\infty \|V(t)\|_\infty \leq L$$

$$\|e_i(t)\|_\infty = \|G_V(s)\|_\infty \|e_{i-1}(t)\|_\infty + \|G_V(s)\|_\infty \|V(t)\|_\infty \leq L$$

- This give us safety conditions in presence of lags and delays.
Simulation was done using Matlab,
Large platoon (60 identical vehicles) is created to check error amplification for vehicle with large indexes.
The platoon moves on straight road.
Desired inter-vehicle distance $L=12m$.
Lag $\tau = 200 \ ms$, sensing delay $\Delta = 200 \ ms$ and propagation delay $\tau_{ci} - \tau_{ci-1} = 50 \ ms$ for $i > 2$

Simulation scenarios:
- Platoon creation from stationary,
- Increasing the speed with maximal acceleration $(5m/s^2)$,
- Moving on fixed speed $(140km/h)$,
- Hard braking,
VI. Simulation

- For clarity, we only show the speed of one of ten vehicles,
- The platoon is stable (the errors are decreasing),
- The platoon is safe (inter-vehicle distances are always bigger than zero),
VII. Conclusion et Perspective

- Highways platooning is addressed,
- Enhanced CTH is used,
- Stability and Safety conditions, in presence of lags and delays, were found,
- Verified by simulations in critical scenarios.
VII. Conclusion et Perspective

- **In the coming works we will:**
  - Study non homogenous platoons \([6]\),
  - Study more complex
    - delay’s model (sensing delays different for the same vehicle)
    - and vehicle model (take motor model into account).
  - Take into account passenger comfort,
  - Make real experiments.
Thanks for listening
References


References