Enhanced flatbed tow truck model for stable and safe platooning in presences of lags, communication and sensing delays
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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).
  - Adaptation in the environment (Maybe, Not needed)
  - Communication system *(need very reliable, not needed)*
  - Trajectory tracking and inter distance keeping (accurate, Not very accurate)
  - *The car is totally autonomous (No, Yes).*
I. INTRODUCTION

• Variable inter-vehicle distances:
  - Distances are proportional to velocity in Constant Time Headway (CTH)
  - 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.

\[ \Delta X = L \]
I. INTRODUCTION

- **Delays and lags:**
  - Lags and times delays make the net engine torque is not immediately equal to the desired torque computed by the controller.

- **Delays types and sources:**
  - **Actuator lags:**
    - The lag in the engine response,
    - The lag of the throttle actuator,
    - The lag of the brake actuator...
  - **Sensing delays:**
    - The delay due to the sensors response time,
    - The delay due to the sensors filter...
  - **Communication delays:**
    - Communication transfer time,
    - Packet drops,
    - Connection loss...
I. INTRODUCTION

- **State of the art:**
  - **Stability with lags and sensing delays:**
    - Study can be found for many control laws [2010: Ling-yun, 2001: Rajamani, Swaroop, Yanakiev].
    - A detailed study when using classical time headway for homogeneous and heterogeneous platoons is found in [Lingyun(2011)].
  - **Effects of communication delays:**
    - The platoon is unstable for **any** propagation delays in the communicated leader information [2001: Hedrick] !!!!!.
    - A solution in [2001: Xiangheng] by synchronizing all the controllers of the vehicles,
    - **But** Clock jitter, which can be seen as a **delay** and may cause **instability** according to [2001: Hedrick] result, was briefly mentioned!!!!!.
    - [Lingyun(2011)] proved string stability for the leader-predecessor and predecessor-successor framework neglecting information delays between vehicles.
    - The effect of losing the communication is presented in [2010: Teo]. It has been proved that string stability can be retained, with limited spacing error, by estimating lead vehicle’s state during losses.
  - **In this Work we prove the stability and the safety of the platoon in presence of all the delays in extension to [2001: Hedrick],**
II. MODELING (Longitudinal Model)

- Newton’s law,

- Applying the exact linearization system,

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

- **Platoon:**
  - Vehicles following each other.

- **The leader:**
  - Driven manually or automatically/it can be virtual or real.

- **The other vehicles:**
  - Run at the same speed keeping desired inter-vehicle distances.

- $L$: Desired inter distance.

- $x_i$: Position of vehicle $i$.

- $v_i$: Speed of vehicle $i$.

- $e_i = x_{i-1} - x_i - L$: Spacing error between vehicle $i$ and vehicle $i-1$. 
III. CONTROL

- Control Objectives.
  - Keep a desired distance between the vehicles,
  - Make the vehicles move at the same speed,
  - Ensure vehicles and platoon stability [1-5],
  - Control on highways [1,3] and in urban areas [2,4],
  - Ensure vehicles and platoon safety \([ICARCV_{14}]\),
  - Increase traffic density,
  - Ensure the stability and safety even in case of:
    - Entire communication loss between vehicles \([ICARCV_{14}]\),
    - **Existence of actuating, sensing lags and communication delays.**
III. CONTROL

- Control law:

\[ W_i = \frac{\dot{e}(t) + \lambda e_i(t) - \lambda h(v_i(t) - V(t)) + \lambda_1 e_{V_i}}{h} \]

\( e_{V_i} \): Is the error between the position of the virtual truck and the vehicle i.

The position of the truck is calculated by integrating V.
II. CONTROL (With delays)

- Modeling of the platoon with delays:
  - Lags $\tau_i$: so $\ddot{x} = W_i \quad \ddot{x} + \tau_i \dot{x} = W_i$
  - Sensing delays $\Delta_i$: $e_i(t), \dot{e}_i(t), v(t)$ $\rightarrow e_i(t - \Delta_i), \dot{e}_i(t - \Delta_i), v(t - \Delta_i)$
  - Communication delays $\tau_{ci}$: so $V(t), X_V \rightarrow V(t - (\Delta_i - \tau_{ci})), X_V (t - (\Delta_i - \tau_{ci}))$
The error function of the $i$-th vehicle becomes:

$$e_i(s) = G_e(s)e_{i-1}(s) + G_V(s)e^{-\tau_{ci}} V(s)$$

Transfer functions:
- $G_e(s), G_V(s)$

Impulse functions:
- $g_e(t), g_V(t)$
IV. STABILITY

- Platoon stability:
  - All state variables are always limited for all the vehicles:

\[
\exists \alpha_i, \beta_i, \gamma_i < \infty: \\
\left\| e_i(t) \right\|_{\infty} \leq \alpha_i \land \left\| \dot{e}_i(t) \right\|_{\infty} \leq \beta_i \land \left\| \ddot{e}_i(t) \right\|_{\infty} \leq \gamma_i \\
\forall i = 1, \ldots, N \quad \text{and} \quad t > 0
\]
IV. STABILITY

- Stability **without** communication delay:

\[ e(s) = G_e(s)e_{i-1}(s) + G_V(s) - \tau \]

- Sufficient stability condition (error do not increase through platoon)

\[ \|e_i(t)\|_\infty \leq \|e_{i-1}(t)\|_\infty \]

- It is sufficient to prove:

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

- We get stability conditions:

\[ \begin{cases} 
\lambda \leq \frac{h - 2(\Delta + \tau) + 2\lambda_1 \tau \Delta}{2(h(\Delta + \tau) - \Delta \tau)} \\
\frac{\lambda_1}{\lambda} < \frac{h}{2} \\
\lambda \geq \frac{\lambda_1 \tau - 1}{h - \tau} \\
h \geq 2(\Delta + \tau)
\end{cases} \]
IV. STABILITY

- **Stability with communication delay:**

  \[ e_i(s) = G_e(s)e_{i-1}(s) + G_V(s)e^{-\tau_i}V(s) \]

- We can’t use \( \|e_i(t)\|_{\infty} \leq \|e_{i-1}(t)\|_{\infty} \)

- We calculate \( e_i \) as a function of \( e_1 \) and \( V \):

  \[
  e_i(s) = G^{i-1}_e(s)e_1(s) + G_V(s)e^{-\Delta_s} \frac{1-(G_e^{\Delta_s})^{i-2}}{1-G_e^{\Delta_s}} V(s)
  \]

- Sufficient stability condition is to prove that the errors is always limited for all the vehicles and all the times:

  \[
  \exists \alpha_i < \infty : \|e_i(t)\|_{\infty} \leq \alpha_i \quad \forall i = 1,...,N \quad \text{and} \quad t > 0
  \]
IV. STABILITY

• **Stability with communication delay:**

  - If $g_e(t), g_V(t)$ are positive impulse functions then we get:
    
    $$e_1(s) = F_e v_0(s) - F_V V(s)$$

    The only problem can appears near low frequencies when $(X_V-x_0)$ become very big

    $$\lambda h(V-V_i) + \lambda_i (X_V-x_0)$$

    $$\left\| e_i(t) \right\|_\infty \leq \left\| G_e(\omega) \right\|_\infty^{i-1} \left\| e_1(t) \right\|_\infty + \left\| G_V(\omega) \right\|_\infty \frac{\left\| 1-(G_e(\omega)e^{-j\Delta_c\omega})i-2 \right\|_\infty}{\left\| 1-G_e(\omega)e^{-j\Delta_c\omega} \right\|_\infty} \left\| V(t) \right\|_\infty < \infty$$

    - Converge to zero
    - Bounded if the propagation delay $\Delta_c$ is bounded

    $$\left\| G_e(\omega) \right\|_\infty = \left\| G_e(0) \right\|_\infty < 1$$

    $$\left\| G_V(\omega) \right\|_\infty = \left\| G_V(0) \right\|_\infty = \frac{\lambda_i}{\lambda + \lambda_i} \Delta_c$$

    $$0 < \left\| 1-G_e(\omega)e^{-j\Delta_c\omega} \right\|_\infty \leq 2$$

    $$\left\| G_e(\omega) \right\|_\infty = \left\| G_e(0) \right\|_\infty < 1$$
We want to limit the maximum error to keep the inter-vehicle distances always bigger than zero:

\[ \| e_i(t) \|_\infty \leq \left( \| G_e(\omega) \|_\infty \| e_{i-1}(t) \|_\infty + \| G_V(\omega) \|_\infty \| V(t) \|_\infty \right) \]

Taking \( \max(\xi) < L \) will limit the max error, we get:

\[ \| G_V(\omega) \|_\infty \leq (1 - \| G_e(\omega) \|_\infty ) \frac{L}{\| V(t) \|_\infty} \]

\[ \tau_{c_i} - \tau_{c_{i-1}} = \Delta_c \leq \frac{L}{\max(V(t))} \]

Limit for communication propagation delay that prevents collisions
V. SAFETY

- For the first error $e_1$:
  \[ e_1(t) = -K_e(s)e_v(s) + K_v(s)a_v(s) \]

- Taking $V = v_0$ we get:
  \[ e_1(t) = K_v(s)a_0(s) \]

\[ |e_1(t)| \leq \|K_v(s)\|_\infty \|a_0(s)\|_\infty \]

\[ \lambda + \lambda_1 \geq h \frac{a_0}{L} \]
VI. SIMULATION

- The leader accelerate from 0 to 140 km/h, then we apply hard braking,
- Scenarios:
  - Platoon creation,
  - Changing speed,
  - High acceleration,
  - Hard braking,
- $L = 10 \, m$
- maximum deceleration $4.5 \, m/s^2$
- **Delays:**
  \[
  \begin{align*}
  \Delta &= 0.25 \, s & \text{Sensing delay} \\
  \tau &= 0.25 \, s & \text{Actuating lag} \\
  \Delta_c &= 50 \, ms & \text{Communication delay }
  \end{align*}
  \]
Inter-vehicle spacing in presence of lags, sensing and communication delays
VII. CONCLUSION et PERSPECTIVE

- Highways platooning is addressed,
- Additional modification of CTH control law is proposed,
- String stability is enhanced,
- Robustness to lags, sensing and communication delays is proved,
- Safety conditions are also found,
- Simulations were done in the following scenarios:
  - Platoon creation,
  - Changing the speed,
  - Emergency stop,
Non-homogenous platoon will be studied,
Non-equal delays case will be also studied:
- $\tau_i \neq \tau_{i-1}$,
- $\Delta_i \neq \Delta_{i-1}$,
- $\tau_{c_i} \neq \tau_{c_{i-1}}$

Real experiments.
References


