Enhanced flatbed tow truck model for stable and safe platooning in presences of lags, communication and sensing delays

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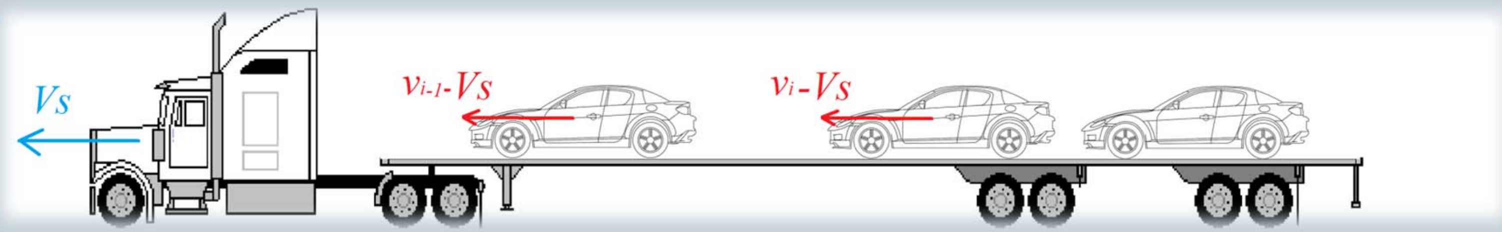

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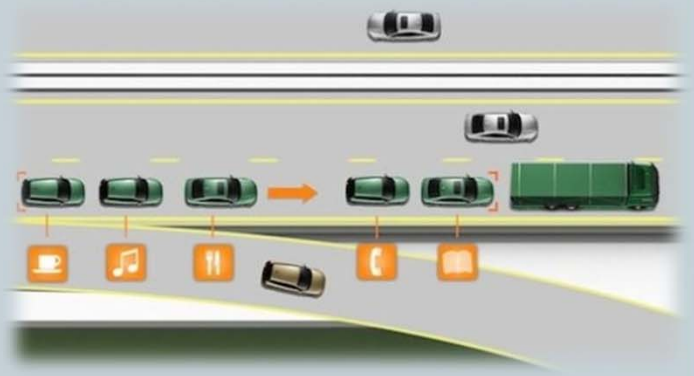
I. INTRODUCTION

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

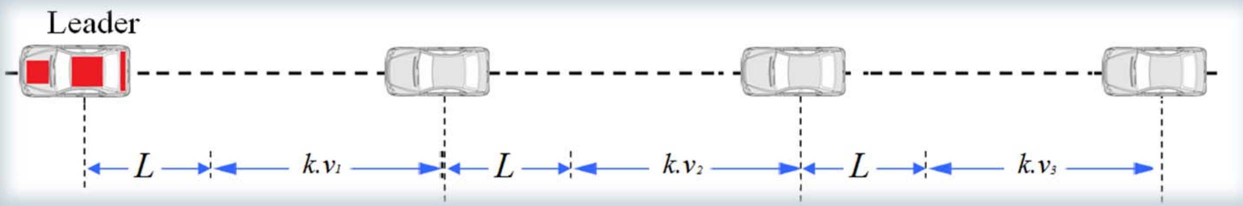


I. INTRODUCTION

- 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).***

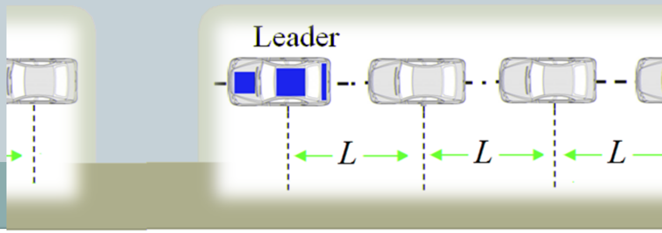
I. INTRODUCTION

- 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.



$$\Delta X = L + hv_i$$

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



$$\Delta X = L$$

I. INTRODUCTION

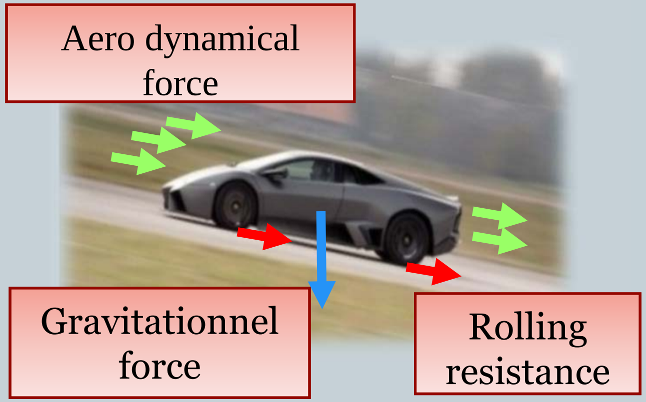
- Delays and lags:
  - Lags and times delays make the net engine torque is not immediately equal to the desired torque computed by the controller.
- Delays types and sources:
  - **Actuator lags:**
    - The lag in the engine response,
    - The lag of the throttle actuator,
    - The lag of the brake 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],

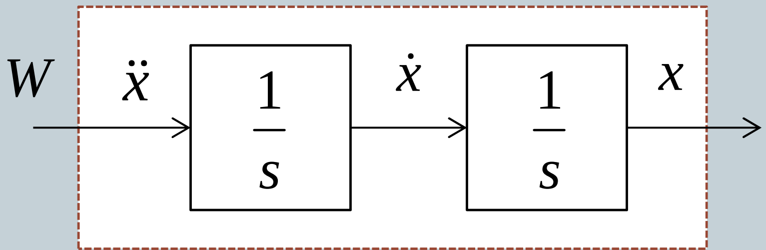
II. MODELING (Longitudinal Model)

- Newton's law,



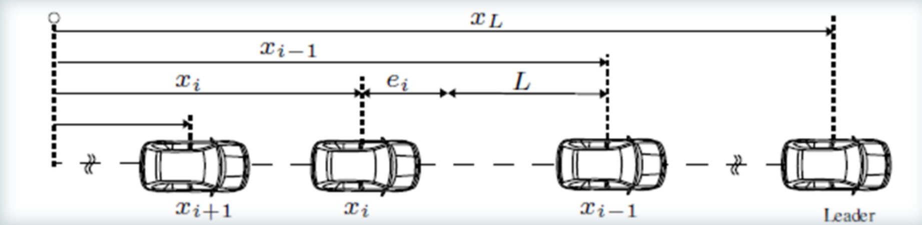
- Applying the exact linearization system,

$$\ddot{x} = W$$



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.

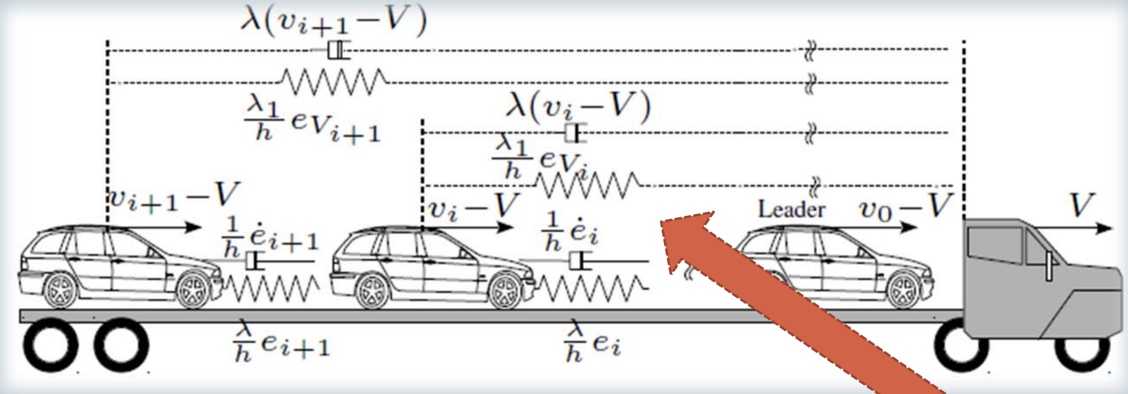


III. CONTROL

- 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 [ICARCV14],
  - Increase traffic density,
  - Ensure the stability and safety even in case of :
    - Entire communication loss between vehicles [ICARCV14],
    - **Existence of actuating, sensing lags and communication delays.**

III. CONTROL

- Control law:



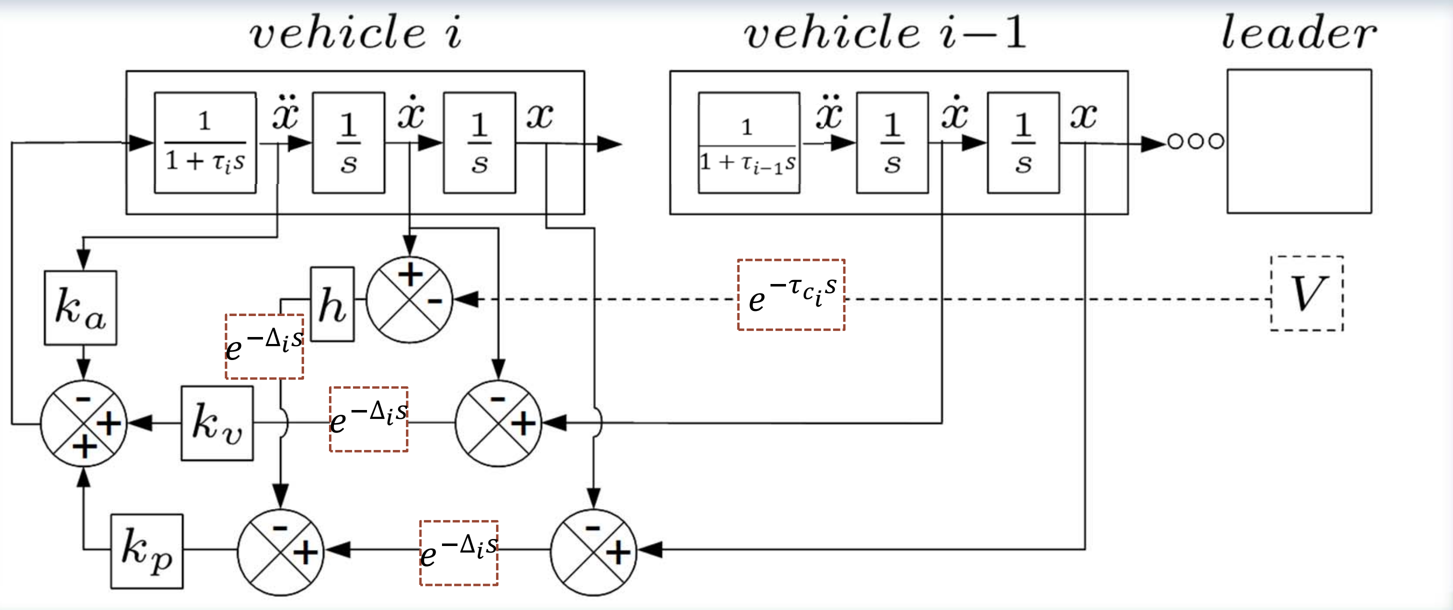
$$W_i = \frac{\dot{e}(t) + \lambda e_i(t) - \lambda h(v_i(t) - V(t)) + \lambda_1 e_{V_i}}{h}$$

New term

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)

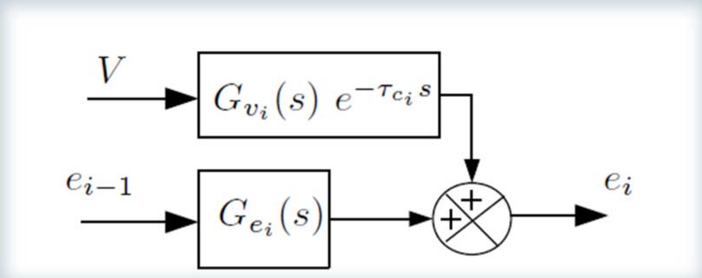
- Modeling of the platoon with delays:
  - Lags τ_i : so $\ddot{x} = W_i$ ➡ $\dddot{x} + \tau_i \ddot{x} = W_i$
  - Sensing delays Δ_i : $e_i(t), \dot{e}_i(t), v(t)$ ➡ $e_i(t-\Delta_i), \dot{e}_i(t-\Delta_i), v(t-\Delta_i)$
  - Communication delays τ_{c_i}: so $V(t), X_V$ ➡ $V\big(t-(\Delta_i - \tau_{c_i})\big), X_V\big(t-(\Delta_i - \tau_{c_i})\big)$



III. CONTROL(With delays)

- The error function of the i-th vehicle becomes:

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



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

$g_e(t), g_V(t)$ Impulse functions

IV. STABILITY

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

$$\exists \alpha_i, \beta_i, \gamma_i < \infty :$$

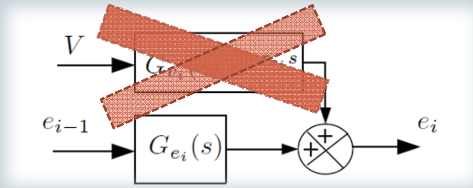
$$\left\| e_i(t) \right\|_\infty \le \alpha_i \;\&\; \left\| \dot{e}_i(t) \right\|_\infty \le \beta_i \;\&\; \left\| \ddot{e}_i(t) \right\|_\infty \le \alpha_i$$

$$\forall i = 1, \ldots, N \quad and \quad t > 0$$

IV. STABILITY

- Stability **without** communication delay:

$$e(s) = G_e(s)e_{i-1}(s) + \cancel{G_V(s)e^{-\tau c_i}V(s)}$$

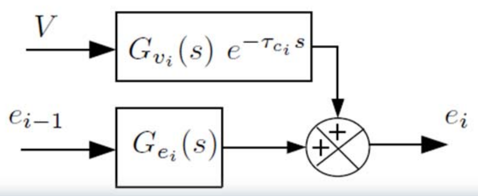


- Sufficient stability condition (error do not increase through platoon) $\|e_i(t)\|_\infty \le \|e_{i-1}(t)\|_\infty$
- It is sufficient to prove: $\left\| \dfrac{e_i(s)}{e_{i-1}(s)} \right\|_\infty = \|G_i(s)\|_\infty \le 1$
- We get stability conditions:

$$\left\{ \lambda \le \frac{h - 2(\Delta+\tau) + 2\lambda_1 \tau\Delta}{2(h(\Delta+\tau) - \Delta\tau)} \quad \& \quad \frac{\lambda_1}{\lambda} < \frac{h}{2} \quad \& \quad \lambda \ge \frac{\lambda_1\tau - 1}{h-\tau} \quad \& \quad h \ge 2(\Delta+\tau) \right\}$$

IV. STABILITY

- Stability **with** communication delay:



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

- We can't use $\left\|e_i(t)\right\|_\infty \le \left\|e_{i-1}(t)\right\|_\infty$
- We calculate e_i as a function of e_1 and V:

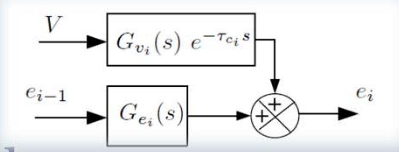
$$e_i(s) = G_e^{i-1}(s)e_1(s) + G_V(s)e^{-\Delta_c s}\frac{1-(G_e e^{-\Delta_c s})^{i-2}}{1-G_e e^{-\Delta_c s}}V(s)$$

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

$$\exists \alpha_i < \infty : \left\|e_i(t)\right\|_\infty \le \alpha_i \quad \forall i = 1,\dots,N \quad and \quad t > 0$$

IV. STABILITY

- Stability **with** communication delay:



  - If $g_e(t), g_V(t)$ are positive impulse functions then we get:

$$e_1(s) = F_e\, v_0(s) - F_V V(s)$$

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

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

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

$$\lambda h(V - v_i) + \lambda_1 (X_V - x_0)$$

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

Converge to zero

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

Bounded if the propagation delay Δ_c is bounded

$$\|G_V(\omega)\|_\infty = \|G_V(0)\|_\infty = \frac{\lambda_1}{\lambda + \lambda_1}\Delta_c$$

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

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

V.SAFETY

- We want to limit the maximum error to keep the inter-vehicle distances always bigger than zero :

$$\|e_i(t)\|_\infty \le \underbrace{\|G_e(\omega)\|_\infty \|e_{i-1}(t)\|_\infty + \|G_V(\omega)\|_\infty \|V(t)\|_\infty}_{\xi} \qquad i = 2,\ldots,N$$

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

$$\|G_V(\omega)\|_\infty \le (1 - \|G_e(\omega)\|_\infty)\frac{L}{\|V(t)\|_\infty} \qquad i = 2,\ldots,N$$

$$\tau_{c_i} - \tau_{c_{i-1}} = \Delta_c \le \frac{L}{\max(V(t))} \qquad i = 2,\ldots,N$$

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:

$$e_1(t) = K_V(s)a_0(s)$$

$$|e_1(t)| \leq \|K_V(s)\|_\infty \|a_0(s)\|_\infty$$

$$\lambda + \lambda_1 \geq h\frac{a_0}{L}$$

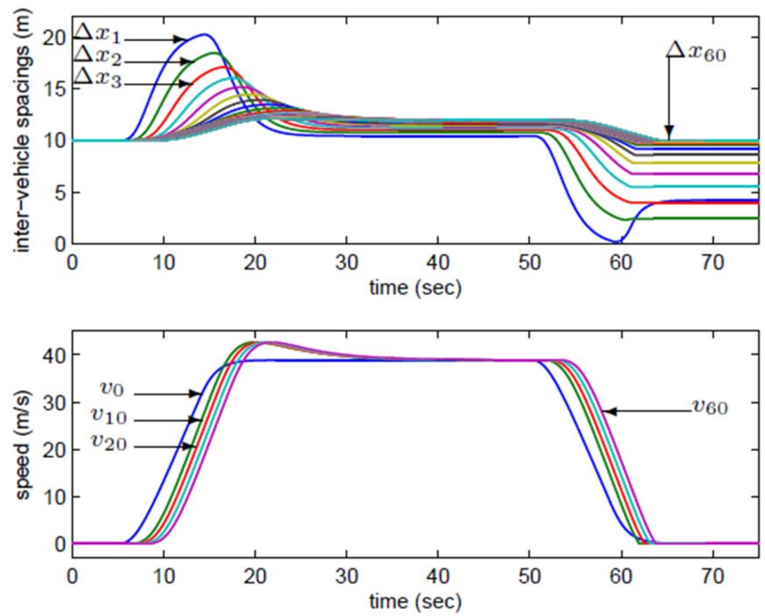
VI.SIMULATION

- 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:**

$\Delta = 0.25\ s$ Sensing delay

$\tau = 0.25\ s$ Actuating lag

$\Delta_c = 50\ ms$ Communication delay



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,

VII. CONCLUSION et PERSPECTIVE

- 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.

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