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

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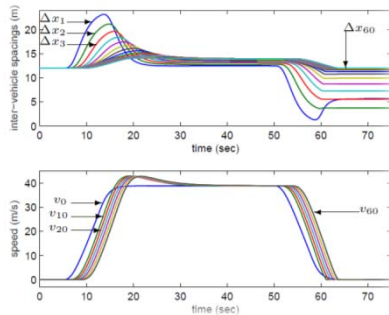
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# Enhanced Flatbed Tow Truck Model

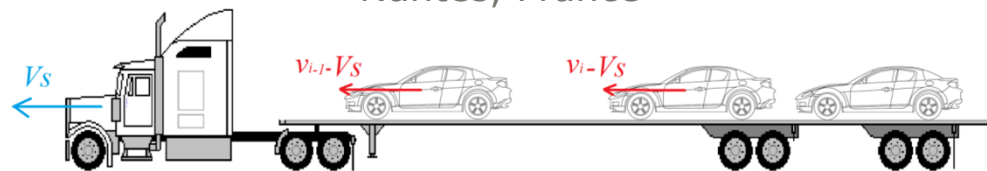
*Stable and Safe Platooning in the Presences of Lags, Communication and Sensing Delays*



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Gaëtan GARCIA  
Philippe MARTINET



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



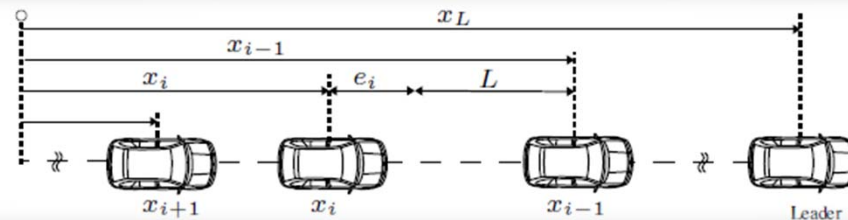
- Flexible (destination, size).
- No need for wide roads.
- Increases road density .
- Reduces congestion.
- Safer (human factor, speed)
- Reduces fuel consumption

# INDEX

- I. Introduction
- II. Modeling:
  - Vehicle,
  - Platoon
- III. Control
- IV. Stability
- V. Safety
- VI. Simulation
- VII. Conclusion

# I. Introduction

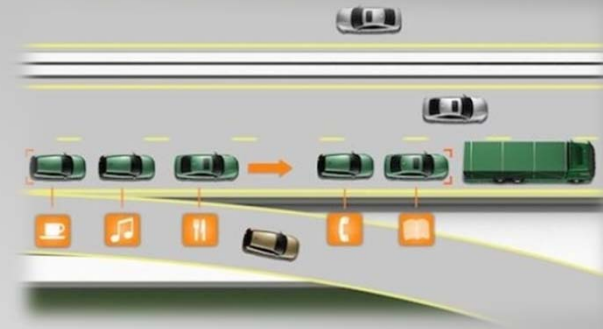
- **Platoon:**
  - Vehicles following each other.
  - The leader:
    - Real or virtual
    - Driven manually or automatically.
  - Other vehicles:
    - Following each other and moving at the same speed
    - Keeping desired distance.



# 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,



*Photo courtesy of Daimler Chrysler*



# I. Introduction

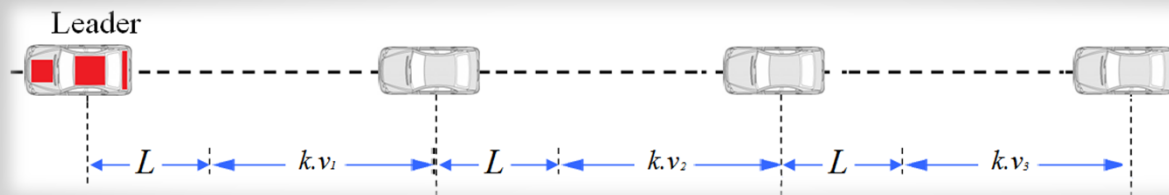
- **Global Control and Local Control :**
  - **Data** (at least from leader, adjacent vehicles)
  - **Sophisticated sensors** (needed, Not needed).
  - **Environment adaptation** (Maybe, Not needed)
  - **Communication system** (need very reliable, no)
  - **Trajectory tracking** and inter distance keeping (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.

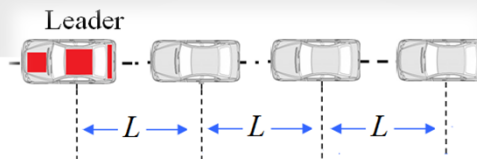


Inter-vehicle distance

$$\Delta X = L + hv_i$$

- **Constants inter-vehicle distances:**

- High traffic density.
- The communication between vehicles is mandatory.

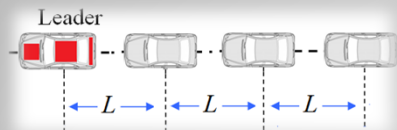


$$\Delta X = L$$

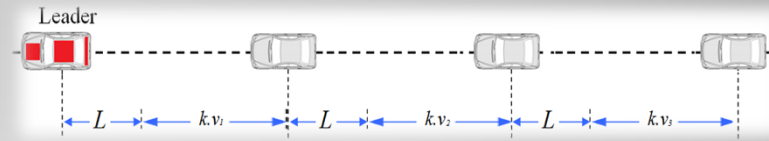


# Platooning

Constant spacing and Variable spacing



$$\Delta X = L$$

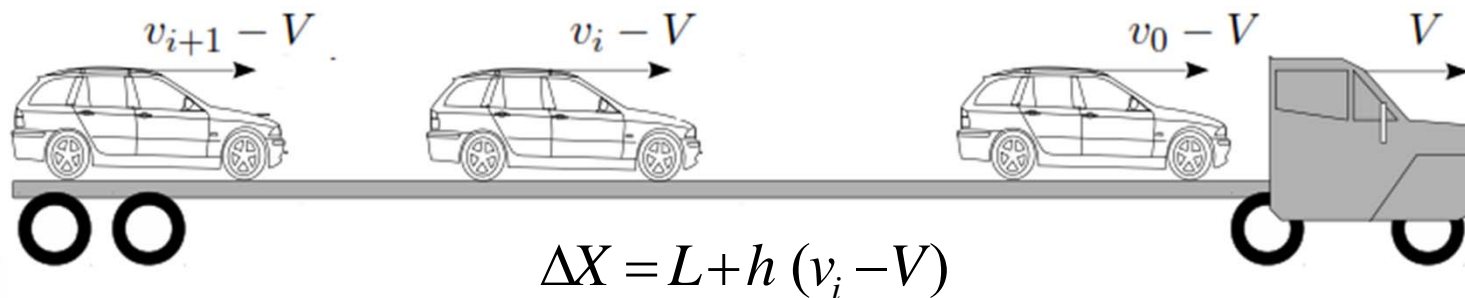


$$\Delta X = L + h v_i$$

High traffic density ← → low  
 mandatory ← → Communication ← → Not important

- Our proposition [3]:

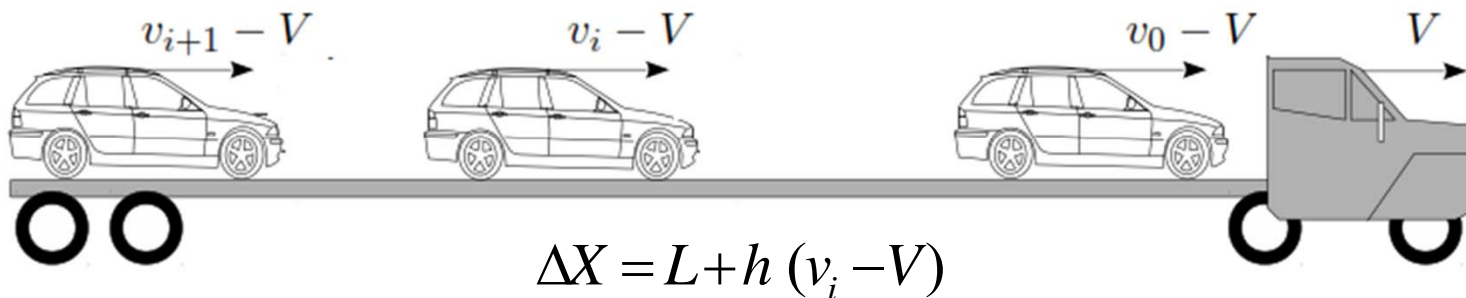
**High** traffic density with  
**low Communication** rate



$$\Delta X = L + h (v_i - V)$$

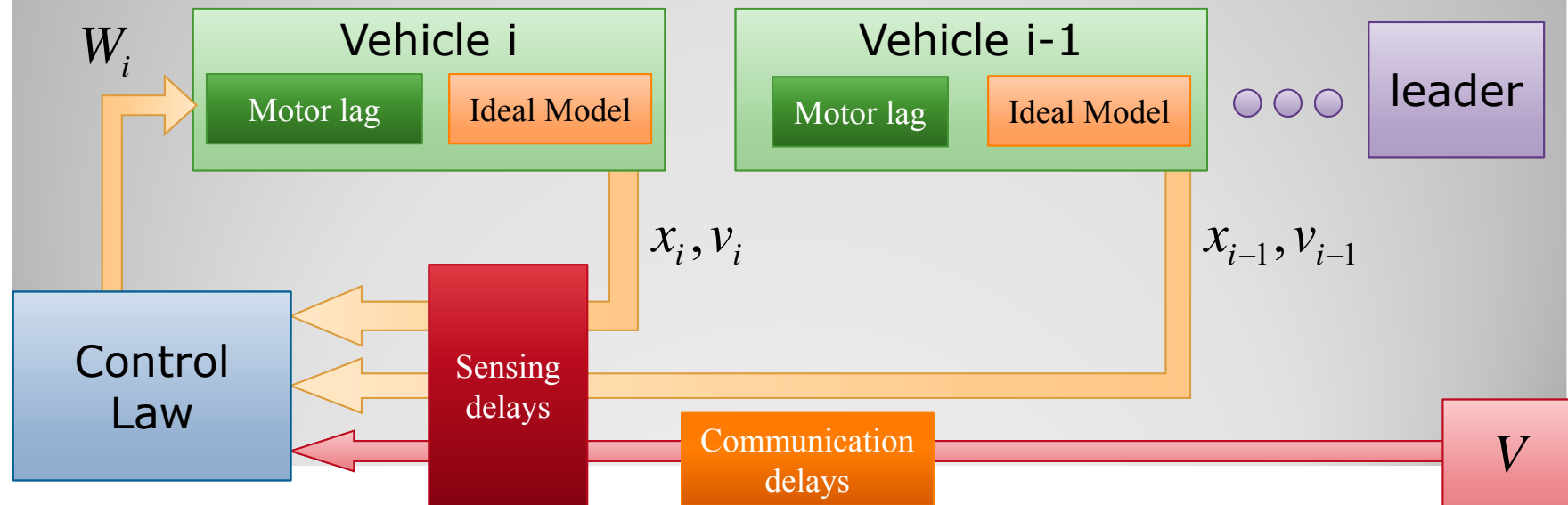
# I. Introduction

- **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  $V$ ),



# I. Introduction

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

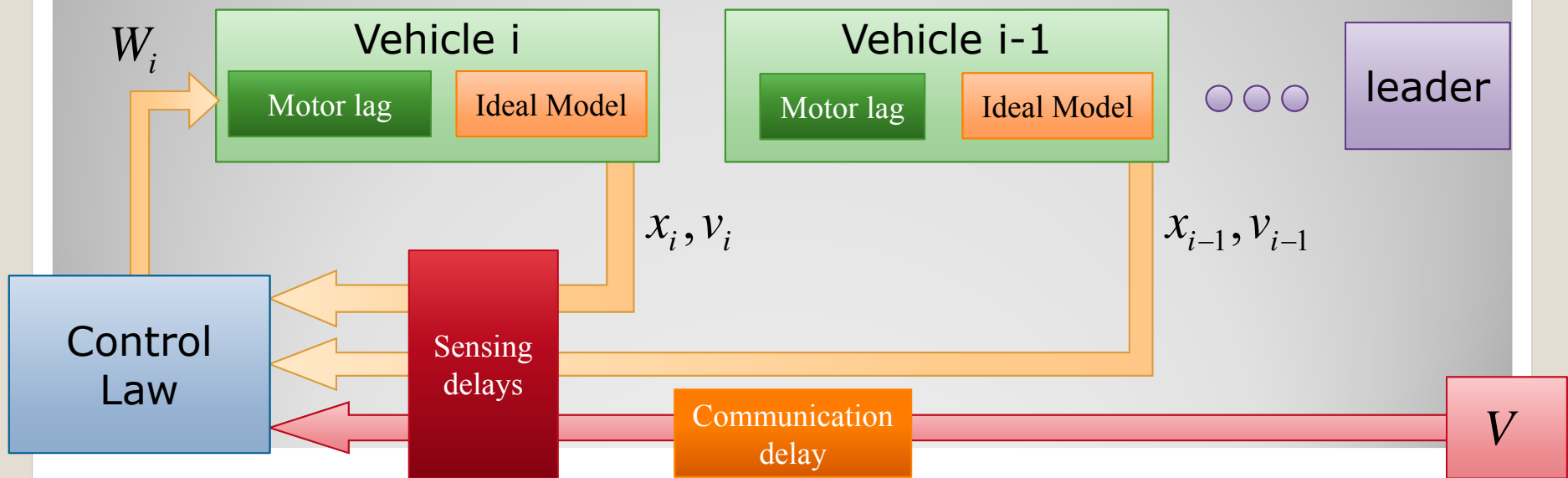


# Objective:

## • 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].



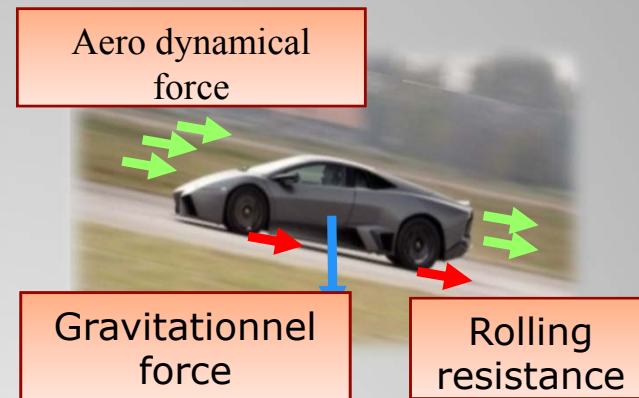
- **No** stability in presence of **propagation** delay in the leader information [7].

- **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.

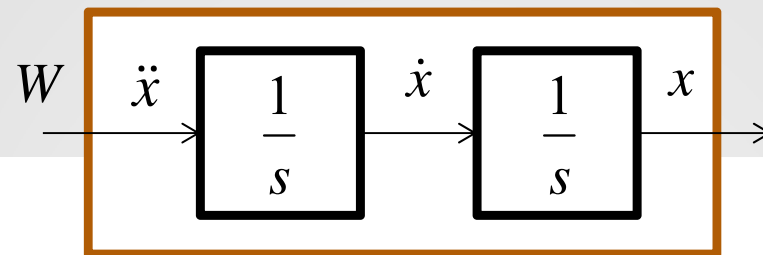
## II. Modeling (vehicle)

- Newton's law,



- Applying the exact linearization system,

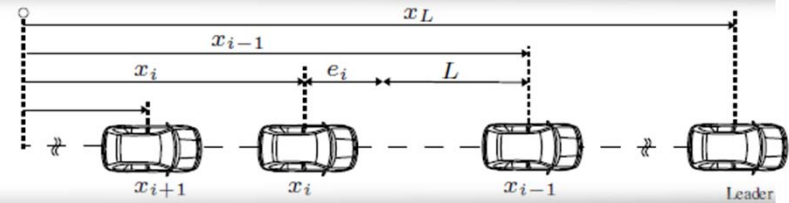
$$\ddot{x} = W$$



# II. Modeling (Platoon)

- **Definitions:**

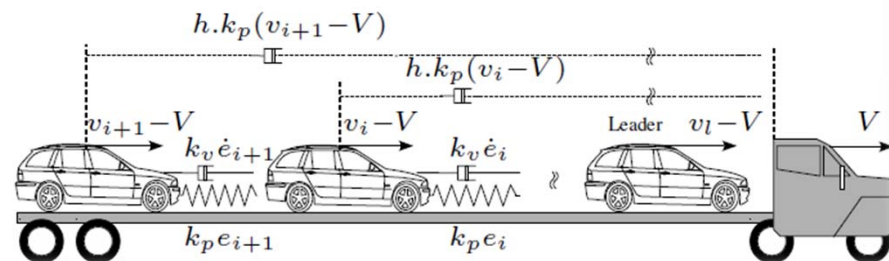
- L: desired inter distance,
- V: shared velocity,
- $x_i, v_i$  Position and speed of the i-th vehicle
- $e_i = x_{i-1} - x_i - L$  the i-th spacing error,



- $X_V$  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):

$$W_i(t) = \frac{\dot{e}_i + \lambda \delta_i}{h}$$

$$\delta_i = e_i - \lambda h v_i$$

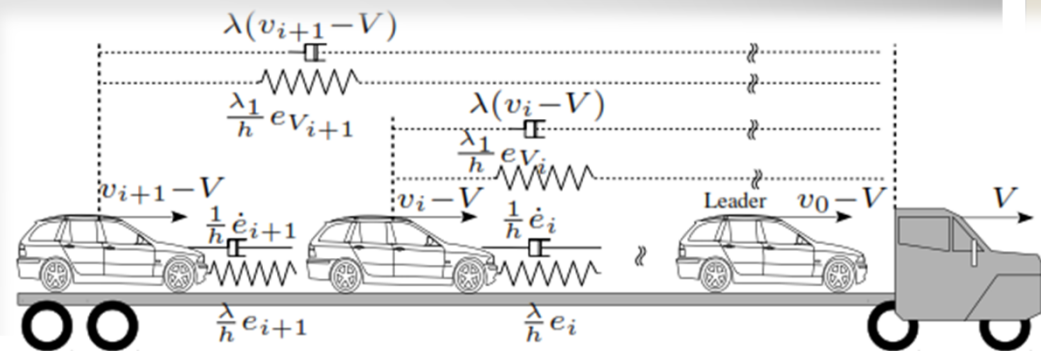
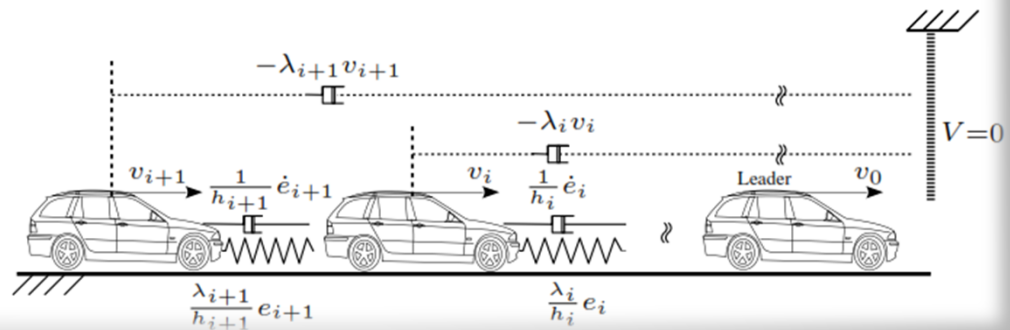
$\lambda, h$  Control parameters

- Proposed control law (enhanced CTH):

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

$$\delta_i = e_i - \lambda h (v_i - V)$$

$$e_V = X_V - x_i - L_V$$

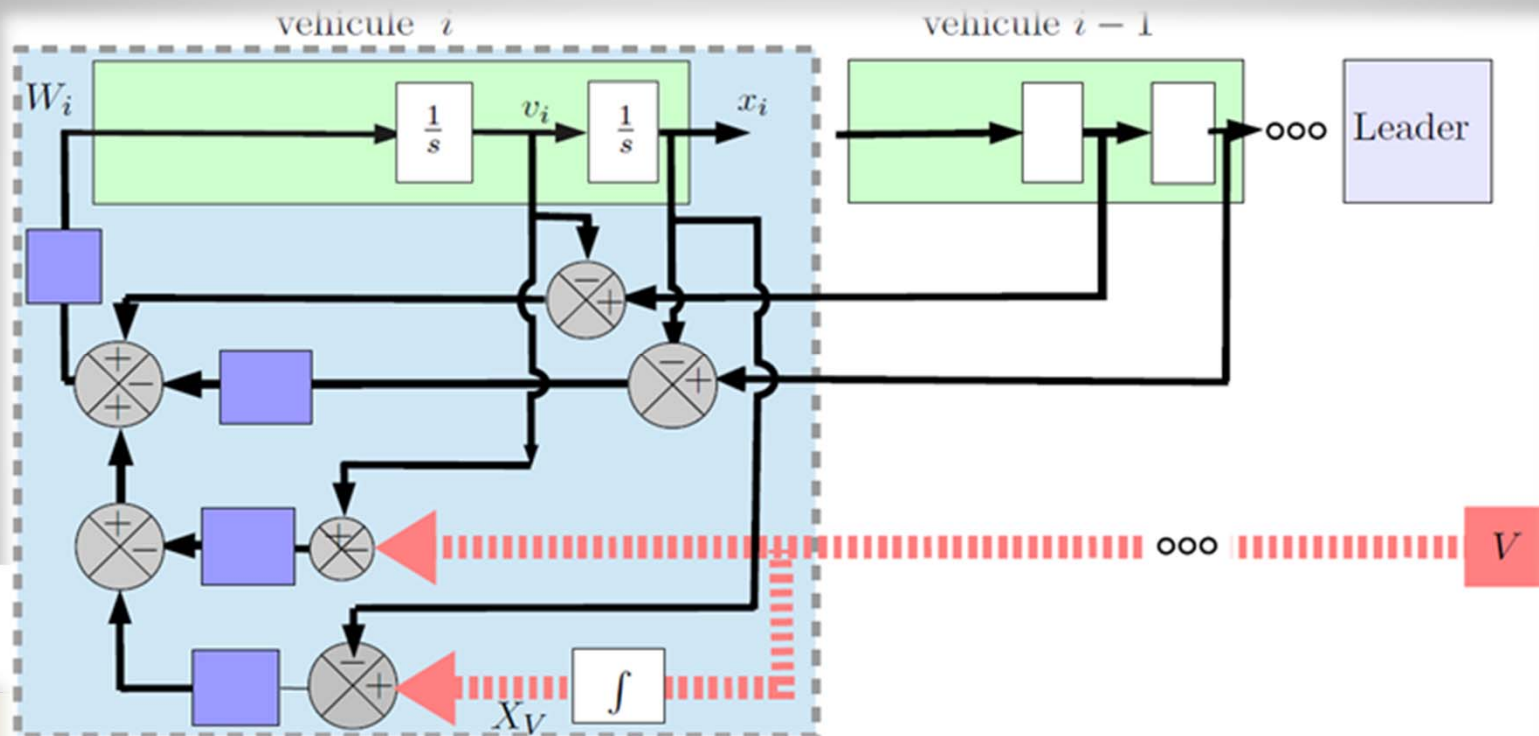


# III. Control

- Control law **without** delays:

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

$$\delta_i(t) = e_i(t) - \lambda h (v_i(t) - V(t))$$



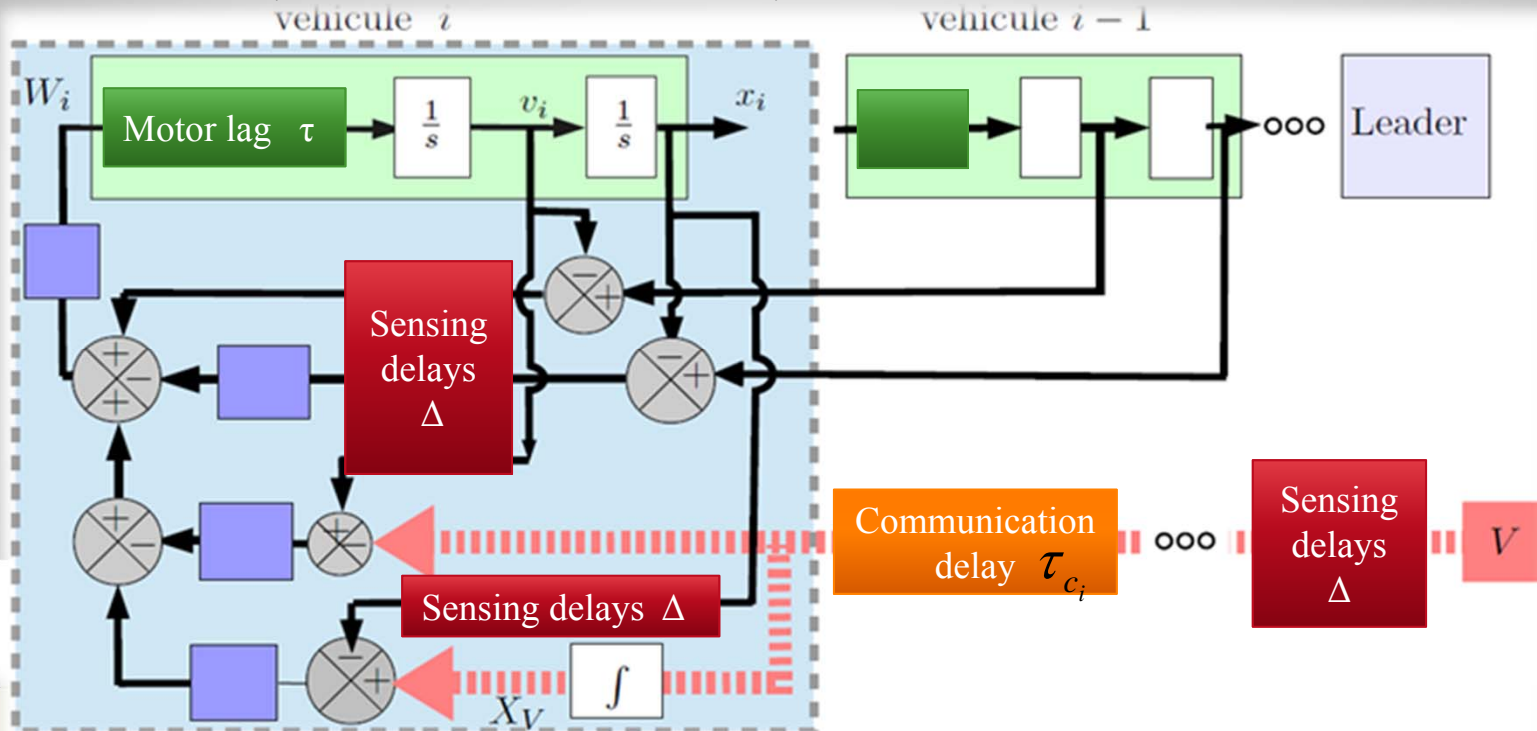
# III. Control

- Control law **with** delays (homogenous):

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

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

$$e_V(t, \tau_{c_i}, \Delta) = X_V(t - (\Delta + \tau_{c_i})) - x_i(t - (t - \Delta)) - L_V$$



## 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  $E_i(s)$ :

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

- $G_x(s)$  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

$$\|e_i\|_{\infty} < \alpha, \text{ where } \alpha < \infty, \quad i = 1 \dots N$$

## 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:

$$\|G(\omega)\|_{\infty} = \|g(t)\|_1$$

- For any linear system  $Y(s) = G(s) U(s)$  we always have:

$$\|y(t)\|_{\infty} \leq \|g(t)\|_1 \|u(t)\|_{\infty}$$

- So for the first error we get:

$$\|e_1(t)\|_{\infty} \leq \|F_e(\omega)\|_{\infty} \|V_0(t)\|_{\infty} + \|F_V(\omega)\|_{\infty} \|V(t)\|_{\infty}$$

- Practically  $\|V_0(t)\|_{\infty}, \|V(t)\|_{\infty}$  are limited, so to make  $e_1(t)$  limited it is sufficient to make  $\|F_e(\omega)\|_{\infty}, \|F_V(\omega)\|_{\infty}$  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  $e_1$  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:

$$\|e_i(t)\|_{\infty} \leq L \quad i = 1, \dots, N$$

- $e_1$  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  $e_i$  :

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

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

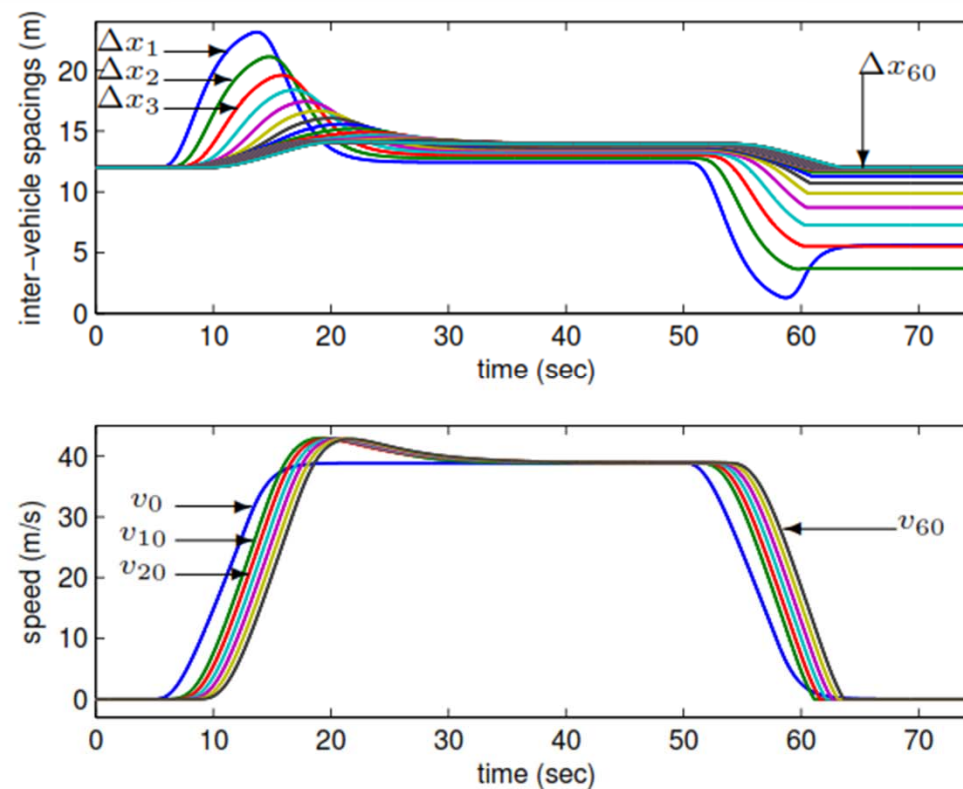
- This give us safety conditions in presence of lags and delays.

## VI .Simulation

- 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  $\tau = 200 \text{ ms}$ , sensing delay  $\Delta = 200 \text{ ms}$  and propagation delay  $\tau_{c_i} - \tau_{c_{i-1}} = 50 \text{ ms}$  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**



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