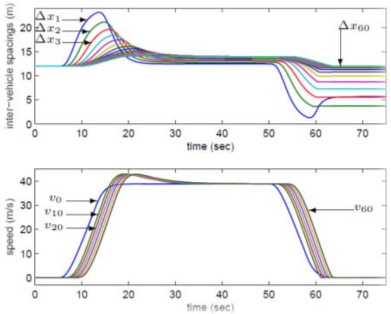
Enhanced Flatbed Tow Truck Model

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



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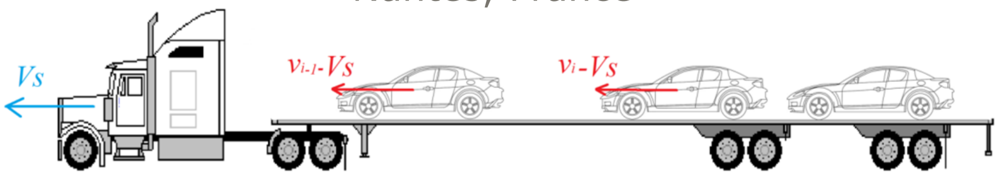

Problematic

- Trafic 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

Moving in compact way

(Platoon)

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

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  - Vehicle,
  - Platoon
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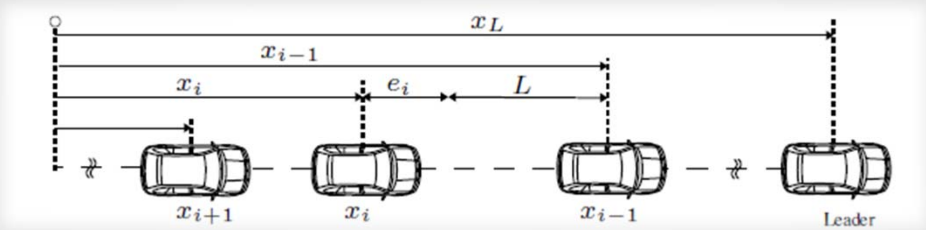
I. Introduction

- **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,

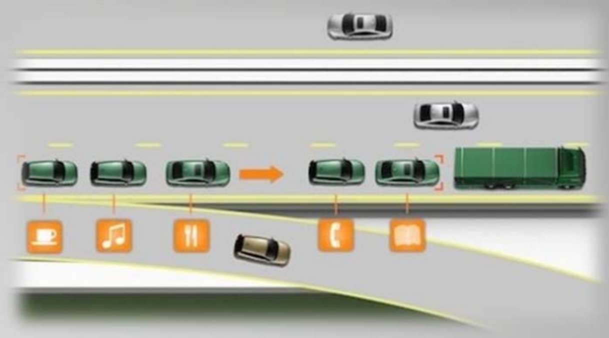


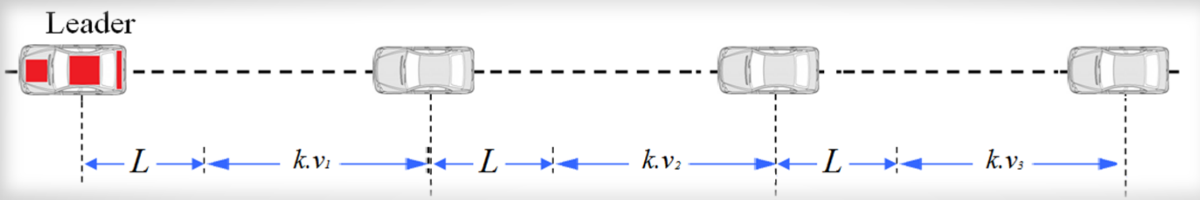
Photo courtesy of DaimlerChrysler

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

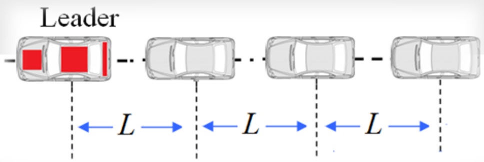
- **Variable inter-vehicle distances :**
  - The distance is not fix (e.g. proportional to velocity in (CTH) Constant Time Headway policy)
  - Low traffic density.
  - Stable without communication.
  - The cars can work autonomously.



Inter-vehicle distance

$$\Delta X = L + hv_i$$

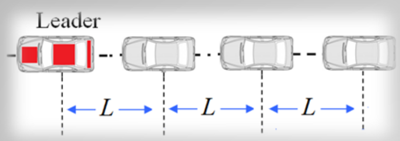
- **Constants inter-vehicle distances:**
  - High traffic density.
  - The communication between vehicles is mandatory.

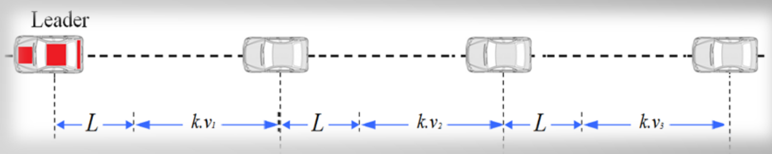


$$\Delta X = L$$

Platooning

Constant spacing and Variable spacing





$$\Delta X = L$$

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

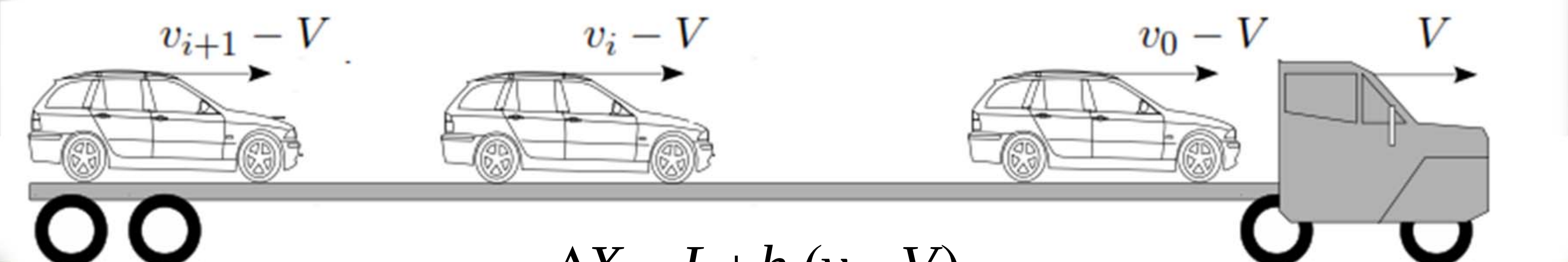
High ← traffic density → **low**

mandatory ← Communication → Not important

- Our proposition **[3]**:

High traffic density with

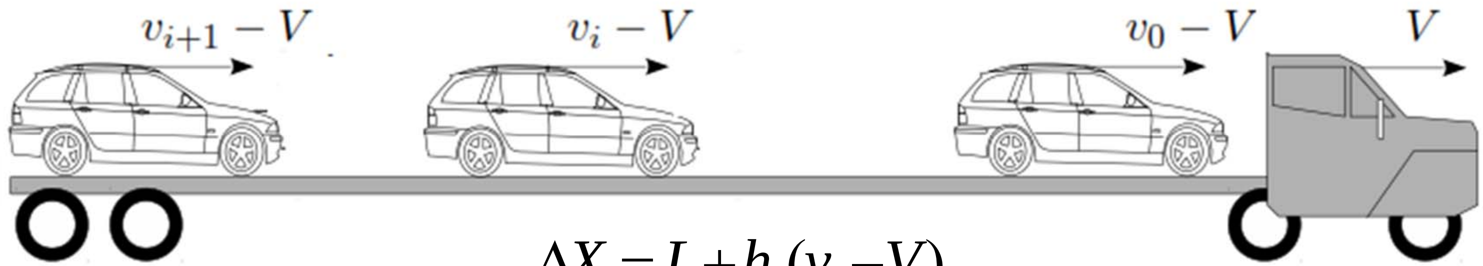
low Communication rate



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

I. Introduction

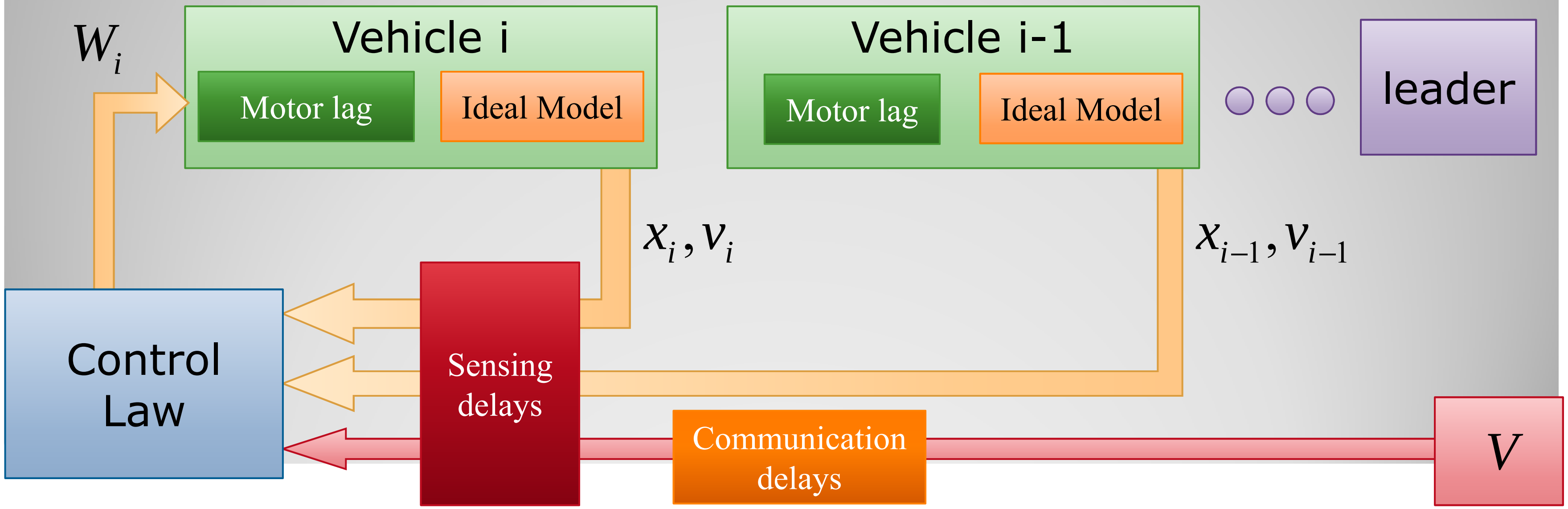
- **The proposed model and law:**
  - We proposed in [3] the flatbed tow truck model,
  - Inter-vehicle distances become proportional to relative velocities instead of absolute velocities.
  - The inter-vehicle distances decrease **largely**,
  - Low communication rate is needed (transmit V),



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

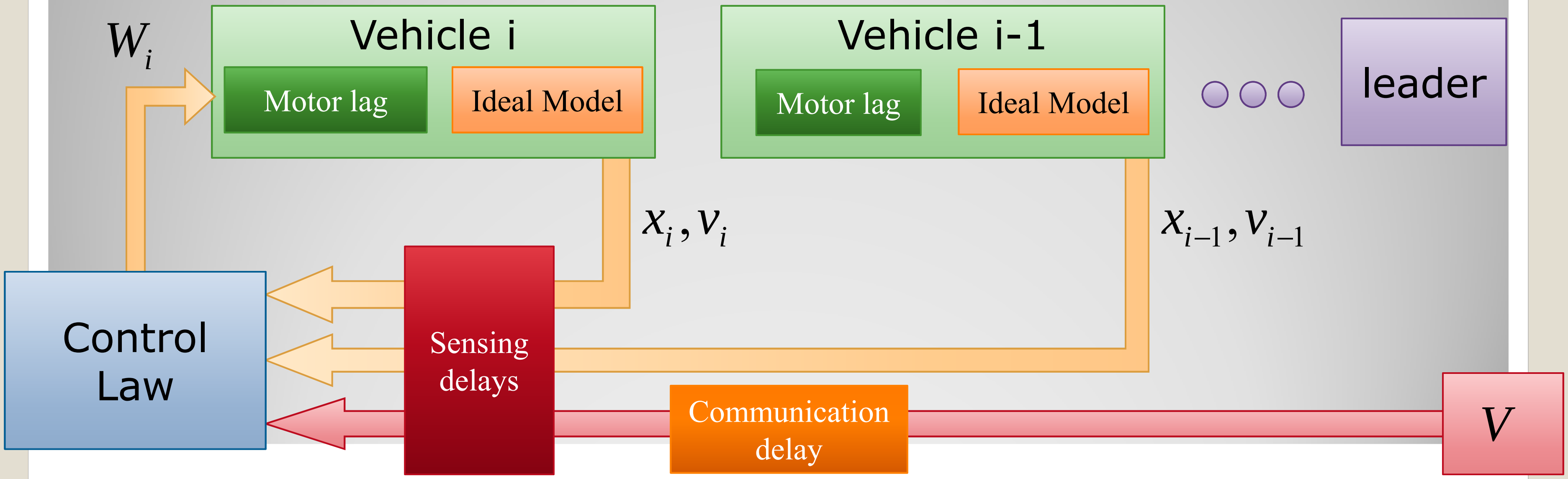
I. Introduction

- **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,



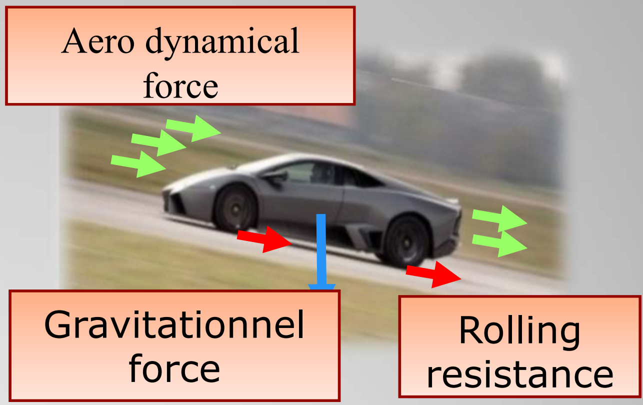
I. Introduction

- **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.

[7] Hedrick, J. K.; Chen, Y. and Mahal, S., **Optimized Vehicle Control/ Communication Interaction in an Automated Highway System**, Institute of Transportation Studies, Research Reports, Working Papers, Institute of Transportation Studies, UC Berkeley.2001

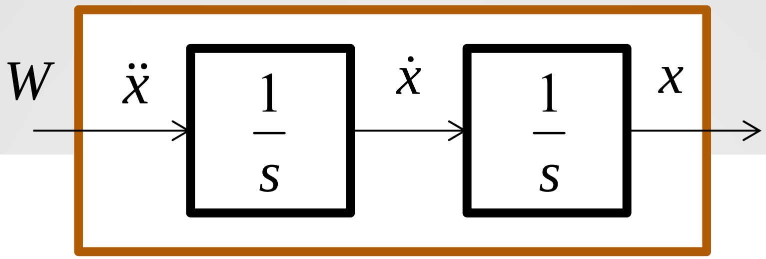
II. Modeling (vehicle)

- Newton's law,



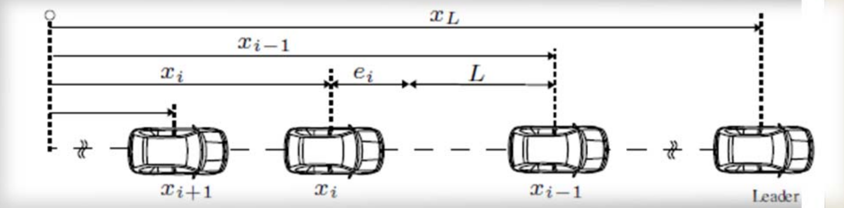
- Applying the exact linearization system,

$$\ddot{x} = W$$

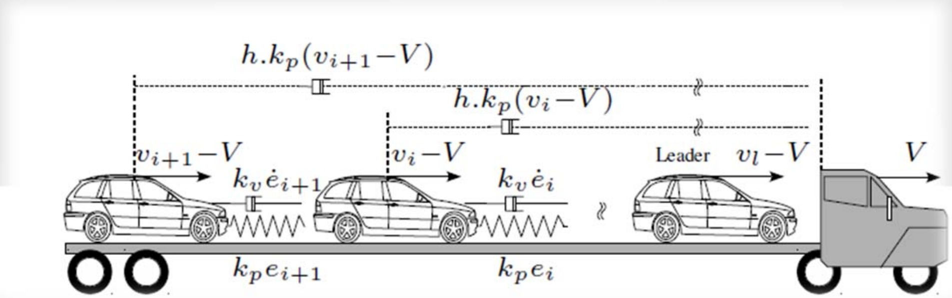


II. Modeling (Platoon)

- **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],

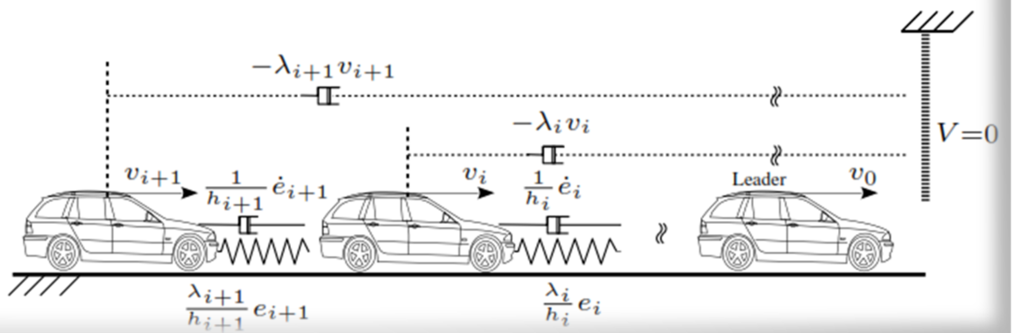
III. Control

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

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

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

λ, h Control parameters

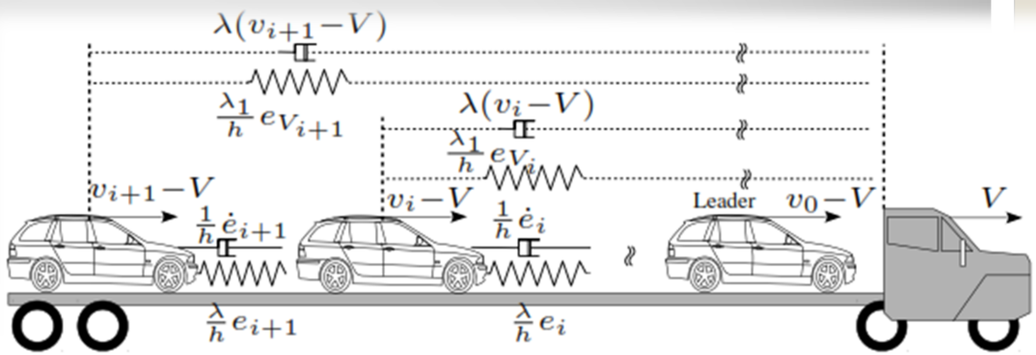


- **Proposed control law (enhanced CTH):**

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

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

$$e_V = X_V - x_i - L_V$$

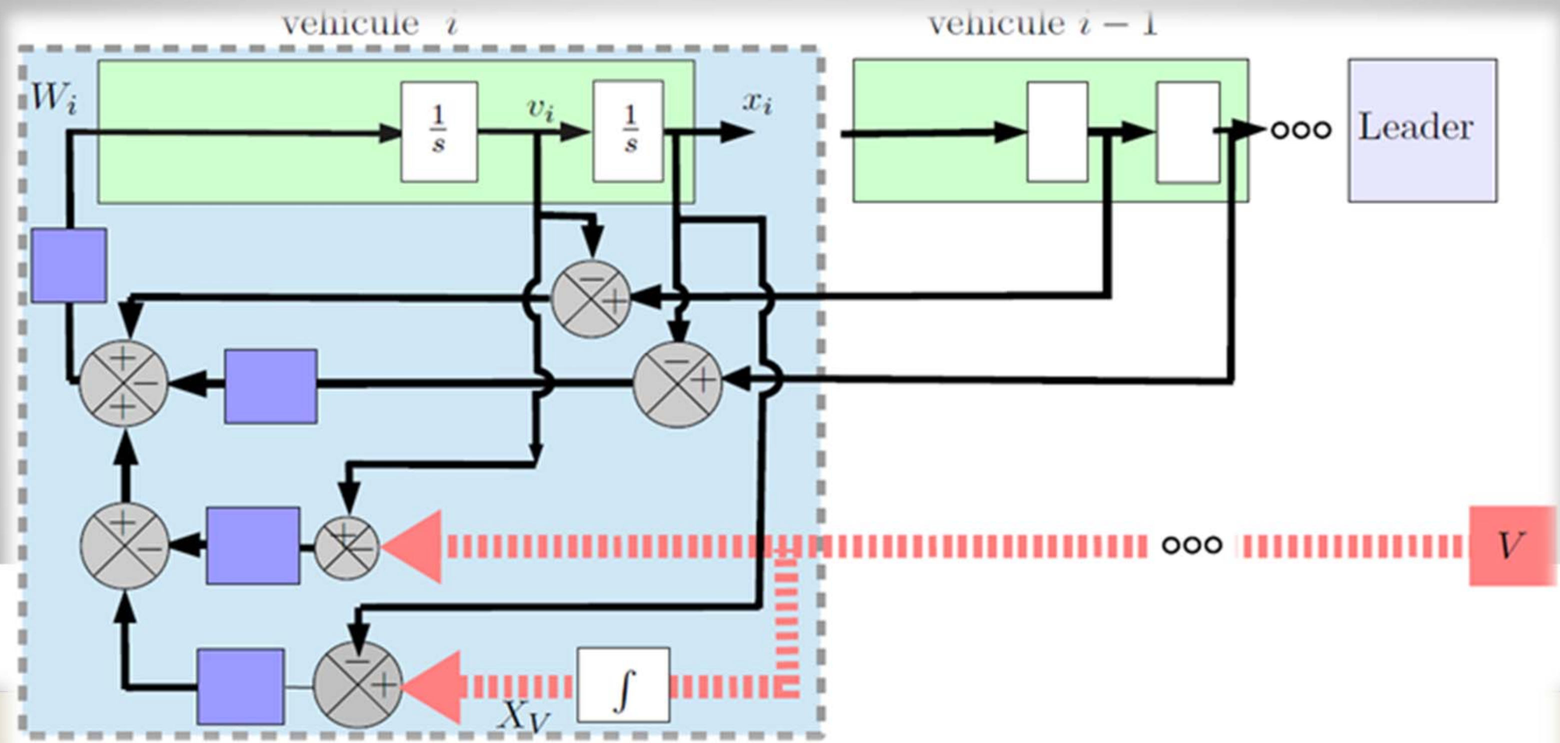


III. Control

- **Control law without delays:**

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

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



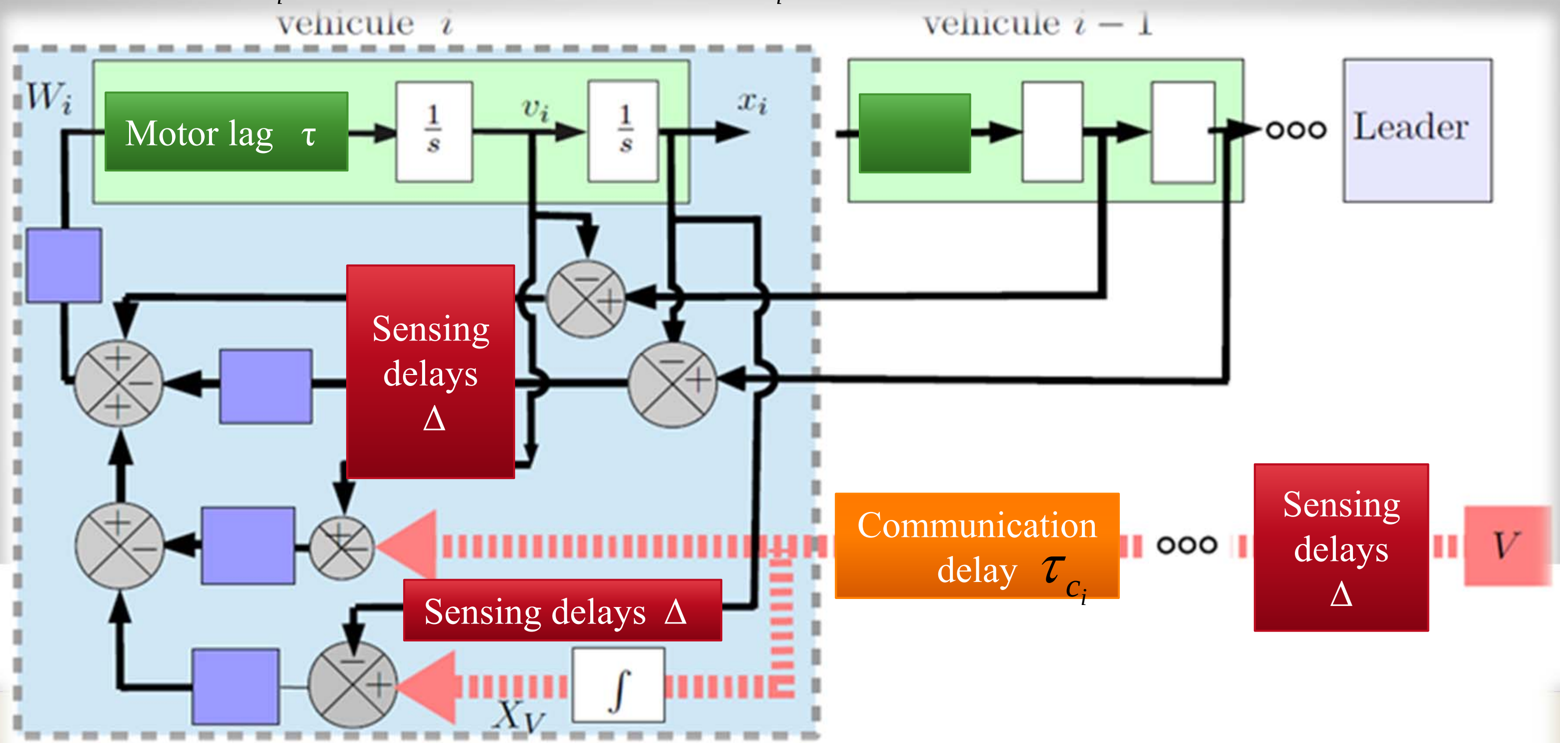
III. Control

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

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

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

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



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

$$\|e_i\|_\infty < \alpha, where \quad \alpha < \infty, \qquad i = 1 \ldots N$$

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:

$$\left\|y(t)\right\|_\infty \le \left\|g(t)\right\|_1 \left\|u(t)\right\|_\infty$$

- So for the first error we get:

$$\left\|e_1(t)\right\|_\infty \le \left\|F_e(\omega)\right\|_\infty \left\|V_0(t)\right\|_\infty + \left\|F_V(\omega)\right\|_\infty \left\|V(t)\right\|_\infty$$

- 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:

$$\|e_i(t)\|_\infty \le L \qquad i = 1,\ldots, N$$

- 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 :

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

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

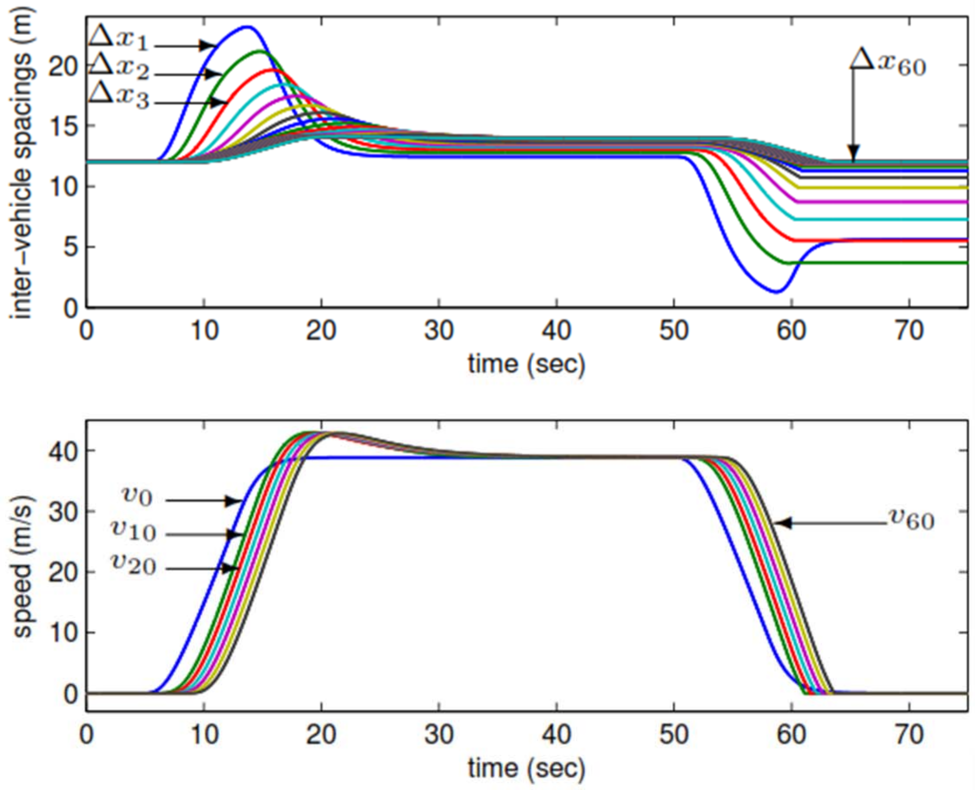
- This give us safety conditions in presence of lags and delays.

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

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- **[5]** A. Ali, G. Garcia, P. Martinet, **Urban Platooning Using a Flatbed Tow Truck Model**, Intelligent Vehicle Symposium, IV 2015, Seoul, South Korea, June 28th - July 1st, 2015.
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