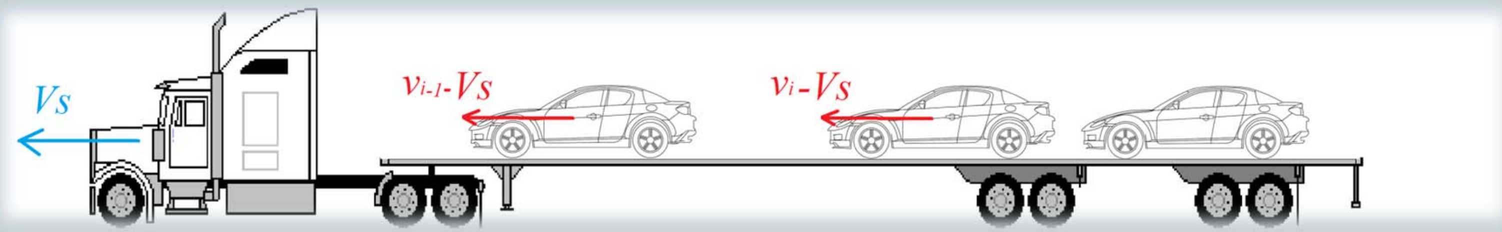
Enhanced flatbed tow truck model for stable and safe platooning in presences of lags, communication and sensing delays

ALAN ALI
GAËTAN GARCIA
PHILIPPE MARTINET



INDEX

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

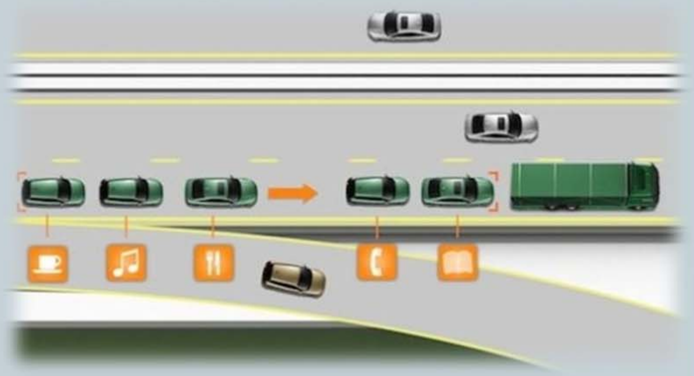


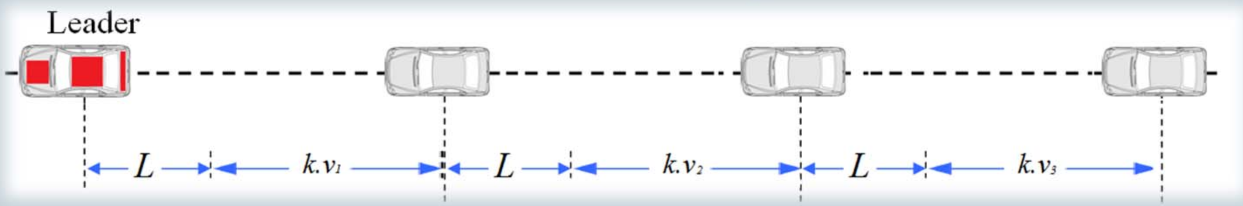
Photo courtesy of DaimlerChrysler

I. INTRODUCTION

- Global Control and Local Control :
  - Data (at least from leader, adjacent vehicles)
  - Sophisticated sensors (needed, Not needed).
  - 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).***

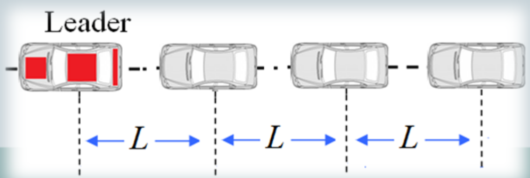
I. INTRODUCTION

- 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

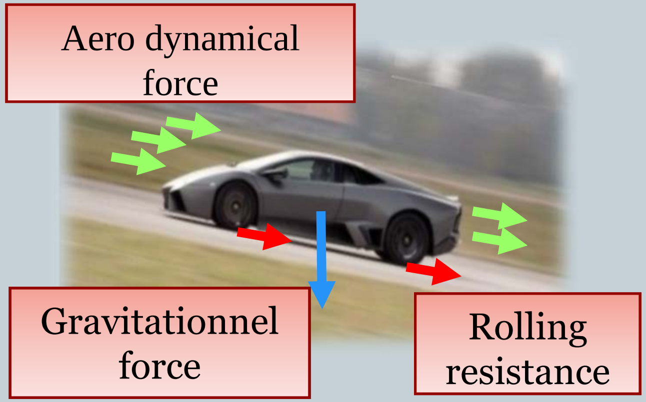
- Delays and lags:
  - Lags and times delays make the net engine torque is not immediately equal to the desired torque computed by the controller.
- Delays types and sources:
  - **Actuator lags:**
    - The lag in the engine response,
    - The lag of the throttle actuator,
    - The lag of the brake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

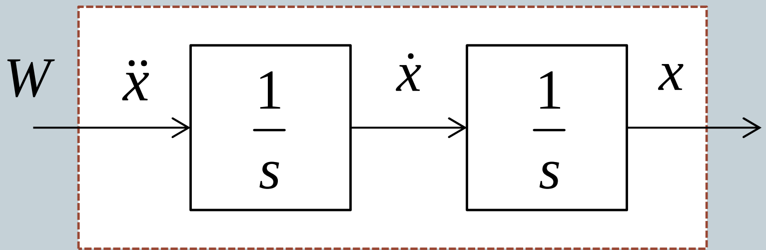
II. MODELING (Longitudinal Model)

- Newton’s law,



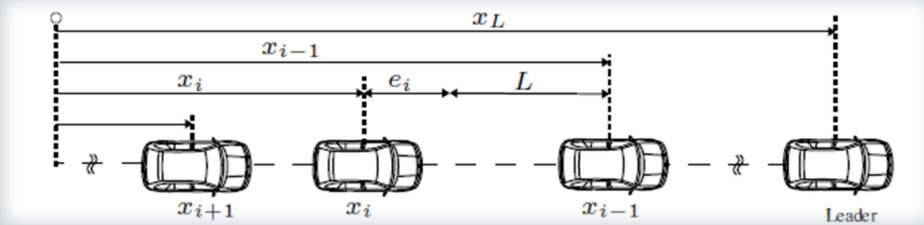
- Applying the exact linearization system,

$$\ddot{x} = W$$



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.

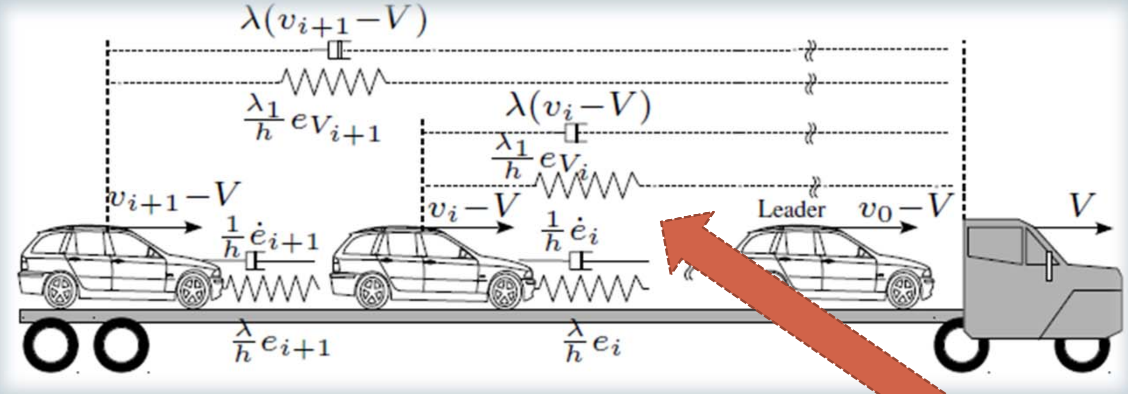


III. CONTROL

- 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:



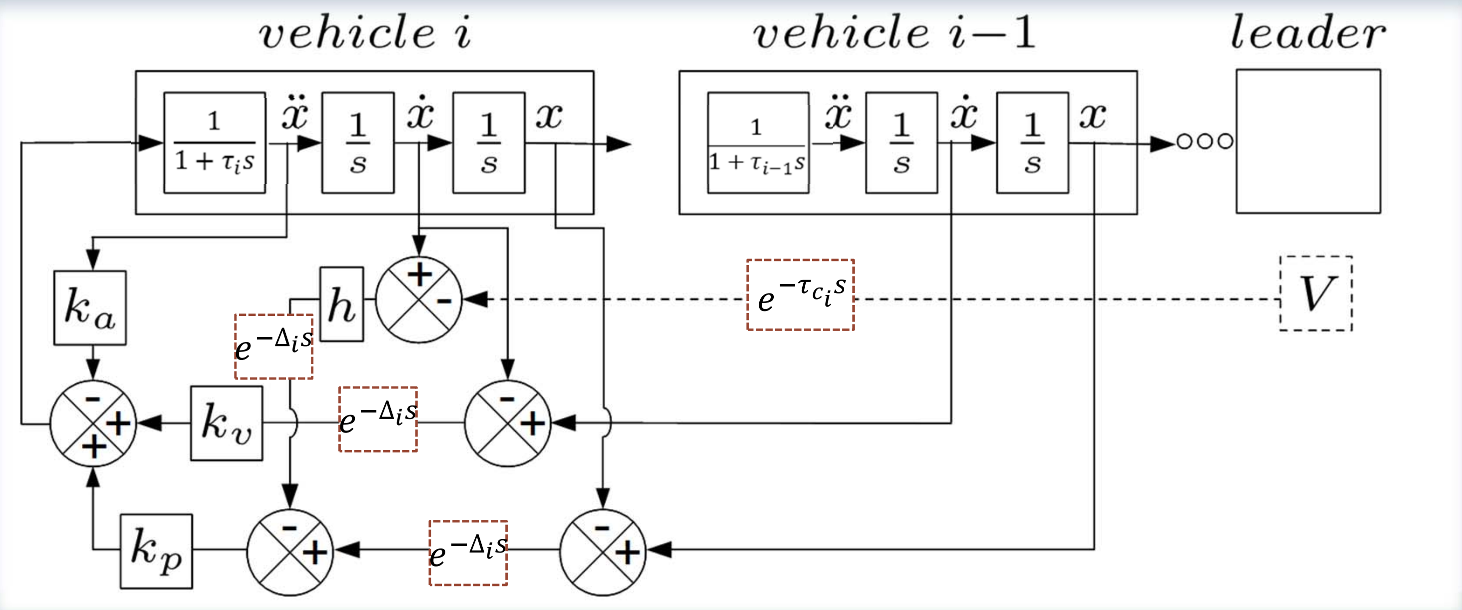
New term

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

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)

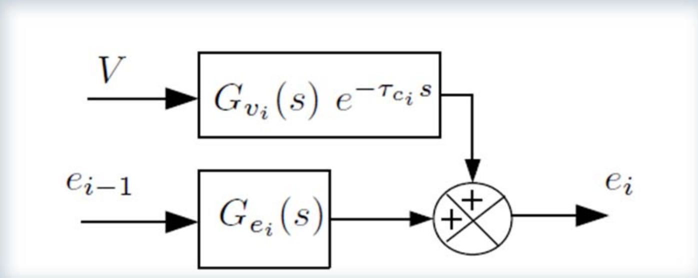
- Modeling of the platoon with delays:
  - Lags τ_i : so $\ddot{x} = W_i \Rightarrow \dddot{x} + \tau_i \ddot{x} = W_i$
  - Sensing delays Δ_i : $e_i(t), \dot{e}_i(t), v(t) \Rightarrow e_i(t-\Delta_i), \dot{e}_i(t-\Delta_i), v(t-\Delta_i)$
  - Communication delays τ_{c_i}: so $V(t), X_V \Rightarrow V\big(t-(\Delta_i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



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:

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

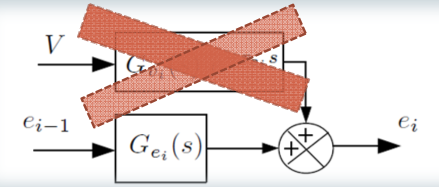
$$\left\| e_i(t) \right\|_\infty \le \alpha_i \;\&\; \left\| \dot{e}_i(t) \right\|_\infty \le \beta_i \;\&\; \left\| \ddot{e}_i(t) \right\|_\infty \le \alpha_i$$

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

IV. STABILITY

- Stability **without** communication delay:

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

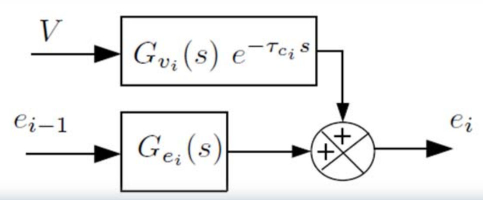


- Sufficient stability condition (error do not increase through platoon) $\|e_i(t)\|_\infty \leq \|e_{i-1}(t)\|_\infty$
- It is sufficient to prove: $\left\|\dfrac{e_i(s)}{e_{i-1}(s)}\right\|_\infty = \|G_i(s)\|_\infty \leq 1$
- We get stability conditions:

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

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 $\|e_i(t)\|_\infty \le \|e_{i-1}(t)\|_\infty$
- We calculate e_i as a function of e_1 and V:

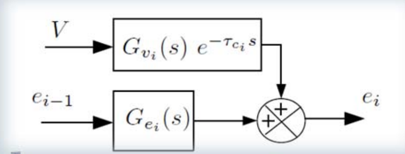
$$e_i(s) = G_e^{i-1}(s)e_1(s) + G_V(s)e^{-\Delta_c s}\frac{1-(G_e e^{-\Delta_c s})^{i-2}}{1-G_e e^{-\Delta_c s}}V(s)$$

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

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

IV. STABILITY

- Stability **with** communication delay:



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

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

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

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

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

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

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

Converge to zero

Bounded if the propagation delay Δ_c is bounded

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

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

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

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

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:

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

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

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

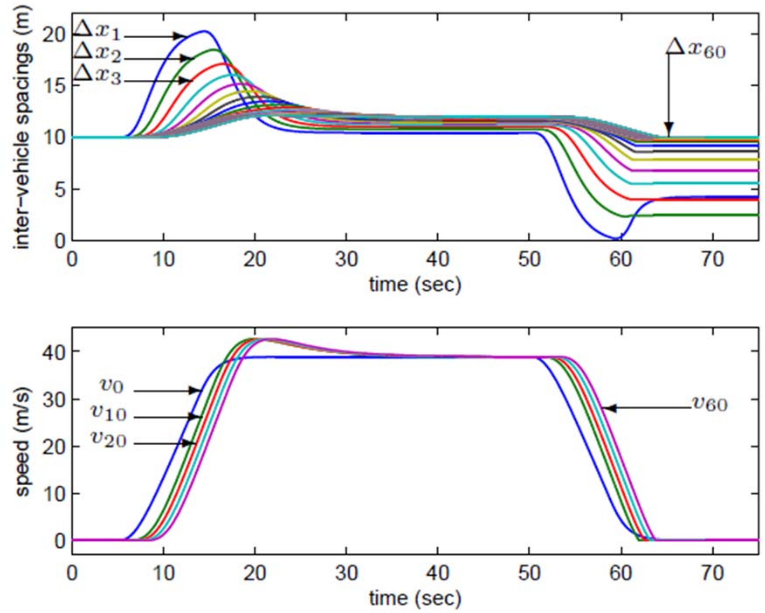
VI.SIMULATION

- 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.

References

[1] - Ali A., Garcia G., and Martinet P., Minimizing the inter-vehicle distances of the time headway policy for platoons control in highways, 10th International Conference on Informatics in Control, Automation and Robotics (ICINCO13), pp. 417-424. SciTePress, Reykjavik, Iceland, July 29-31, 2013.

[2] - Ali A., Garcia G., and Martinet P., Minimizing the inter-vehicle distances of the time headway policy for urban platoon control with decoupled longitudinal and lateral control, 16th international IEEE Conference on Intelligent Transportation Systems - (ITSC), pp. 1805- 1810,The Hague, The Netherlands, 6-9 Oct. 2013.

[3] - Ali A., Garcia G., and Martinet P., The flatbed platoon towing model for safe and dense platooning on highways, IEEE Intelligent Transportation Magazine 2014, to be published.

[4] - Ali A., Garcia G., and Martinet P., Urban platooning using a flatbed tow truck model, will be submitted for publication.

[5] - Ali A., Garcia G., and Martinet P., Safe platooning in the event of communication loss using flatbed tow truck mode, the 13th International Conference on Control, Automation, Robotics and Vision, ICARCV 2014 , to be published.

[6] - Ali A., Garcia G., and Martinet P., String stability of platoons in presences of lags, communication and sensing delays using flatbed tow truck model. Will be submitted for publication.

[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

[8] - Lingyun, Xiao and Feng, Gao, Practical String Stability of Platoon of Adaptive Cruise Control Vehicles, IEEE Transactions on Intelligent Transportation Systems, vol.12, no.4, pp.1184,1194, Dec. 2011

[9] - Ling-yun, Xiao and Feng, Gao, Effect of information delay on string stability of platoon of automated vehicles under typical information frameworks,Journal of Central South University of Technology, Vol.17, no.6, pp 1271-1278, Dec.2010

[12] - Rajamani, R. and Shladover S., An experimental comparative study of autonomous and co-operative vehicle-follower control systems, Transp. Res. Part C, vol. 9, no. 1, pp. 15–31, Feb. 2001.

[15] - Swaroop, D. and Rajagopal, K., A review of constant time headway policy for automatic vehicle following. In Proceedings IEEE Intelligent Transportation Systems, pp. 65-69, 2001.

[16] Teo, R.; Stipanovic, D.M. and Tomlin, C.J., Decentralized Spacing Control of a String of Multiple Vehicles Over Lossy Datalinks,, IEEE Transactions on Control Systems Technology, vol.18, no.2, pp.469,473, March 2010.

[17] Xiangheng, Liu; Goldsmith, A. and Mahal, S.S.; Hedrick, J.K., ”Effects of communication delay on string stability in vehicle platoons,” Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE, vol., no., pp.625,630, 2001

[18] - Yanakiev, D. and Kanellakopoulos, Ioannis, Longitudinal control of automated CHVs with significant actuator delays, IEEE Transactions on Vehicular Technology, vol.50, no.5, pp.1289,1297, Sep 2001