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Queensland University of Technology
Brisbane Australia

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Two Longitudinal Fault Tolerant Control Architectures for Autonomous Vehicle

M.R. Boukhari¹, A. Chaibet², M. Boukhni² and S. Glaser¹

*

Abstract

Two Fault Tolerant schemes for more reliable spacing control of an autonomous vehicle are presented in this paper. The nonlinear longitudinal model of the vehicle is tackled by mean of the Lipschitz representation. Based upon this representation, a state feedback integral controller is designed, as well as, a fault estimation observers. The Lyapunov theory is used ensuring H_∞ criterion and \mathcal{L}_2 -gain norm in the development of the Linear Matrix Inequality constraints. Simulation results are addressed to validate the proposed FTC schemes in different autonomous vehicle scenarios.

Keywords:

Autonomous Driving, Fault-Tolerant Control, Fault Estimation, Linear Matrix Inequality.

1. Introduction

Driverless vehicles have received an important consideration by the scientific community in the two last decades. In fact, the self-driving technologies offer a more effective transportation systems. Thus, the passengers and road users safety is enhanced, the traffic jam is handled more efficiently and the fuel consumption is decreased. However, such an achievements need to improve more safety and reliability in case of fault occurrence. From this perspective, a significant research efforts have been conducted and have advanced the vehicle fault tolerant control [1]. Further, the topic of longitudinal fault tolerant control appears to enhance reliability for application as the collision avoidance [2], the spacing control [3] and the variants of the adaptive cruise control [4, 5].

Indeed, the longitudinal fault tolerant control to track desired velocity of an *Automated Highway System (AHS)* in presence of actuator and parametric faults is presented in [6, 7]. Thus, a nonlinear controller is designed based upon the *Dynamic Surface Control (DSC)* to ensure closed-loop stability by passive manner. Furthermore, a switching logic, using *Fault Detection and Diagnosis (FDD)* and *Fault Managment System (FMS)*, swaps from the passive to the active approach when the stability can not be achieved. In [8], authors presented a passive fault tolerant control, based upon *Sliding Mode Control (SMC)*, to overcome actuator faults affecting the engine and brake systems in *AHS* application. The aim was to use a *Constant Time Headway Policy* [9] to ensure collision avoidance in faulty scenarios, and reducing oscillations caused by slinky effects which may propagate along a string of following vehicles. In [10], a multi-sensor switching strategy for longitudinal spacing control to guarentee fault tolerance was introduced. The sensors considered were the camera, the Lidar sensor and the Radar sensor. Thus, every sensor had its corresponding estimator and feedback controller, in such a way that the loop satisfying the minimum cost function is switched on. In [11], the *Cooperative Adaptive Cruise Control (CACC)* system subjected to communication latency between vehicles

was studied. The CACC is based upon wireless communication in the platooning application, therefore, the authors aim to apprehend the latencies effect in wireless link taking advantage of the robustness of the H_∞ passive controller.

The autonomous vehicle must be able to adjust its speed and to maintain a safe distance with the front vehicle, in such a way that the autonomous vehicle can stop safely in case of emergency. Furthermore, inter-distance policies for longitudinal control are based upon information about the vehicle velocity [12, 13, 14]. Thus, it is clear that inaccuracies or faults in the vehicle speed sensor can corrupt the inter-distance reference leading to injurious control actions. Thereby, a fault tolerant control strategy must be carried out to deal with faults in the speed sensor, and enhance vehicle safety.

The main contribution of this paper is to handle the vehicle speed sensor's additive faults, by adopting a fault tolerant control strategy. The vehicle longitudinal dynamic nonlinearity satisfied the *Lipschitz* condition which permitted us to use the *Descriptor Observer* [15, 16, 17, 18], and the *Proportional and Integral Observer* techniques [19, 20]. These techniques lead us to estimate accurately the sensor additive faults. Furthermore, the advantage of the proposed strategies is the avoidance of control structure reconfiguration.

The present paper is organized as follows: in section 2 vehicle longitudinal and inter-distance models are addressed. In the section 3, the description and the design of the Fault Tolerant Control (FTC) strategy is given. While the validation of these techniques by some simulation examples were devoted on the section 4. Concluding remarks and perspective of this work are presented in the section 5.

Throughout this paper, some specific notations are used for more clearness. Thus, we summarize:

- \mathbb{I}, \mathbb{O} are the identity matrix and the zero matrix of appropriate dimensions respectively;
- The symbol "*" in the matrices represents the transposed element in the symmetric position ;
- Subscript "T" indicates matrix transposition ;
- The notation $\mathcal{H}(\cdot)$ denotes the Hermitian of the matrix, for example $\mathcal{H}(A) = A^T + A$.

2. Vehicle and Inter-Distance Modeling

2.1. Vehicle dynamics

The following assumptions are made to describe the vehicle longitudinal model [21, 22] (see Fig. 1):

- The road is supposed to be plane (no slope and no inclination);
- The vehicle longitudinal behaviour is decoupled from the lateral one, thus the steering is null;
- The yaw, pitch and roll dynamics are not considered;
- The tire radius is supposed to be constant;
- There is no longitudinal slip between the tire and the road.

Considering the above assumptions, the longitudinal vehicle dynamic can be expressed by the following equations:

$$\begin{cases} m\dot{V}_x(t) &= \sum_{i=1}^4 F_{x_i}(t) - F_a(t) \\ \bar{J}_r \dot{\omega}_{r_i}(t) &= T_m(t) - rF_{x_i}(t) - rF_{r_i}(t) - T_{b_i}(t), i = 1, 2 \\ J_r \dot{\omega}_{r_i}(t) &= -rF_{x_i}(t) - rF_{r_i}(t) - T_{b_i}(t), i = 3, 4 \end{cases} \quad (1)$$

Adopting a single track modeling by defining :

$$T_{b_f} = T_{b_1} + T_{b_2}, T_{b_r} = T_{b_3} + T_{b_4}, T_{r_f} = r(F_{r_1} + F_{r_2}), T_{r_r} = r(F_{r_3} + F_{r_4}), F_{x_f} = F_{x_1} + F_{x_2}, F_{x_r} = F_{x_3} + F_{x_4}, \dot{\omega}_{r_f} = \dot{\omega}_{r_1} = \dot{\omega}_{r_2}, \dot{\omega}_{r_r} = \dot{\omega}_{r_3} = \dot{\omega}_{r_4}, \bar{J}_r = \bar{J}_{r_1} + \bar{J}_{r_2}, J_r = J_{r_3} + J_{r_4}$$

TABLE 1: Vehicle Parameters

Notation	Definition	Unit
m	Vehicle mass	Kg
V_x	Vehicle speed	ms^{-1}
F_{x_i}	Tire/road force of the i^{th} wheel	N
F_a	Aerodynamic force	N
\bar{J}_r	Global inertia of the front axle	$Kg.m^2$
\bar{J}_{r_i}	Inertia of i^{th} front wheel	$Kg.m^2$
$\dot{\omega}_{r_i}$	Acceleration of the i^{th} wheel	$rad.s^{-2}$
T_m	The engine torque	Nm
r	The tire radius	m
F_{r_i}	The rolling force of the i^{th} wheel	N
T_{b_i}	The braking torque of the i^{th} wheel	Nm
T_{r_f}/T_{r_r}	The rolling torque of front/rear axle	Nm
J_r	Global inertia of the rear axle	$Kg.m^2$
J_{r_i}	Inertia of i^{th} rear wheel	$Kg.m^2$

We obtain the following equation:

$$\begin{cases} m\dot{V}_x(t) = F_{x_f}(t) + F_{x_r}(t) - F_a(t) \\ \bar{J}_r\dot{\omega}_{r_f}(t) = T_m(t) - rF_{x_f}(t) - T_{r_f}(t) - T_{b_f}(t) \\ J_r\dot{\omega}_{r_r}(t) = -rF_{x_r}(t) - T_{r_r}(t) - T_{b_r}(t) \end{cases} \quad (2)$$

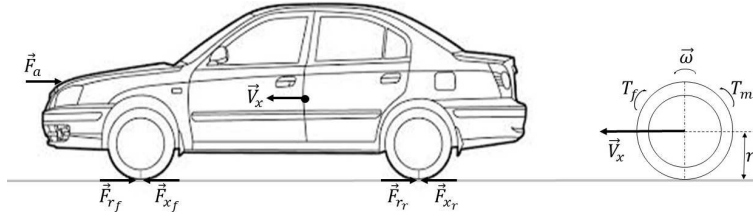


FIGURE 1: Vehicle longitudinal dynamics

Substituting F_{x_f} and F_{x_r} in equation (1) leads to:

$$m\dot{V}_x(t) = \frac{1}{r}[T_m(t) - T_{b_f}(t) - T_{b_r}(t) - T_{r_f}(t) - T_{r_r}(t) - \bar{J}_r\dot{\omega}_{r_f}(t) - J_r\dot{\omega}_{r_r}(t)] - F_a(t) \quad (3)$$

The longitudinal slip ratio hypothesis can be written as:

$$\lambda = \frac{r\omega_r - V_x}{\max(r\omega_r, V_x)} = 0$$

Leads to $r\omega_r = V_x$, then $r\dot{\omega}_r = \dot{V}_x$. Substituting $\dot{\omega}_r$ in (3), we obtain:

$$(m + \frac{\bar{J}_r + J_r}{r^2})\dot{V}_x(t) = \frac{1}{r}[T_m(t) - T_{b_f}(t) - T_{b_r}(t) - T_{r_f}(t) - T_{r_r}(t)] - F_a(t) \quad (4)$$

Denoting $T_b = T_{b_f} + T_{b_r}$, $T_r = T_{r_f} + T_{r_r}$, we get:

$$J_{eq}\dot{V}_x(t) = T_{eq}(t) - aV_x(t) - bV_x^2(t) \quad (5)$$

Where $J_{eq} = (rm + \frac{\bar{J}_r + J_r}{r})$, $T_{eq} = T_m - T_f - T_r$, $F_a = aV_x + bV_x^2$ and a and b are aerodynamic coefficients. T_{eq} is the torque given by the engine and the brake system, its dynamic is subjected to loss and to decay rate, to overcome this problem we assume a first order dynamic, with a time constant τ [23]:

$$\dot{T}_{eq}(t) = \frac{1}{\tau}(-T_{eq}(t) + u(t)) \quad (6)$$

Finally, the vehicle longitudinal dynamic is given in the quadratic form by combining (5) and (6) as follows:

$$\begin{bmatrix} \dot{V}_x(t) \\ \dot{T}_{eq}(t) \end{bmatrix} = \begin{bmatrix} -a & 1 \\ J_{eq} & J_{eq} \\ 0 & \frac{-1}{\tau} \end{bmatrix} \begin{bmatrix} V_x(t) \\ T_{eq}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ \frac{1}{\tau} \end{bmatrix} u(t) + \begin{bmatrix} -b \\ J_{eq} \\ 0 \end{bmatrix} V_x^2 \quad (7)$$

The model (7) can be written in the following Lipschitz nonlinear form:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + Gg(x(t)) \\ y(t) = Cx(t) \end{cases} \quad (8)$$

With:

$$x = \begin{bmatrix} V_x \\ T_{eq} \end{bmatrix}, A = \begin{bmatrix} -a & 1 \\ J_{eq} & J_{eq} \\ 0 & \frac{-1}{\tau} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \\ \frac{1}{\tau} \end{bmatrix}, G = \begin{bmatrix} -b \\ J_{eq} \\ 0 \end{bmatrix}, g(x) = V_x^2, C = \begin{bmatrix} 1 & 0 \end{bmatrix}.$$

Taking into account the exogenous disturbances:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + Gg(x(t)) + Wd(t) \\ y(t) = Cx(t) \end{cases} \quad (9)$$

Where $d(t)$ is the disturbance signal, and W the disturbance distribution matrix of appropriate dimension.

2.2. The inter-distance model

The control objective is to ensure a safe distance between the leader vehicle and the follower (the controlled) one. This distance must be dynamic, in such a way that the follower vehicle adjusts automatically its speed and maintains a safe distance from the leader vehicle. Furthermore, in order to avoid possible vehicle instability due to sensor faults, a FTC control is designed to ensure the insensitivity against the occurring faults. While the fault tolerance is achieved by maintaining an acceptable performance and stability properties without changing the structure of the controller. This control technique requires the estimation of this fault. In [13], authors define the desired inter-distance $dist(V_x)$ policy as follows (see Fig. 2):

$$dist(V_x) = d_{stop} + hV_x \quad (10)$$

Where d_{stop} represents the inter-distance while stopping and h corresponds to the headway time.

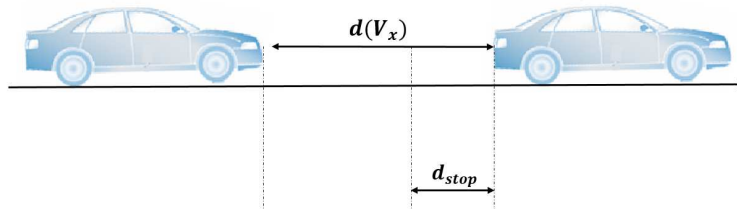


FIGURE 2: The inter-distance model

3. Fault Tolerant Control Strategy

The active Fault Tolerant Control accomodation strategy is based upon the separation principle. This method requires the fault estimation by an observer in order to compensate the faults effect in the closed loop control. This principle is depicted in Fig. 3. Thus, the feedback controller uses the output signal obtained by subtracting the measurment signal and the estimated faults [24].

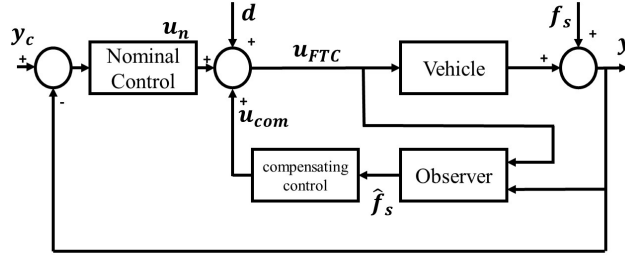


FIGURE 3: The Fault Tolerant Control strategy

To apply this design method, we have to synthesize a state feedback controller and an observer, for that the following assumptions are helpful:

Assumption 1. The nonlinear terms are considered to be a smooth Lipschitz function satisfying the following relation:

$$\|g(x_1) - g(x_2)\| \leq L\|x_1 - x_2\| \quad (11)$$

Where $x_1, x_2 \in R^n$, and L is a positive Lipschitz constant.

Assumption 2. The faults $f_s(t)$ / the disturbances $d(t)$ are assumed to be bounded additive signals affecting the measurments / the system:

$$\begin{cases} \|f_s(t)\| \leq f_{max} \\ \|d(t)\| \leq d_{max} \end{cases} \quad (12)$$

Where f_{max} and d_{max} are constant scalars.

Lemma 1 (Schur Complement). Given the matrices $S \in R^{n \times n}$, $M \in R^{n \times m}$, and $\Gamma \in R^{m \times m}$, thus the following implication holds [25]:

$$S + M\Gamma^{-1}M^T \leq 0, \Gamma < 0 \Leftrightarrow \begin{bmatrix} S & M \\ M^T & \Gamma \end{bmatrix} \leq 0 \quad (13)$$

Lemma 2. Consider matrices A , and B , and scalar δ the following inequality holds [26]:

$$A^T B + B^T A \leq \delta A^T A + \delta^{-1} B^T B \quad (14)$$

Lemma 3. Consider the positive scalar α (called also decay rate) and the Lyapunov function V , the derivative of V can be bounded by α as follows [27]:

$$\dot{V}(t) \leq -2\alpha V \quad (15)$$

3.1. Controller design

For the nonlinear *Lipschitz* model (9), the robust and stabilisable control with integral action has the following form:

$$u_n = - \begin{bmatrix} K & K_I \end{bmatrix} \begin{bmatrix} x \\ x_I \end{bmatrix} \quad (16)$$

Where K, K_I are the proportional and integral gains respectively, x is state vector of system (9) and $x_I = \int y_c(t) - y(t)$ ($y(t)$ is the output signal, $y_c(t)$ is the reference signal). From (9) and (16) an augmented system can be written as follows:

$$\begin{cases} \dot{\bar{X}}(t) &= \bar{A}\bar{X}(t) + \bar{B}u(t) + \bar{G}g(x(t)) + \bar{W}d(t) + \Lambda y_c(t) \\ y(t) &= \bar{C}\bar{X}(t) \end{cases} \quad (17)$$

Where:

$$\bar{X} = \begin{bmatrix} V_x \\ T_{eq} \\ x_I \end{bmatrix}, \bar{A} = \begin{bmatrix} -a & 1 & 0 \\ J_{eq} & J_{eq} & 0 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \bar{B} = \begin{bmatrix} 0 \\ 1 \\ \tau \\ 0 \end{bmatrix}, \bar{G} = \begin{bmatrix} -b \\ J_{eq} \\ 0 \\ 0 \end{bmatrix}, g(x) = V_x^2, \bar{C} = [1 \quad 0 \quad 0], \Lambda = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

and $\bar{W} = \begin{bmatrix} W \\ 0 \end{bmatrix}$. We obtain the following augmented controller:

$$u = -\bar{K}\bar{X} \quad (18)$$

Substituting (18) in (17), one can obtain the following closed-loop model:

$$\dot{\bar{X}} = (\bar{A} - \bar{K}\bar{B})\bar{X} + \bar{G}g(x(t)) + \bar{W}d(t) \quad (19)$$

The control pupose is to design a gain \bar{K} ensuring the vehicle stability, such that the unknown disturbances are minimized by the following H_∞ criterion:

Criterion 1. *The effect of the external disturbances d are minimized using a criterion γ such that [28]:*

$$\int_0^\infty (\bar{X}^T \bar{X} - \gamma^2 d^T d) dt \leq 0 \quad (20)$$

Theorem 1. *The augmented closed-loop Lipschitz system (19) is asymptotically stable by the state feedback controller (18), if there exists a symmetric definite positive matrix P^{-1} , matrix Y , and positive scalars γ, λ, α and δ , such that the following LMI holds:*

$$\begin{bmatrix} \Omega & 0 & \bar{W}P^{-1} & \bar{G}P^{-1} & P^{-1} & P^{-1} \\ * & -\gamma^2 \mathbb{I} & 0 & 0 & 0 & 0 \\ * & * & -\lambda^2 \mathbb{I} & 0 & 0 & 0 \\ * & * & * & -\delta^{-1} \mathbb{I} & 0 & 0 \\ * & * & * & * & -\mathbb{I} & 0 \\ * & * & * & * & * & -\mathbb{I} \end{bmatrix} \leq 0 \quad (21)$$

Where $\Omega = \mathcal{H}(P^{-1}\bar{A}) + \mathcal{H}(\bar{B}Y) + (\delta L^2 + 1 + 2)\mathbb{I} + 2\alpha P^{-1}$

Proof. Consider the following *Lyapunov* function, where $P = P^T > 0$ is a symmetric difinite matrix:

$$V(\bar{X}) = \bar{X}^T P \bar{X} \quad (22)$$

Adopting *Criterion. 1*, and an \mathcal{L}_2 -gain form, minimizing the transfert from the known input u to the state vector \bar{X} , we obtain:

$$\dot{V}(\bar{X}) + 2\bar{X}^T \bar{X} - \gamma^2 d^T(t)d(t) - \lambda^2 u^T(t)u(t) < 0 \quad (23)$$

Using *Lemma. 3*:

$$\dot{V}(\bar{X}) + 2\bar{X}^T \bar{X} - \gamma^2 d^T(t)d(t) - \lambda^2 u^T(t)u(t) + 2\alpha V < 0 \quad (24)$$

Substituting V and its derivative in (24), and using *Assumption. 1* and *Lemma. 2*, implies the following quadratic form:

$$\begin{bmatrix} \bar{X} \\ u \\ d \end{bmatrix}^T \begin{bmatrix} \Omega_1 & \mathbb{O} & P\bar{W} \\ \mathbb{O} & -\lambda^2 \mathbb{I} & \mathbb{O} \\ \bar{W}^T P & \mathbb{O} & -\gamma^2 \mathbb{I} \end{bmatrix} \begin{bmatrix} \bar{X} \\ u \\ d \end{bmatrix} < 0 \quad (25)$$

Where $\Omega_1 = \mathcal{H}((\bar{A} - \bar{B}\bar{K})P) + \delta L^2 \mathbb{I} + \delta^{-1} P\bar{G}\bar{G}^T P + 2\mathbb{I} + 2\alpha P$

Using the *Schur Complement*, and pre-post multiplying by $\text{diag} [P^{-1} \quad \mathbb{I} \quad \mathbb{I} \quad \mathbb{I}]$:

$$\begin{bmatrix} \Omega_2 & \mathbb{O} & \bar{W}P^{-1} & \bar{G}P^{-1} \\ \mathbb{O} & -\lambda^2 \mathbb{I} & \mathbb{O} & \mathbb{O} \\ P^{-1}\bar{W}^T & \mathbb{O} & -\gamma^2 \mathbb{I} & \mathbb{O} \\ P^{-1}\bar{G}^T & \mathbb{O} & \mathbb{O} & -\delta^{-1} \mathbb{I} \end{bmatrix} < 0 \quad (26)$$

Where $\Omega_2 = \mathcal{H}(P^{-1}\bar{A}) + \mathcal{H}(\bar{B}Y) + \delta L^2 P^{-1}P^{-1} + 2P^{-1}P^{-1} + 2\alpha P^{-1}$, and $Y = KP^{-1}$.

Using twice the *Schur Complement*, we obtain the LMI constraint of (21). □

3.2. Proportional and Integral Observer Fault Estimation (PIO)

The system (9) subjected to sensor faults is written as follows:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + Gg(x(t)) + Wd(t) \\ y(t) = Cx(t) + Ff_s(t) \end{cases} \quad (27)$$

Where $f_s(t)$ is the sensor fault signal, and F the fault distribution matrix.

The proportional and Integral observer of the system (27) are given as the form proposed in [29]:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Gg(\hat{x}(t)) + Bu(t) + L_p(y - C\hat{x} - F\hat{f}_s) \\ \dot{\hat{f}}(t) = L_I(y - C\hat{x} - F\hat{f}_s) \end{cases} \quad (28)$$

The aim is to calculate the observer's proportional and integral gains ensuring the asymptotic convergence. For that we consider the states error $e = x - \hat{x}$, the faults error $e_f = f - \hat{f}$, and the free fault case residual signal

$r = N(y - \hat{y}) = NC_0e(t)$ (N is a weighting matrix, and $C_0 = \begin{bmatrix} C & \mathbb{0} \end{bmatrix}$). Implies the error dynamics (29).

$$\begin{cases} \dot{e}(t) &= (A - L_p C)e(t) + G\tilde{g} + Wd(t) - L_p F e_f(t) \\ \dot{e}_f(t) &= \dot{f}_s(t) - L_l C e(t) - L_l F e_f(t) \end{cases} \quad (29)$$

Where $\tilde{g} = g(x(t)) - g(\hat{x}(t))$. Based upon (28) and (29), the augmented system (30) is written.

$$\begin{cases} \dot{Z}_1(t) &= (A^* - L^* C^*)Z_1(t) + G^* \tilde{g} + W_1 d(t) \\ \dot{Z}_2(t) &= A^* Z_2(t) + L^* C^* Z_1(t) + G^* g(\hat{x}(t)) + B^* u(t) + W_2 \dot{f}_s(t) \end{cases} \quad (30)$$

Where $Z_1(t) = \begin{bmatrix} e(t) \\ e_f(t) \end{bmatrix}$, $Z_2(t) = \begin{bmatrix} \hat{x}(t) \\ \hat{f}_s(t) \end{bmatrix}$, $A^* = \begin{bmatrix} A & \mathbb{0} \\ \mathbb{0} & \mathbb{0} \end{bmatrix}$, $L^* = \begin{bmatrix} L_p \\ L_l \end{bmatrix}$, $C^* = \begin{bmatrix} C & F \end{bmatrix}$, $B^* = \begin{bmatrix} B \\ \mathbb{0} \end{bmatrix}$, $G^* = \begin{bmatrix} G \\ \mathbb{0} \end{bmatrix}$, $W_1 = \begin{bmatrix} W \\ \mathbb{0} \end{bmatrix}$, $W_2 = \begin{bmatrix} \mathbb{0} \\ \mathbb{I} \end{bmatrix}$

The signal r must be insensitive to external disturbance signal d , for that we adopte the following criterion:

Criterion 2. The H_∞ criterion ensuring the disturbances rejection is written as follows:

$$\int_0^\infty (r^T r - \gamma^2 d^T d) dt \leq 0 \quad (31)$$

Therefore, the PIO (28) and the dynamics (29) are asymptotically stable via the Criterion. 2, if the LMI condition summarized in the Theorem. 2 holds.

Theorem 2. The nonlinear Lipschitz Proportional and Integral Observer (28) is asymptotically stable, if there exist positive definite matrices P_1 and P_2 , matrices N and U_1 , and positive scalars δ , λ and γ , such that the following LMI is verified:

$$\begin{bmatrix} \Delta_1 & C^* L^* P_2 & \mathbb{0} & \mathbb{0} & P_1 W_1 & P_1 G^* & C_0^T N^T & \mathbb{0} \\ * & \Delta_2 & P_2 B^* & P_2 W_2 & \mathbb{0} & \mathbb{0} & \mathbb{0} & P_2 G^* \\ * & * & -\lambda^2 \mathbb{I} & \mathbb{0} & \mathbb{0} & \mathbb{0} & \mathbb{0} & \mathbb{0} \\ * & * & * & \mathbb{0} & \mathbb{0} & \mathbb{0} & \mathbb{0} & \mathbb{0} \\ * & * & * & * & -\gamma^2 \mathbb{I} & \mathbb{0} & \mathbb{0} & \mathbb{0} \\ * & * & * & * & * & -\delta^{-1} \mathbb{I} & \mathbb{0} & \mathbb{0} \\ * & * & * & * & * & * & -\mathbb{I} & \mathbb{0} \\ * & * & * & * & * & * & * & -\delta^{-1} \mathbb{I} \end{bmatrix} < 0 \quad (32)$$

Where:

$$\begin{aligned} \Delta_1 &= \mathcal{H}(P_1 A^* - U_1 C^*) + \delta L^2 \mathbb{I} + \mathbb{I} \\ \Delta_2 &= \mathcal{H}(P_2 A^*) + \delta L^2 \mathbb{I} + \mathbb{I} \end{aligned}$$

Proof. Consider the following multiple Lyapunov function, where $P_1 = P_1^T > 0$ and $P_2 = P_2^T > 0$ are symmetric definite positive matrices:

$$V = Z_1^T P_1 Z_1 + Z_2^T P_2 Z_2 \quad (33)$$

Deriving (33) and using *Criterion. 2*, and the \mathcal{L}_2 -gain form, we get:

$$\dot{V} + r^T r + Z_2^T Z_2 - \lambda^2 u^T u - \gamma^2 d^T d \leq 0 \quad (34)$$

Using *Assumption. 1*, and *Lemma. 2*, one have the quadratic form of (35).

$$\begin{bmatrix} Z_1 \\ Z_2 \\ u \\ \dot{f}_s \\ d \end{bmatrix}^T \begin{bmatrix} \Delta'_1 & C^{*T} L^{*T} P_2 & \mathbb{O} & \mathbb{O} & P_1 W_1 \\ * & \Delta'_2 & P_2 B^* & P_2 W_2 & \mathbb{O} \\ * & * & -\lambda^2 \mathbb{I} & \mathbb{O} & \mathbb{O} \\ * & * & * & \mathbb{O} & \mathbb{O} \\ * & * & * & * & -\gamma^2 \mathbb{I} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ u \\ \dot{f}_s \\ d \end{bmatrix} \leq 0 \quad (35)$$

Where:

$$\begin{aligned} \Delta'_1 &= \mathcal{H}(P_1(A^* - L^* C^*)) + \delta L^2 \mathbb{I} + \delta^{-1} P_1 G^* G^{*T} P_1 + C_0^T N^T N C_0 + \mathbb{I} \\ \Delta'_2 &= \mathcal{H}(P_2 A^*) + \delta L^2 \mathbb{I} + \delta^{-1} P_2 G^* G^{*T} P_2 + \mathbb{I} \end{aligned} \quad (36)$$

Using three times the *Schur Complement*, and denoting $U_1 = P_1 L^*$, yields the LMI constraint of (32). \square

3.3. Descriptor Observer Fault Estimation (DO)

From (9) an augmented system can be written as follows:

$$\begin{cases} E \dot{\bar{x}}(t) = \bar{A} \bar{x} + \bar{G} g(x(t)) + \bar{B} u(t) + \bar{W} d(t) + \bar{F} \bar{f}_s \\ y = \bar{C} \bar{x} = C_0 \bar{x} + \bar{f}_s \end{cases} \quad (37)$$

$\bar{x} = \begin{bmatrix} x \\ f_s \end{bmatrix}$, $E = \begin{bmatrix} \mathbb{I} & \mathbb{O} \\ \mathbb{O} & \mathbb{O} \end{bmatrix}$, $\bar{A} = \begin{bmatrix} A & \mathbb{O} \\ \mathbb{O} & \mathbb{O} \end{bmatrix}$, $\bar{G} = \begin{bmatrix} G \\ \mathbb{O} \end{bmatrix}$, $\bar{B} = \begin{bmatrix} B \\ \mathbb{O} \end{bmatrix}$, $\bar{W} = \begin{bmatrix} W \\ \mathbb{O} \end{bmatrix}$, $\bar{F} = \begin{bmatrix} \mathbb{O} \\ \mathbb{I} \end{bmatrix}$, $\bar{f}_s = F f_s$, $\bar{C} = \begin{bmatrix} C & F \end{bmatrix}$, and $C_0 = \begin{bmatrix} C & \mathbb{O} \end{bmatrix}$.

The nonlinear *Lipschitz Descriptor Observer* leading to estimate the system's states and the sensor faults is written as follows :

$$\begin{cases} \bar{E} \dot{z} = S z + \bar{G} g(\hat{x}(t)) + \bar{B} u(t) \\ \hat{x} = z + L y \end{cases} \quad (38)$$

$S = \begin{bmatrix} A & \mathbb{O} \\ -C & -\mathbb{I} \end{bmatrix}$, $L = \begin{bmatrix} \mathbb{O} \\ \mathbb{I} \end{bmatrix}$, $\bar{E} = \begin{bmatrix} \mathbb{I} + \Theta C & \Theta \\ RC & R \end{bmatrix}$, and Θ , and R are chosen in such a way that \bar{E} is nonsingular [30].

Let us define the error $e = \bar{x} - \hat{x}$, and the free faults residual $r = M(y - \hat{y}) = M C_0 e$ (where M is a weighting matrix), yields the following error dynamic:

$$\dot{e}(t) = \tilde{S} e(t) + \tilde{G} \tilde{g} + \tilde{W} d(t) \quad (39)$$

$$\text{With } \tilde{g} = g(x(t)) - g(\hat{x}(t)), \tilde{S} = \bar{E}^{-1}S = \begin{bmatrix} A + \Theta R^{-1}C & \Theta R^{-1} \\ -CA - (R^{-1} + C\Theta R^{-1})C & -R^{-1} - C\Theta R^{-1} \end{bmatrix}, \tilde{G} = \bar{E}^{-1}\bar{G} = \begin{bmatrix} G \\ -CG \end{bmatrix},$$

$$\tilde{W} = \bar{E}^{-1}\bar{W} = \begin{bmatrix} W \\ -CW \end{bmatrix}$$

From (9) and (39), we have the following augmented system:

$$\begin{bmatrix} \dot{e}(t) \\ \dot{\hat{x}}(t) \end{bmatrix} = \begin{bmatrix} \tilde{S} & \mathbb{O} \\ \mathbb{O} & A \end{bmatrix} \begin{bmatrix} e(t) \\ x(t) \end{bmatrix} + \begin{bmatrix} \tilde{G} & \mathbb{O} \\ \mathbb{O} & G \end{bmatrix} \begin{bmatrix} \tilde{g} \\ g(x(t)) \end{bmatrix} + \begin{bmatrix} \mathbb{O} \\ B \end{bmatrix} u(t) + \begin{bmatrix} \tilde{W} \\ W \end{bmatrix} d(t) \quad (40)$$

The stability of the system (40) is ensured, using the *Criterion. 2*, and the \mathcal{L}_2 -gain form, if the LMI condition summarized in the *Theorem. 3* holds.

Theorem 3. *The nonlinear augmented Lipschitz Descriptor System is asymptotically stable, if there exist positive definite matrices P_{11} , P_{12} , and P_2 , matrices N_1 , N_2 , and M , positive scalars λ , γ , and δ , such that the following LMI condition is satisfied:*

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} & \mathbb{O} & \mathbb{O} & P_{11}W & P_{11}G & C^T M^T & \mathbb{O} \\ * & \Phi_{21} & \mathbb{O} & \mathbb{O} & -P_{12}CW & -P_{12}CG & \mathbb{O} & \mathbb{O} \\ * & * & \Phi_{31} & P_2B & P_2W & \mathbb{O} & \mathbb{O} & P_2G \\ * & * & * & -\lambda^2\mathbb{I} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & -\gamma^2\mathbb{I} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & * & -\delta^{-1}\mathbb{I} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & * & * & -\mathbb{I} & \mathbb{O} \\ * & * & * & * & * & * & * & -\delta^{-1}\mathbb{I} \end{bmatrix} < 0 \quad (41)$$

With:

$$\begin{aligned} \Phi_{11} &= \mathcal{H}(P_{11}A) + \mathcal{H}(N_1C) + \delta L^2\mathbb{I} + \mathbb{I} \\ \Phi_{12} &= N_1 - A^T C^T P_{12}^T - C^T N_2^T \\ \Phi_{21} &= -\mathcal{H}(N_2) + \mathbb{I} \\ \Phi_{31} &= \mathcal{H}(P_2A) + \delta L^2\mathbb{I} + \mathbb{I} \end{aligned} \quad (42)$$

The estimated fault is written as follows:

$$\hat{f}_s = -(F^T F)^{-1} F^T \hat{f}_s \quad (43)$$

Where:

$$\hat{f}_s = \begin{bmatrix} \mathbb{O} & \mathbb{I} \end{bmatrix} \hat{x} \quad (44)$$

Proof. Consider the following *Lyapunov* function, where $P_1 = P_1^T > 0$ and $P_2 = P_2^T > 0$ are symmetric definite positive matrices, of appropriate dimensions:

$$V(e(t), x(t)) = \begin{bmatrix} e \\ x \end{bmatrix}^T \begin{bmatrix} P_1 & \mathbb{O} \\ \mathbb{O} & P_2 \end{bmatrix} \begin{bmatrix} e \\ x \end{bmatrix} \quad (45)$$

Deriviting (45) and using *Criterion. 2*, and the \mathcal{L}_2 -gain form, we get equation (46).

$$\dot{V}(e(t), x(t)) + r^T r + x^T x - \gamma^2 d^T d - \lambda^2 u^T u \quad (46)$$

Using *Assumption. 1*, and *Lemma. 2*, yields the equation (47).

$$\begin{bmatrix} e \\ x \\ u \\ d \end{bmatrix}^T \begin{bmatrix} \Gamma_1 & \mathbb{O} & \mathbb{O} & P_1 \tilde{W} \\ * & \Gamma_2 & B^T P_2 & P_2 W \\ * & * & -\lambda^2 \mathbb{I} & \mathbb{O} \\ * & * & * & -\gamma^2 \mathbb{I} \end{bmatrix} \begin{bmatrix} e \\ x \\ u \\ d \end{bmatrix} < 0 \quad (47)$$

With:

$$\begin{aligned} \Gamma_1 &= \mathcal{H}(P_1 \tilde{S}) + \delta L^2 \mathbb{I} + \delta^{-1} P_1 \tilde{G} \tilde{G}^T P_1 + C_0^T M^T M C_0 + \mathbb{I} \\ \Gamma_2 &= \mathcal{H}(P_2 A) + \delta L^2 \mathbb{I} + \delta^{-1} P_2 G G^T P_2 + \mathbb{I} \end{aligned}$$

Using the *Schur Complement* twice, yields equation (48).

$$\begin{bmatrix} \Gamma'_1 & \mathbb{O} & \mathbb{O} & P_1 \tilde{W} & P_1 \tilde{G} & C_0^T M^T \\ * & \Gamma_2 & B^T P_2 & P_2 W & \mathbb{O} & \mathbb{O} \\ * & * & -\lambda^2 \mathbb{I} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ * & * & * & -\gamma^2 \mathbb{I} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & -\delta^{-1} \mathbb{I} & \mathbb{O} \\ * & * & * & * & * & -\mathbb{I} \end{bmatrix} < 0 \quad (48)$$

And $\Gamma'_1 = \mathcal{H}(P_1 \tilde{S}) + \delta L^2 \mathbb{I} + \mathbb{I}$.

Substituting \tilde{S} , \tilde{G} , and \tilde{W} by their values, and taking $P_1 = \begin{bmatrix} P_{11} & \mathbb{O} \\ \mathbb{O} & P_{12} \end{bmatrix}$, $N_1 = P_{11} \Theta R^{-1}$, and $N_2 = P_{12} (R^{-1} + C \Theta R^{-1})$,
Implies equation (49).

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} & \mathbb{O} & \mathbb{O} & P_{11} W & P_{11} G & C^T M^T \\ * & \Phi_{21} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ * & * & \Gamma_2 & B^T P_2 & P_2 W & \mathbb{O} & \mathbb{O} \\ * & * & * & -\lambda^2 \mathbb{I} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & -\gamma^2 \mathbb{I} & \mathbb{O} & \mathbb{O} \\ * & * & * & * & * & -\delta^{-1} \mathbb{I} & \mathbb{O} \\ * & * & * & * & * & * & -\mathbb{I} \end{bmatrix} < 0 \quad (49)$$

Using the *Schur Complement* yields the LMI constraint of (41). □

4. Simulation results

In this section, simulations have been performed in order to show the effectiveness of the proposed FTC structures of vehicle driving scenarios. The LMI conditions developed above for such the controller and the observers were resolved using the *penlab solver* which run under the *Yalmip* environment [31]. Thus, the LMIs developed are solved, and give the following solutions:

- For the Controller :

$$K = 10^4 \begin{bmatrix} -1.7399 \\ 1.5747 \end{bmatrix}, K_I = -0.3727 * 10^4; \text{ with } P^{-1} = 10^3 * \begin{bmatrix} 1.0574 & 0.9293 & 0.1645 \\ 0.9293 & 1.2497 & 0.3350 \\ 0.1654 & 0.3350 & 0.9532 \end{bmatrix}, \lambda = 0.0055, \gamma = 0.0033, \\ \alpha = 0.0002$$

- For the *Proportional and integral observer*:

$$L_p = \begin{bmatrix} -2.8605 \\ 5.6037 \end{bmatrix}, L_I = \begin{bmatrix} 22.7274 \\ -0.5799 \end{bmatrix}, \text{ and } P_1 = \begin{bmatrix} 38.7735 & 1.7723 & 10.6408 & 0.4298 \\ 1.7723 & 15.4934 & 1.5384 & 1.9737 \\ 10.6408 & 1.5384 & 13.0298 & 1.1650 \\ 0.4298 & 1.9737 & 1.1650 & 23.1656 \end{bmatrix}, \lambda = 0.3662, \gamma = 0.023,$$

$$P_2 = \begin{bmatrix} 6.5789 & -4.6569 & -0.0800 & 0.0266 \\ -4.6569 & 18.8529 & -0.1052 & -0.1294 \\ -0.0800 & -0.1052 & 0.0318 & 0.4454 \\ 0.0266 & -0.1294 & 0.4454 & 17.8108 \end{bmatrix}$$

- For the *Descriptor observer*:

$$\bar{E} = \begin{bmatrix} 0.2968 & 0 & -0.7032 & -0.2672 \\ -1.1999 & 1.0000 & -1.1999 & 0.0240 \\ 2.3570 & 0 & 2.3570 & -0.8756 \\ -0.3328 & 0 & -0.3328 & 0.8898 \end{bmatrix}, \text{ and } R = \begin{bmatrix} 0.4158 & 2.8839 \\ 0.7453 & -1.2691 \end{bmatrix}, \Theta = \begin{bmatrix} -0.7174 & 0.2841 \\ -0.8577 & -1.9111 \end{bmatrix},$$

$$P_{11} = \begin{bmatrix} 3.4789 & 1.2250 \\ 1.2250 & 3.5056 \end{bmatrix}, P_{12} = \begin{bmatrix} 4.2255 & 2.0013 \\ 2.0013 & 3.4122 \end{bmatrix}, P_2 = \begin{bmatrix} 4.5470 & 2.2896 \\ 2.2896 & 3.7373 \end{bmatrix}, \gamma = 0.0619, \text{ and } \lambda = 0.3833.$$

TABLE 2: Vehicle parameters

parameter	value	Unit
J_{eq}	480	$Kg.m$
a	17.45	Kgm^{-1}
b	0.019	Kgs^{-1}
τ	0.05	s
h	1	s

The additive sensor fault used in this simulation has the following form:

$$f_s(t) = (0.01t - 2) + \sin(2\pi t) \quad (50)$$

The *Stop and Go* maneuver is considered in this work. This scenario is summarized as follows:

The vehicle leader moves with an initial speed of $20ms^{-1}$, the following vehicle evolves with initial velocity of $25ms^{-1}$. Since the desired longitudinal distance is around $40m$. In order to control this distance, the follower must decrease. While decelerating to reach the speed of $20ms^{-1}$. At $t = 15s$, the additive sensor fault is occurred (in the form of (50)), we can notice that the following vehicle maneuver without FTC could lead to loss of vehicle control and stability, while its behavior with FTC is kept stable, and the desired spacing is preserved. At $t = 24s$, the vehicle follower carries out a deceleration until to stop, and thereafter at $t = 40s$ the vehicle accelerates to reach a velocity of $20ms^{-1}$. At $t = 65s$, the leader decelerates until to stop.

The comparison of speed profiles are given on Fig. 6. Furthermore, the vehicle follower maneuver is carried out with success with respect to the passengers comfort where the reasonable boundaries in acceleration range are from $-0.3ms^{-2}$ to $0.3ms^{-2}$ as depicted on Fig. 7. Moreover, the *DO* and *PIO* observers are designed to estimate the longitudinal vehicle speed the Figs. 4, 5 and the additive sensor fault Fig. 8 show the good estimation. Fig. 9 shows the additive sensor fault influence in the inter-distance, while the applied torque is depicted in Fig. 10. The Fig. 11 shows output control signal, displaying the performance of the proposed FTC control in comparison with vehicle without FTC.

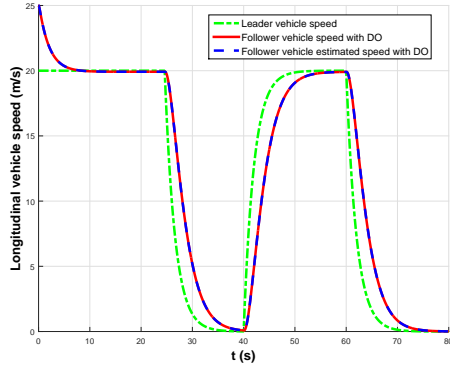


FIGURE 4: Vehicle estimated speed with DO observer

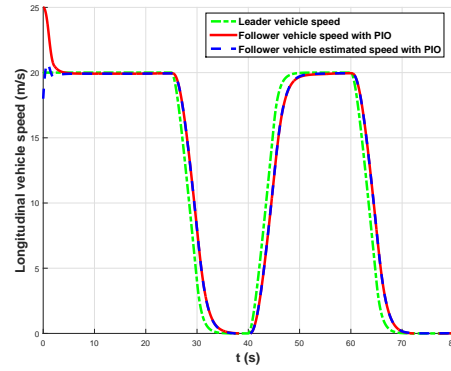


FIGURE 5: Vehicle estimated speed with PI observer

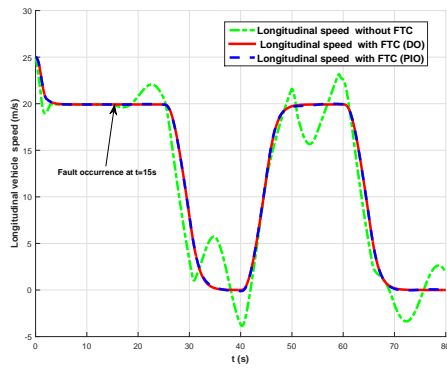


FIGURE 6: Speed profiles

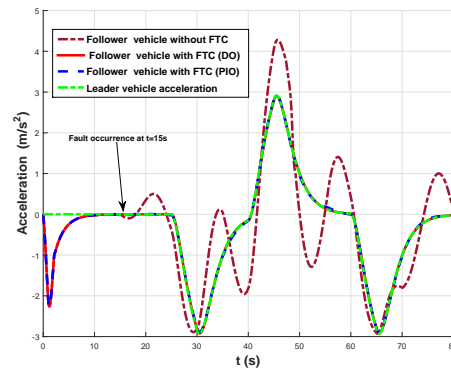


FIGURE 7: Accelerations comparison

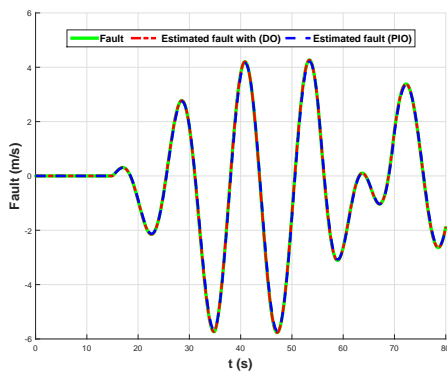


FIGURE 8: The additive sensor fault

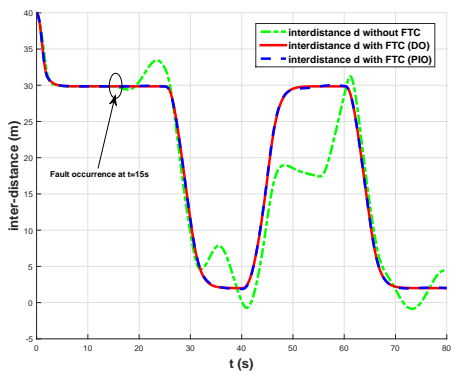


FIGURE 9: The vehicle inter-distance

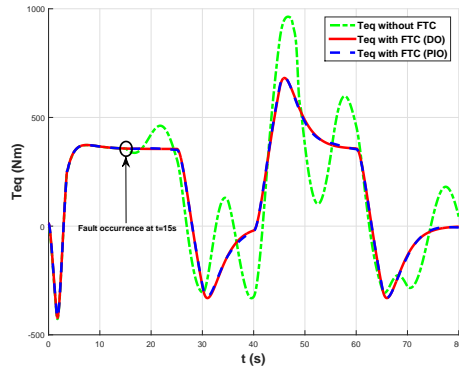


FIGURE 10: The applied torque comparison

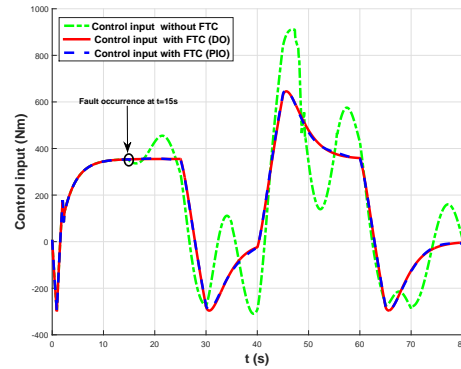


FIGURE 11: The output control signal comparison

The following remarks can be summarized:

- The estimated vehicle speeds converge quickly toward the real one;
- The estimated fault converges to the real one;
- The performances obtained are good as well in dynamics as in statics;
- The observation errors are steered to zero in finite time.

The fruitful simulation results presented above, prove the effectiveness of the *FTC* strategy in managing the occurrence of additive sensor faults. In addition, the additive fault is well estimated, and the fault accommodation maintains the vehicle stability in faulty cases.

5. Conclusion

In this paper, the reliability of the spacing control for an autonomous vehicle was performed. The emphasis is to give on sensor fault tolerant controller scheme. Furthermore, the design of the proposed fault-tolerant scheme is based upon a state feedback integral controller ensuring robustness against disturbances, and a fault estimation observer. Indeed, two observers techniques were designed, the *Descriptor Observer* and the *Proportional and Integral Observer*. The controller and observers gains were done by solving the LMI constraints that ensure the H_∞ criterion and the \mathcal{L}_2 -gain form. To illustrate the ability of the proposed *FTC* architectures, computation simulations have been carried out to give well performance of the fault detection and control law design in some scenarios of automated driving where the performances and the vehicle stability are kept with respect of the passenger comfort. In future work, experimental tests should therefore be implemented on prototype vehicle.

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