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Design of monitoring concepts for motion control of autonomous heavy vehicles

Master's thesis in Automotive Engineering

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Department of Mechanics and Maritime Sciences,
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Abstract

Currently, the major trend in the automotive industry is to develop autonomous vehicles. All OEMs are focusing on increasing automation in their vehicles. Increase in automation leads to the design of complex safety-critical control algorithm. As the motion control controls the driving dynamics of the whole autonomous vehicle, any faults by the motion control may lead to hazardous events. So, in order to ensure safety, the outputs of the motion control should be monitored to check if the vehicle is following the intended path. The main objective of the thesis is to design an algorithm to detect faults affecting the motion on complete vehicle level. The first part of this report contains findings of a literature review on functional safety, monitoring concepts and fault detection methods. After completing the literature review on different fault detection method, it is found that monitor based on forward dynamics is best suited for this application. The monitor is modelled based on the single-track model of vehicle. It is discovered that the acceleration is more sensitive to torque faults than longitudinal velocity for monitoring longitudinal dynamics. For lateral dynamics, the yaw rate is chosen to monitor as it is found to be sensitive enough to detect faults. The designed monitor is improved by making it adaptive monitor in order to ensure safety and robustness. Suitable threshold values are composed based on the safety goals provided in order to classify as a fault. The designed monitor is validated in the simulation environment by injecting appropriate faults. From the results it is found, the monitor based on forward dynamics detects the faults in longitudinal acceleration and yaw rate quickly, thus ensures safety.

Keywords: Functional Safety, Automated Driving, Vehicle Dynamics, control system, monitoring concepts.

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Ajay Kumar and Swasthik Bhandary, Gothenburg, October 2019

Contents

List of symbols

A	m^2	The frontal cross-sectional area of the tractor
α_f	rad	Front wheel slip angle
α_r	rad	Rear wheel slip angle
a_x	m/s^2	Longitudinal acceleration of the tractor
a_y	m/s^2	Lateral acceleration of the tractor
c_d	-	Air resistance coefficient
C_f	N/rad	Front wheel cornering stiffness
C_r	N/rad	Rear wheel cornering stiffness
δ_f	rad	Front road wheel angle
F_{air}	N	Air drag resistance force
F_{fx}	N	Longitudinal force acting on front axis along the vehicle coordinate
F_{fxw}	N	Longitudinal force acting on front axis along the wheel coordinate
F_{fy}	N	Lateral force acting on front axis along the vehicle coordinate
F_{fyw}	N	Lateral force acting on front axis along the wheel coordinate
F_{grad}	N	Resistance force due to road gradient
f_r	-	Rolling resistance coefficient
F_{roll}	N	Rolling resistance force
F_{rx}	N	Longitudinal force acting on rear axis along the vehicle coordinate
F_{ry}	N	Lateral force acting on rear axis along the vehicle coordinate
g	m/s^2	Gravity constant
I_z	kg*m^2	Moment of inertia along z-axis at center of gravity
L	m	Wheel base of the tractor
l_f	m	Distance from the center of gravity to front axle
l_r	m	Distance from the center of gravity to rear axle
m	kg	Mass of the tractor
R	m	Effective radius of the wheel
ρ	kg/m^3	Density of air
θ	rad	Road pitch angle
T_b	Nm	Braking torque generated at the wheel
T_{bfl}	Nm	Front left wheel brake torque
T_{bfr}	Nm	Front right wheel brake torque
T_{brl}	Nm	Rear left wheel brake torque
T_{brr}	Nm	Rear right wheel brake torque
T_p	Nm	Power-train torque generated at the wheel
v_{fxv}	m/s	Longitudinal velocity acting on front axis along the vehicle coordinate
v_{fxw}	m/s	Longitudinal velocity acting on front axis along the wheel coordinate

v_{fyv}	m/s	Lateral velocity acting on front axis along the vehicle coordinate
v_{fyw}	m/s	Lateral velocity acting on front axis along the wheel coordinate
v_{rx}	m/s	Longitudinal velocity acting on rear axis along the vehicle coordinate
v_{ry}	m/s	Lateral velocity acting on rear axis along the vehicle coordinate
v_x	m/s	Longitudinal velocity acting on the vehicle
v_y	m/s	Lateral velocity acting on the vehicle
w_z	rad/s	Yaw rate acting on the vehicle

List of Figures

List of Tables

1

Introduction

1.1 Background

Autonomous vehicles are the future of transportation as they offer solutions to current transportation problems by decreasing congestion and increasing efficiency, safety and productivity. Currently, a major trend in the automotive industry is developing autonomous driving technology for different category of vehicles in the market. All OEMs are focusing on increasing automation in their vehicles. The long term goal is to achieve full automation [1]. The Volvo Group has a vision of developing future autonomous trucks to take advantage of its market potential.
Main elements in the context of manual or automated driving are perception, decision and control. Perception refers to the process of interpreting the surrounding traffic and the environment. Next step is decision making which usually refers to path planning, which includes avoiding the obstacles and optimising the path. The final step is control of the vehicle which refers to the execution of planned actions required to follow the intended path [2].
Based on the level of driving automation, SAE J3016 classifies vehicle automation in 6 levels, from level '0' to level '5'. Level '0' being no automation and level '5' referring to full automation, illustrated in table 1.1. From level 0 to level 2, a human driver monitors the driving environment and carries out the fallback performance of a dynamic driving task. For level 3, the monitoring of the driving environment is carried out by the automated driving system and fallback measures is carried out by driver in case of system failure. For level 4 and level 5, there is complete automation of driving functionality where the driver's tasks (execution, monitor, a fallback if required) are executed entirely by the Automated driving system [3]. The main difference between level 4 and level 5 driving automation is that level 5 system is capable of carrying out all driving functionality for all the driving modes when compared with level 4 system. This thesis work is mainly focusing on level 4 and level 5 of driving automation.

Summary of Levels of Driving Automation for On-Road Vehicles

This table summarizes SAE International's levels of *driving* automation for on-road vehicles. Information Report J3016 provides full definitions for these levels and for the italicized terms used therein. The levels are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or *automated driving system*, as appropriate.

The table also shows how SAE's levels definitively correspond to those developed by the Germany Federal Highway Research Institute (BASt) and approximately correspond to those described by the US National Highway Traffic Safety Administration (NHTSA) in its "Preliminary Statement of Policy Concerning Automated Vehicles" of May 30, 2013.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
Human driver **monitors the driving environment**								
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system **("system") monitors the driving environment**								
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

Table 1.1: SAE levels in driving automation [3].

1.2 Vehicle motion functionality architecture

Vehicle architecture here refers to how the vehicle model is organized by different layer based on its function. The reference vehicle motion architecture for automated driving consists of different layers as shown in figure 4.1. On the left is the vehicle environment. The topmost part is the traffic situation management (TSM), the second layer is the vehicle motion management (VMM), and the bottom-most part is called a motion support device (MSD). Layer on the right is the human-machine interface (HMI).

Vehicle environment incorporates vehicle sensors mounted on the vehicle to sense the surrounding environment. It also includes other functions such as vehicle to vehicle (V2V) communication, vehicle to infrastructure (V2I) communication and map information [4].

TSM provides information regarding the traffic surrounding the vehicle, surrounding road/lanes and the information regarding the surrounding road users. The vehicle is provided with effective traffic information in advance to follow the specific route to avoid accidents. The main function of TSM is to expound the surrounding traffic and environment by taking inputs from various sensors. Based on the information available, TSM carries out path planning by considering VMM capabilities and outputs velocity profile request and curvature profile request [4].

VMM comprises the vehicle motion control with energy management and stability control by considering capabilities of MSD. The VMM layer gets the input request from TSM and then determines appropriate brake torque distribution, power-train torque and steering angle required at the wheel to fulfil the request. VMM also

estimates current states of the vehicle such as yaw rate, velocities, slip angle etc. Additionally, VMM also provides vehicle minimum and maximum level capability to TSM [4].
MSD comprises of the actuators such as brakes, power-train and steering required to generate requested motion of the vehicle. This layer also includes the sensors which incorporate the present condition and capability of each device and provides this information to VMM [4].
HMI comprises of the buttons or sensors such as steering wheel angle sensor, brake and accelerator pedal sensor, which helps in the motion functionality of the vehicle [4]. The autonomous vehicle is a self-driving vehicle which can sense the environment and can move safely with no human intervention. This domain is absent in fully autonomous trucks.

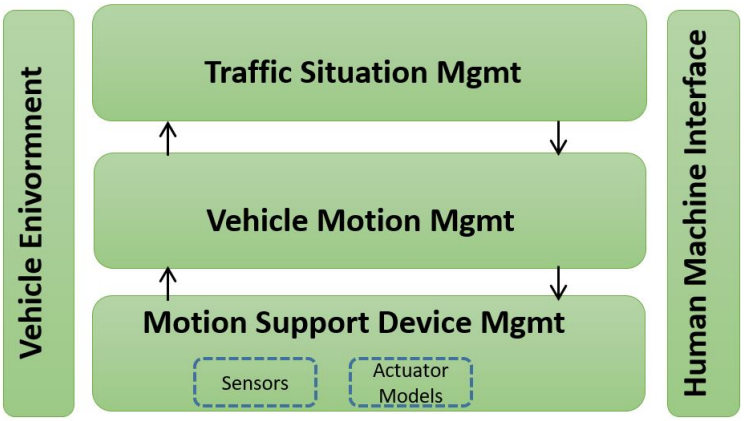

Figure 1.1: Reference architecture of vehicle motion functionality [4].

1.3 Why to monitor VMM?

Motion-control controls the driving dynamics of the whole autonomous vehicle. It controls all the available actuators (Brake, steering, power-train etc) to safely and efficiently follow the intended path. Some other functions of VMM are slip control of wheels, stability control, torque vectoring, steering by braking and vehicle combination stability control [4].
Increased automation leads to the design of complex safety-critical control algorithm, this in turn, increases the number of potential sources of faults. These faults can be safety-critical and may lead to hazardous events [5]. Since safety is paramount, it should always be guaranteed. Therefore, there is a need for a monitor to continuously monitor the outputs of the VMM and evaluate, if it leads to correct vehicle behavior. Therefore, a monitoring system has to be developed to check for any malfunction behavior in the motion control system. This is the main motivation for this thesis.

1.4 Objective

The thesis aims to design monitoring concepts to continuously monitor the input/output of the vehicle motion management layer to detect the faults that affect the motion of autonomous truck on complete vehicle level. The monitoring model should be able to predict the dynamic behaviour of the truck. The designed algorithms should be simple, accurate but also be able to detect the faults quickly and effectively to guarantee a safe state of the truck when there is malfunction behavior. The designed monitoring algorithm should not be allowed to adapt to genuine faults, which may lead to the safety-critical situation, thus ensuring the safety of the truck's motion. But also the monitoring system should ensure robustness by adapting quickly and efficiently to false-positive error and avoid unnecessary shutdowns of the motion control system. Hence there will be a trade-off between the sensitivity and detection time of the monitoring concepts. If delayed, it may lead to a hazardous situation. To make the monitoring independent of the data coming from the actuators themselves, the state variables can also be obtained from other sources of information like e.g. the chassis IMUs.

1.5 Goals

Following are the goals of the this thesis work.

- To decide what monitoring concepts have to be designed for the detection of fault in the motion control system of the fully autonomous truck.
- The designed monitor should be checked for suitability for Functional safety and should be adapted to it.
- The decided monitoring concepts are designed for the tractor.
- The monitoring concepts have to be evaluated by implementing in the simulation with the vehicle model.
- The evaluation involves test design, injection of the fault, coming up with safety threshold, also recording and post-processing of measured data.
- To define advantages and disadvantages of the designed monitoring concept for use in fully autonomous trucks.

1.6 Scope of the thesis

Below mentioned are the scope of this thesis work.

- The monitoring concept for the autonomous truck is highly challenging and development of a high fidelity model is of high cost and time-consuming, so it is required to limit our monitoring system to be simple but, it should be well efficient to monitor the lateral and longitudinal dynamic behaviour of the autonomous truck.
- The thesis is focused on tractor only.
- Limits in the Operational Driving Domain (ODD), i.e. the vehicle is assumed to be driven in a good highway road in a good weather condition and, the

coefficient of friction between the tire and road is considered to be high (dry asphalt).
- In this thesis, hazard analysis and risk assessment (HARA) process or breaking down into safety goals will not be carried, safety goals will be provided by Volvo.

1.7 Research questions

Before starting the literature study, following research question are defined.
- What are the various types of monitoring concepts currently being used in different industries and how to adapt them to this thesis?
- Which are the state variables needed to be considered while designing the monitoring system?
- How to integrate the designed safety monitoring concepts in the context of functional safety?
- What kind of faults can be caught by the monitoring system and in within what detection time?
- How to validate the monitoring concept in a simulation environment?

2
Literature review

The literature review is carried out regarding functional safety, ISO 26262, monitoring concepts and fault detection methods. In this section, the findings of the literature review are presented. First literature review on concepts related to functional safety is presented. In the next section, various monitoring methods currently being used in the industry are listed. For the purpose of understanding the concepts, few general definitions are introduced below.

2.1 General definitions

- **Fault**
  According to ISO 26262 fault is defined as abnormal condition that can cause an element or an item to fail [6]. Fault can be defined in another way as an unpermissive deviation in the output of the system from the acceptable condition [7].
- **Fault detection**
  Determination of the malfunction behaviour that occurs in a system with a specific detection time [7].
- **Failure**
  Termination of an intended behaviour of an element or an item due to a fault manifestation [6]. Another definition is permanent interruption of a system's ability to perform a required function under specified operating conditions [7].
- **Error**
  Discrepancy between a computed, observed or measured value or condition, and the true, specified or theoretically correct value or condition [6].
- **Fault injection**
  Method to evaluate the effect of a fault within an element by inserting faults, errors, or failures in order to observe the reaction by observation points [6].
- **Hazard**
  Potential source of harm caused by malfunctioning behaviour of the item [6].
- **Hazardous event**
  Combination of a hazard and an operational situation [6].
- **Safe state**
  Operating mode, in case of a failure, of an item without an unreasonable level of risk [6].
- **Safety**
  Absence of unreasonable risk [6].

- **Malfunction**
  For a given operating conditions, the system will fail or disable to perform the desired task. [6].

- **Monitoring**
  A device or an algorithm used to determine a condition of the system through continuously observing the system and checking its real-time behaviour [7].

2.2 Functional safety and ISO 26262

Safety is the absence of unreasonable risk of physical injury or to the people's health directly or indirectly. The main function of the monitor is to detect fault effecting the motion on the whole vehicle level which may lead to the hazardous event which causes injury or damage to people and the system. To detect the malfunction, the problem should be viewed from a functional safety point of view, i.e. safety depends on whether the system functions correctly or not in response to its inputs [8]. Functional Safety is the part of the overall safety of a system or piece of equipment that depends on the system operating correctly in response to its inputs. Definition of functional safety according to ISO 26262, is "absence of unreasonable risk due to hazards caused by malfunctioning behaviour of E/E systems" [8]. With the advancement in automotive technology, it increases the complexity of E/E systems, mechatronic systems and software. This, in turn, results in increased risks from failures of the system. High levels of automation require functional safety throughout the product life cycle [9]. To achieve functional safety in automotive systems, ISO 26262 standard has been formed [6].

Before the existence of ISO 26262, the automotive industry was using the international electrotechnical commission (IEC) IEC 61508 as a functional safety standard for the development of any safety-related applications [10]. Then in the year 2011, the international organisation for standardization(ISO) developed ISO 26262 as a functional safety standard for the development of electrical and electronic systems in the Automotive industry [6][11]. ISO 26262 is a risk-based approach to manage potential harm originating during operation of the system to achieve functional safety [11]. Functional safety is achieved through the use of safety measures which in turn used to come up with safety mechanisms. So ISO 26262 provides a framework to get freedom from unacceptable risks due to malfunction of the system, thus improving the safety and quality of electrical and electronic system [11]. ISO 26262 is represented in the form of a V-model, indicating different stages involved during the development of the product and is shown in figure 2.1.

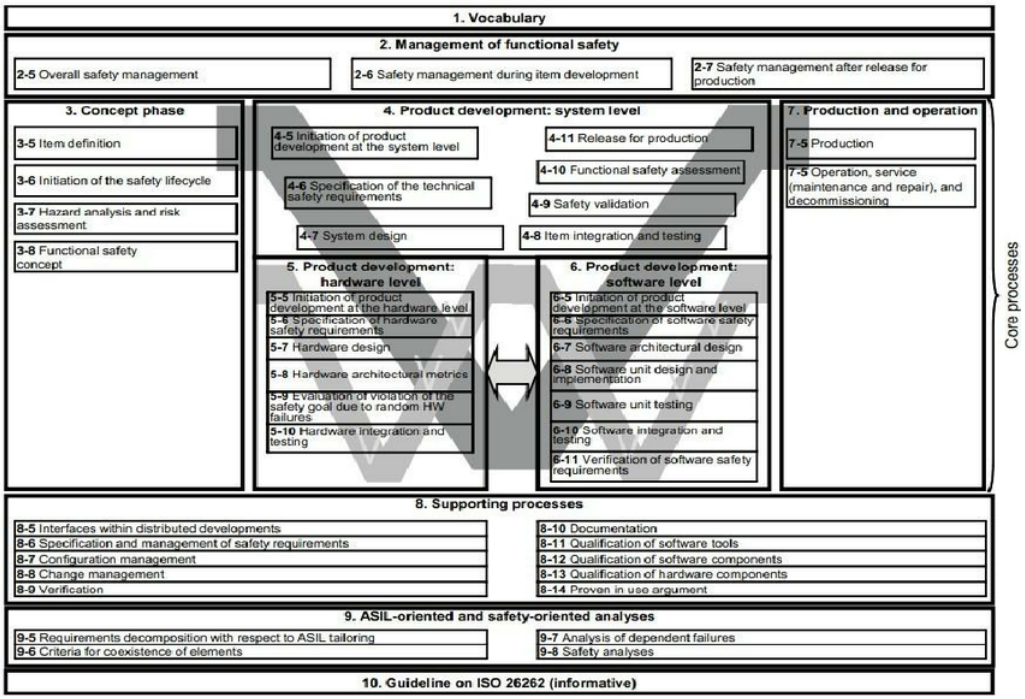

Figure 2.1: Overview of ISO 26262 [11].

The first phase in ISO 26262 is the concept phase. It involves writing the item definition. The item here refers to a system to which ISO 26262 is applied that implements a function. Next step is carrying out hazard analysis and risk assessment (HARA) for the considered item. The process of HARA is illustrated in figure 2.2 below.

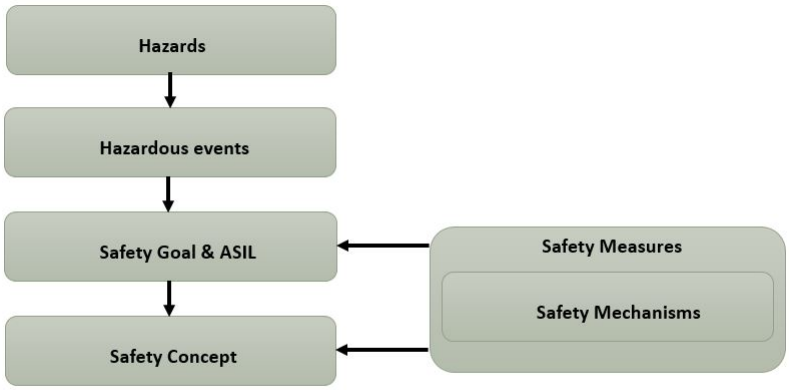

Figure 2.2: Safety mechanism in ISO 26262 framework [12].

The main purpose of HARA is to identify and classify hazards originating from the considered system that needs a reduction in risk. For classifying the hazardous event, an automotive safety integrity level (ASIL) is assigned to it based on following parameters [2].

- Severity (S0-S3): Severity is the measurement of how severe is the harm of the considered hazardous event, the range given is from S0 to S3, S0 refers that there will be no injuries and S3 means there will be life threatening injuries [2].
- Controllability (C0-C3): Controllability refers to the measurement of how probable driver or the system at risk to gain control such that they are able to avoid from hazardous event taking place. The range of controllability is from C0 to C3, where C0 means the controllable in general where as C3 means that less than 90 percent of the driver or system barely able to avoid harm [2].
- Exposure(E0- E4): Exposure refers to the probability of the hazardous event taking place. It ranges from E0 to E4 where E0 refers that hazardous event occurs less than once a year and E4 refers to hazardous event occurs in almost every driving scenarios [2].

Based on the above-mentioned parameters an ASIL rating (QM, A, B, C, D) is assigned to each Hazardous event as shown in the table 2.1. QM being risk associated with the hazardous event is nil and does not require any safety measures. ASIL-D refers to the risk associated with the hazardous event is highest and requires a stringent level of safety measures.

Severity	Exposure	Controllability		
Extent of harm to individual(s) that can occur in hazardous situation	Probability of exposure regarding operational conditions	Ability to avoid a specified harm through timely reactions		
		C1 - Simple	C2 - Normal	C3 - Difficult
S1 - Light and moderate injuries	E1 – Very low	QM	QM	QM
	E2 - Low	QM	QM	QM
	E3 – Medium	QM	QM	A
	E4 - High	QM	A	B
S2 – Severe and life-threatening injuries (survival probable)	E1 – Very low	QM	QM	QM
	E2 - Low	QM	QM	A
	E3 – Medium	QM	A	B
	E4 - High	A	B	C
S3 – Life-threatening injuries (survival uncertain), fatal injuries	E1 – Very low	QM	QM	A
	E2 - Low	QM	A	B
	E3 – Medium	A	B	C
	E4 - High	B	C	D

Table 2.1: ASIL levels according to ISO 26262 [2].

To avoid these malfunctions from taking place, a set of safety goals are formulated. To achieve these safety goals, functional safety concepts are composed. In order to avoid or mitigate the failures, it requires coming up with 'safety measures'. 'Safety measures' may have 'safety mechanisms' to detect faults or control failures in order to maintain a 'safe state' [13].

2.3 Functional safety in context of motion

With the increase in driving automation, the number of hazards due to malfunction also increases. In automated driving, many of the hazards are of the ASIL-D level.

This means that these hazards can occur commonly (exposure is high), and difficult to control when it occurs (controllability is low) and may be life-threatening (severity is high) [2]. Some of the examples of such events and their corresponding ASIL rating are given in table 2.2. Therefore, to ensure functional safety, the system should be free from unacceptable risk caused by faults. It is succeeded by avoiding the hazardous event from taking place, which in calls for safety concepts and measures. In this case, it is achieved by monitoring the VMM.

Function	Class	Worst case environment / failure	Evaluation	ASIL
Propulsion	Omission	Railway crossing / No acceleration	S3, E1, C2	QM
	Omission	Highway / No acceleration	S1, E4, C1	QM
	Commission	City (traffic light) / Sudden acceleration	S3, E4, C3	D
	Stuck at value	City / Constant acceleration	S3, E4, C3	D
Braking	Omission	City / Loss of brake	S3, E4, C3	D
	Commission	Highway / Sudden brake	S3, E4, C3	D
	Stuck at value	Highway / Constant retardation	S2, E4, C2	B
Steering	Omission	Highway / Loss of steering	S3, E4, C3	D
	Commission	Highway / Sudden steering angle	S3, E4, C3	D
	Stuck at value	Highway / Constant steering angle	S3, E4, C3	D

Table 2.2: Examples of hazards and their corresponding ASIL classification [2].

2.4 Monitoring concepts

The main purpose of the monitor in this application is to check for any malfunction behaviour in the VMM, which may lead to a hazardous event. Software-based monitoring and control have been introduced in the form of electronic throttle control (ETC). Software monitoring was introduced through an alliance of German automotive manufacturers called 'EGAS' group. Standard safety architecture used for monitoring purposes in Automotive applications as per EGAS consists of three levels [14], as shown in the figure 2.3.

- Level 1: First level is functional level which consists of software to carryout certain functions.
- Level 2: This is the monitoring level which consists software for detecting faults in the level 1 software.
- Level 3: This is the controller monitoring level which contains software to check whether the controller on which level 1 and level 2 software resides is working fine or not.

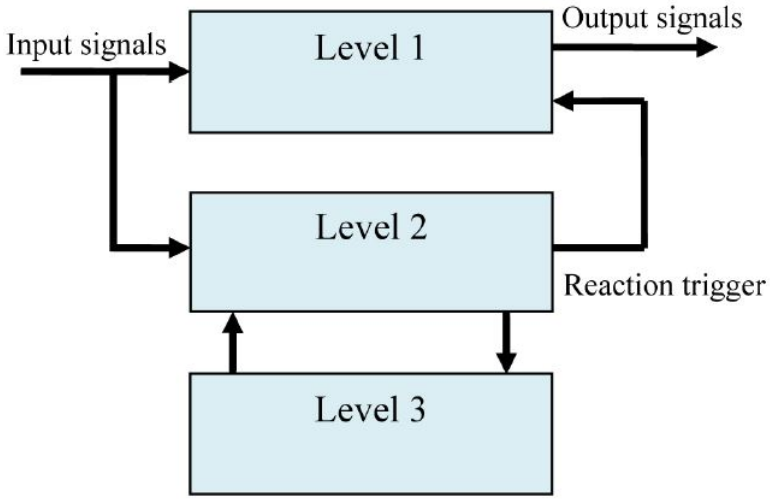

Figure 2.3: Three level safety architecture recommended by the E-Gas standard [14].

Monitoring is carried out by fault detection i.e. constantly checking the theoretical values with real values and compare it with the predefined value to be considered as a fault. Fault detection usually consists of three steps.

- Calculation of theoretical or expected value, for example in this particular application requested velocity from TSM as input to VMM can be considered as expected value.
- Calculation of actual or feedback value, for instance actual velocity generated due the torques from the output of the VMM can be considered as actual value.
- Comparison of both theoretical with actual values by calculating error or residual. This error is checked with predefined value to classify as a fault.

Depending on what to monitor or how to monitor there are many methods through which faults can be detected few of them are given below.

2.4.1 Forward and inverse dynamics

In the modelling and simulation of vehicle dynamics for design and optimization of drive-trains based on the direction of the calculation, it can be classified as forward and inverse dynamic simulation [15]. Inverse dynamics refers to the process of finding forces and moments from the motion, whereas, calculating the motion from known forces or torques is called 'forward dynamics problem'. The schematic representation of forward and inverse dynamics used is shown in the figure 2.4. In the context of the autonomous drive instead of the driver, there will be an automated driving system.

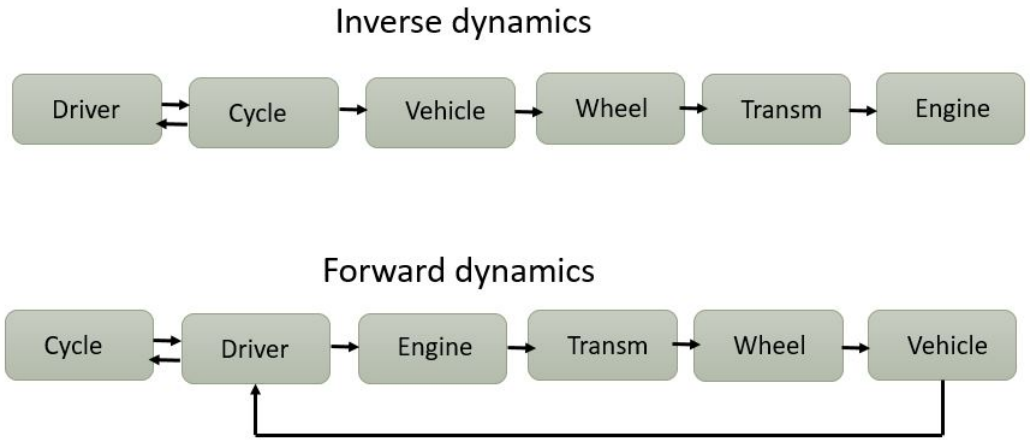

Figure 2.4: Schematic representation of forward and inverse dynamics [16].

2.4.1.1 Inverse dynamics

The monitor design based on inverse dynamics model would take TSM outputs such as velocity request and curvature request as inputs. Using the vehicle dynamics equilibrium equations, the corresponding torques and steering angles can be calculated. These can be compared with the torques and steering angles which are outputs of VMM to come up with the error and compared with a threshold to be considered as a fault.

2.4.1.2 Forward dynamics

The forward dynamic simulation typically involves solving of ordinary differential equations, which takes the inputs from the driver such as accelerator, brakes, and steering input, to calculate the vehicles states [16]. In this application, the inputs for the monitor designed on the basis of forward dynamics will be outputs of VMM such as power-train torque, brake torques and steering angle. On solving the vehicle dynamics equilibrium ODEs, the vehicle state variables can be calculated. These obtained state variables can be compared with outputs of the TSM as a reference to detect faults.

2.4.2 Signal based fault detection

Signal based fault detection methods typically make use of measured signals from sensors instead of models for fault detection. Some of the signals in the system contain information about the process. Faults in the process are reflected in these signals, based on this the symptoms can be generated. Then, the symptom analysis is carried out and the diagnostic decision can be made from this information. A schematic representation of signal-based fault diagnosis is shown in figure 2.5. Signal based monitoring has many applications in real-time monitoring [17]. In dynamical processes, it is common to use time-domain signals for fault detection [17]. For this particular application, the measured state variables such as acceleration, speed,

yaw rate from sensors such as IMUs, Wheel speed sensors, LIDAR etc. can be used to monitor the VMM. Since sensors are the reactive type, there will be a time delay in measuring the states of the vehicle. Therefore, the monitor design based on measured signals will be slow in detecting the fault

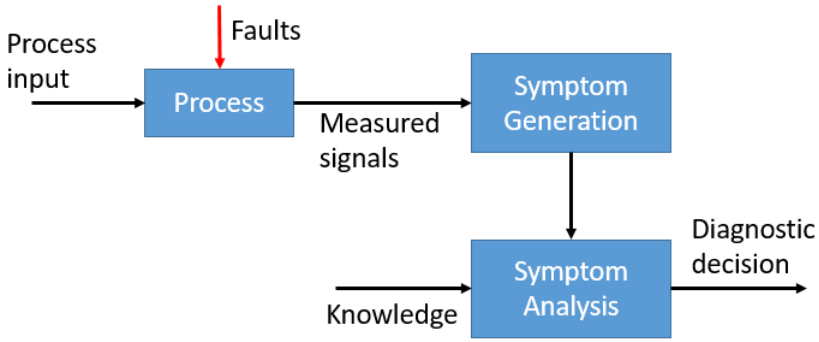

Figure 2.5: Schematic of signal based fault detection [17].

2.4.3 Structural analysis

Structural analysis (SA) is one of the model-based fault detection and isolation technique which is derived based on the bond graph [18]. The graph-based tool is used to check whether a fault of interest is detect-able and isolatable [19]. The structural analysis uses a model of the structure to represent the relationship between the variables and equations used to define the model. In this method, the variables used in the structural model are classified into known and unknown variables. All the variables which represent dynamic and algebraic states are classified under unknown variables. While control inputs and direct sensor measurements are classified as known variables. The main objective of this method is to find analytically redundant relations in the system which contain redundant information by eliminating the unknown variables from the known ones [16].
To check, whether the fault of interest is detectable or not, fault detectability analysis is carried out using Dulmage–Mendelsohn (DM) decomposition. Through DM decomposition, a structural model can be decomposed into three parts: underdetermined part M^-, just-determined part M^0 and over-determined part M^+ as shown is the figure 2.6. Here underdetermined part represents that the number of equations is less than the number of unknown variables, whereas just determined part indicates that the number of equations is equal to the number of unknown variables and overdetermined part shows that the number of equations is more than the number of unknown variables. If the fault lies in the over-determined part then the fault is detectable [19].
Next step is to find minimal structurally overdetermined (MSO) sets where the number of equations is more than the unknowns. Using these MSO sets, a residual can be formed by eliminating the unknown variables. The determined residuals can be used to detect and isolate faults. SA method not only detects the fault quickly and efficiently but also, it helps to isolate the sensors or components in the system

[21]. It is simple and efficient for complex systems. Unlike other traditional methods, the computational complexity of the SA is substantially lower, hence can detect the fault quickly [22]. This method does not require a full model of the system which has to be diagnosed, however, only the structure of the model is necessary. To conclude, SA is a suitable method for detecting and isolating faults in the components and sensor.

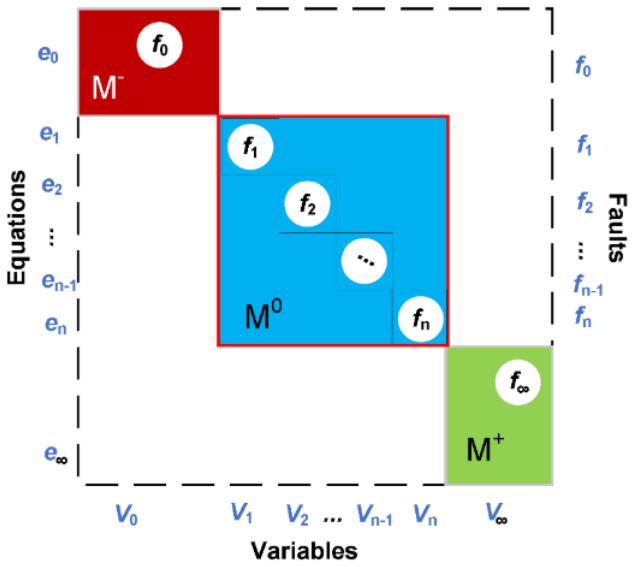

Figure 2.6: The schematic diagram of DM decomposition where, e_0 - e_∞ represents the equations; V_0 - V_∞ represents the system variables; f_0 - f_∞ represents the fault variables [19].

2.5 Desired attributes of a fault detection method

- Safety: Monitor should not miss any fault i.e. a fault has occurred and monitor fails to detect, in order to ensure safety.
- Detection time : Since safety is paramount, the designed monitor must detect faults as soon as possible [23].
- Sensitivity: Monitor should be sensitive to faults of interest [23].
- Robustness: Monitor should be insensitive to disturbances in system, uncertainties in the modelling and measurement noises [23].
- Adaptability: Monitor should be adoptable to different operating condition for which it is designed [23].
- Computational complexity: Monitor should be computationally less complex and also should take less storage [23].

2.6 Conclusion of the literature review

Signal based fault detection can be used to detect faults, but the main disadvantage of this method is that faults will not be detected instantly since there will always be

a delay in sensing. Structural analysis is a powerful and simple tool to detect and isolates faults quickly and efficiently, but as mentioned above it is mainly suitable for detecting and isolating faults in components and sensors. Fault detection based on inverse and forward dynamics is quick and simple, but inverse dynamics had a disadvantages when compared with forward dynamics. Disadvantage is that it is not possible to monitor state variables as it monitors torques and steering angle. Currently, the given VMM model is similar to inverse dynamics i.e. it takes velocity and curvature request as input and gives torques and steering angle as outputs, simple solution to monitor is to go backwards i.e. by checking whether the outputs of VMM leads to given inputs. So forward dynamics is best suited for designing monitor as it is quick, simple and will be able to monitor states variables of the vehicle which is required to adapt the monitor to functional safety.

3
Methodology

As explained in section 1.3, VMM determines the brake torque, power-train torque, steering angle based on the input requested from the TSM. As mentioned under section 1.1, this thesis work is concentrated on level 4 and level 5 of driving automation. In these levels, the driver task of ensuring the overall safety of the vehicle is completely taken care of by VMM. Any fault in the VMM may lead the vehicle to a hazardous event. Hence this thesis is focused on the design of monitoring concept to check the output of the VMM if it fulfils the curvature/acceleration requested from traffic situation management. The design of the monitor is also dependent on the level of risk associated during each hazardous event, which can be further explained under section 3.4.
Based on the content from section 2.4.1, it is evident that the design of VMM is similar to inverse dynamics. The simplest way to design the monitor for this application is by going backwards i.e. whether the outputs of the VMM leads to inputs. So to detect the fault quickly and efficiently, "Forward dynamic method" is chosen. The general overview of monitoring concept is shown in figure 5.6. As mentioned under section 1.6, work is focused on 4x2 (2WD) vehicle (tractor only). To be specific, it is front-wheel steered and rear-wheel driven vehicle.

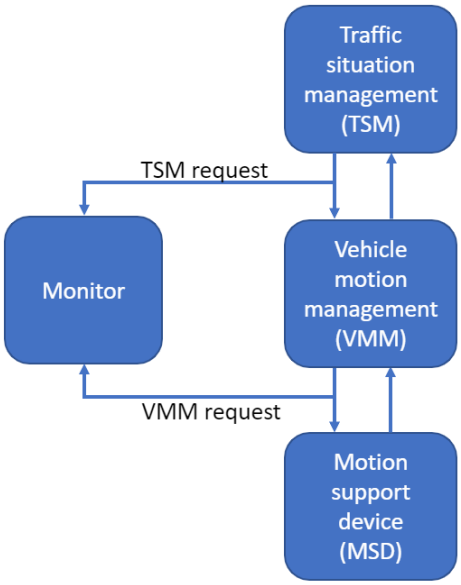

Figure 3.1: Block diagram representation of monitoring concept

The figure 3.2 represents the plan of action that has been followed to carry out the thesis work in a most efficient way.

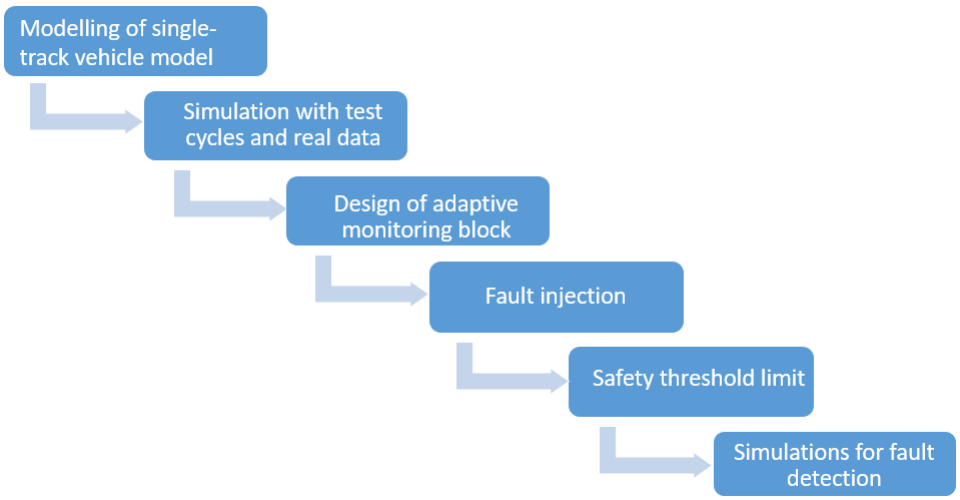

Figure 3.2: Plan of actions

3.1 Modelling of the monitor

The schematic representation of the concept used to monitor the outputs of VMM is shown in figure 3.3. The first step in the fault detection technique is the generation of residuals. In this thesis work, the VMM gets velocity and curvature request from TSM as the input signal. Then VMM will determine the corresponding torques i.e. power-train and brake torques and steering angle required at the wheel. Here, it is very important to monitor the control outputs from the VMM to prevent any hazardous event from taking place. To accomplish this, the control outputs from the VMM i.e. Power-train torque, brake torque and steering angle are fed into the monitoring system. By using the forward dynamics method, the monitor will calculate the corresponding state variables like acceleration and yaw rate. Later on, the determined state variables of the monitor are compared with requested state variables from TSM to check, whether, it leads the vehicle in the intended path. If there exists any deviation, then it is considered as error [10]. In general, there may be a small error present in the control output from the VMM, which can be accepted [10]. The forward dynamics method is modelled based on the single-track model of vehicle dynamics. Section 3.2 provides furthermore details on single track model.

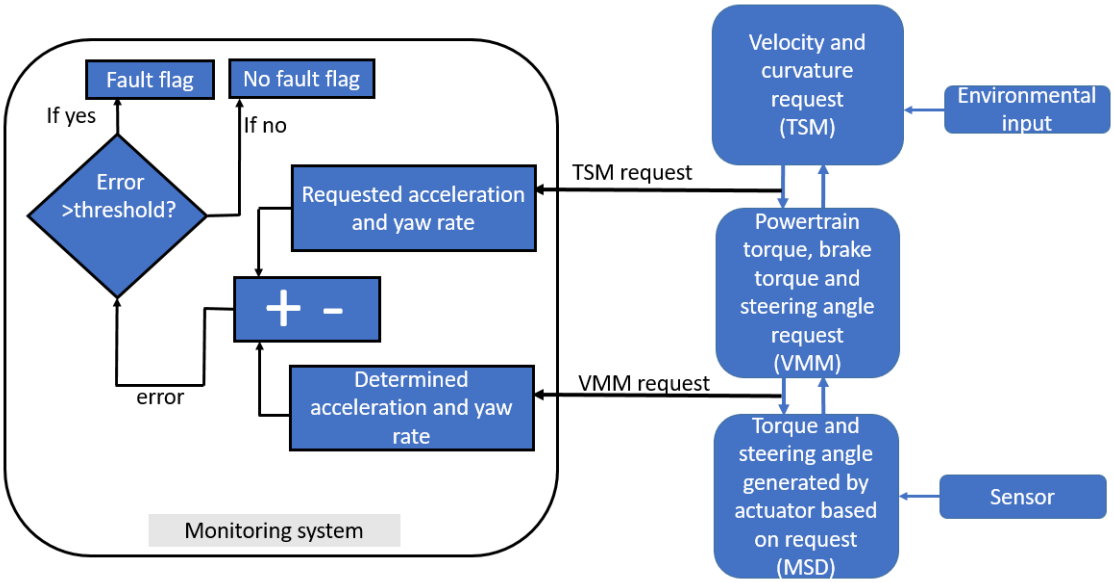

Figure 3.3: Schematic representation of vehicle motion management monitoring system [13]

3.2 Single track vehicle model

In order to predict the dynamic behaviour of the truck single track or two-track model can be used. Since the effect of lateral load transfer is not being considered the single-track model is used to design the monitor. In a single-track model, front and rear pairs of wheels of each axle are approximated as one single tyre. Figure 3.4 represents the single-track vehicle model with two-axles applicable for lateral and longitudinal dynamics of the vehicle, with only front-wheel steered.

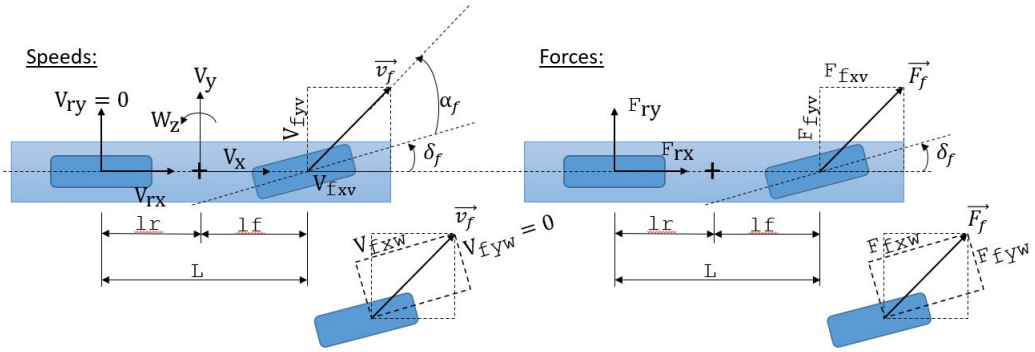

Figure 3.4: Single track model of vehicle dynamics [4]

The inputs to the monitor are power-train torque T_p, brake torques T_b and front steering angle δ_f. During the motion of the Truck, these above torques generate longitudinal forces at front F_{fxw} and rear wheel F_{rxw}. Since the monitor is based on single track model and the truck is rear wheel driven, the longitudinal forces for front axle will be the brake force generated by sum of front left wheel brake torque

T_{bfl} and front right wheel brake torque T_{bfr}.

$$F_{fxw} = \frac{T_{bfl} + T_{bfr}}{R} \tag{3.1}$$

Since the truck considered is rear wheel driven, the longitudinal forces for rear axle will force generated by sum of rear left wheel brake torque T_{brl}, right wheel brake torque T_{brr} and power-train torque T_p.

$$F_{rxw} = \frac{T_{brl} + T_{brr} + T_p}{R} \tag{3.2}$$

During the application of the front steering angle δ_f, the lateral forces generated at the front wheel F_{fyw} and rear wheel F_{ryw} depends on cornering stiffness C_f, C_r and the slip angles α_f, α_r as shown below,

$$F_{fyw} = -C_f * \alpha_f \tag{3.3}$$

$$F_{ryw} = -C_r * \alpha_r \tag{3.4}$$

At the front axle, transformation of the longitudinal force F_{fxw} and lateral force F_{fyw} from wheel coordinate system to vehicle coordinate system F_{fx}, F_{fy}, is given by,

$$F_{fx} = F_{fxw} * \cos(\delta_f) - F_{fyw} * \sin(\delta_f) \tag{3.5}$$

Since the term $F_{fyw} * sin(\delta_f)$ is very small when compared with $F_{fxw} * cos(\delta_f)$, it is neglected.

$$F_{fy} = F_{fxw} * \sin(\delta_f) + F_{fyw} * \cos(\delta_f) \tag{3.6}$$

Since the term $F_{fxw} * sin(\delta_f)$ is very small when compared with $F_{fyw} * cos(\delta_f)$, it is neglected.

At the rear axle, since the rear wheel is non-steered, Transformation of the forces from wheel coordinate system F_{rxw}, F_{ryw}, to vehicle coordinate system F_{rx}, F_{ry}, is as follows,

$$F_{rx} = F_{rxw} \tag{3.7}$$

$$F_{ry} = F_{ryw} \tag{3.8}$$

The angle between the direction in which wheel is actually travelling and the direction towards which wheel is heading is called slip angle. The slip angle on front axis α_f and rear axis α_r of the vehicle is given by,

$$\alpha_f = \arctan(\frac{v_y + l_f * w_z}{abs(v_x)}) - \delta_f \tag{3.9}$$

$$\alpha_r = \frac{v_y - l_r * w_z}{abs(v_x)} \tag{3.10}$$

During motion of the truck there exist various forces which offer resistance to the motion. When the vehicle starts moving there exists a rolling resistance force F_{roll}. Since the truck moves through air there exists air drag force which increases with increase in the speed of the vehicle v_x. In addition to these resistance forces, if the vehicle is moving along the slope then there exists the road gradient resistance force F_{grad}. The expression of each resistance forces are given below,

Air resistance force,

$$F_{air} = 0.5 * \rho * A * c_d * v_x^2 \tag{3.11}$$

Rolling resistance force,

$$F_{roll} = f_r * m * g * \cos\theta \tag{3.12}$$

Road gradient resistance force,

$$F_{grad} = m * g * \sin\theta \tag{3.13}$$

By considering the equations from 3.1 to 3.13, state variables such as longitudinal velocity and acceleration, lateral velocity and acceleration, yawrate and acceleration are calculated by solving the equilibrium equations for longitudinal and lateral dynamics as shown below. .

$$\dot{v}_x = \frac{F_{fx} + F_{rx} - F_{roll} - F_{grad} - F_{air}}{m} + w_z * v_y \tag{3.14}$$

$$\dot{v}_y = \frac{F_{fy} + F_{ry}}{m} - w_z * v_x \tag{3.15}$$

$$\dot{w}_z = \frac{F_{fy} * l_f - F_{ry} * l_r}{I} \tag{3.16}$$

$$w_z = \int \dot{w}_z \tag{3.17}$$

$$a_y = \dot{v}_y + w_z * v_x \tag{3.18}$$

$$a_x = \dot{v}_x - w_z * v_y \tag{3.19}$$

Longitudinal velocity and acceleration can be used to monitor longitudinal dynamics. Out of them acceleration a_x is chosen to monitor because it is found to be more sensitive to torque faults than velocity. For monitoring lateral dynamics yawrate w_z is chosen to monitor, as it is found to be sensitive to steering fault. The above-determined state variables are then compared with state variables requested from TSM to calculate the error value.

Thus completes the first step in the design of monitoring concept. Before moving on to the next step i.e. coming up with safety threshold limits, the model is simulated with different test cycles to validate its performance. During the fault-free simulation, the result obtained from one of the test cycles is shown below.

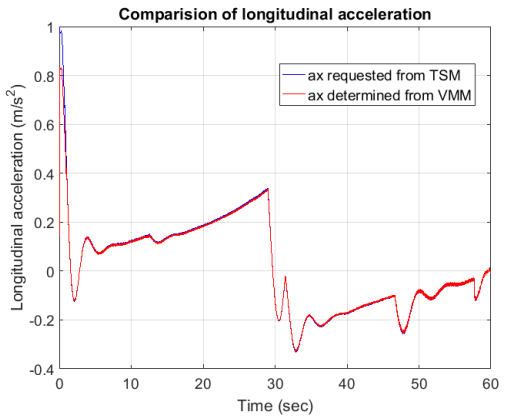

Figure 3.5: Comparison of requested and determined longitudinal acceleration

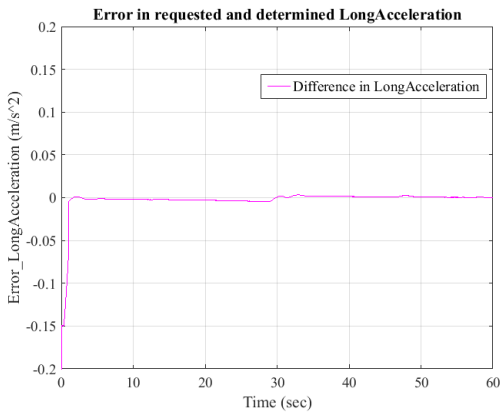

Figure 3.6: Plot representation of error value between longitudinal acceleration

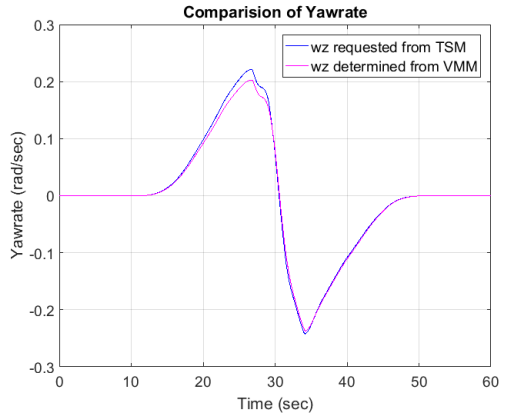

Figure 3.7: Comparison of requested and determined yawrate

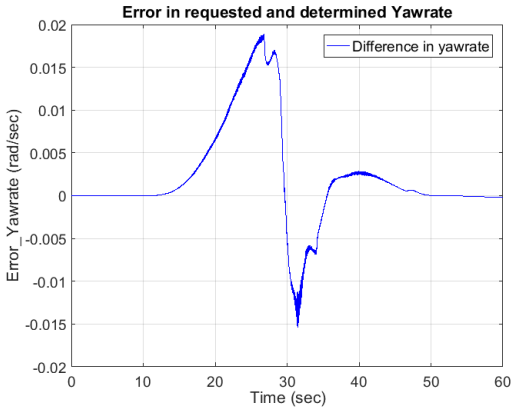

Figure 3.8: Plot representation of error in yawrate

From the figures. 3.5, 3.7, it is clearly observed that the requested and determined values of longitudinal acceleration a_x and yawrate w_z are almost in agreement with each other. Therefore, the resulting error value between them are relatively small as shown in figures. 3.6, 3.8. Now, the simulation is carried out with logged data, recorded during the vehicle testing in the real world driving scenario. This simulation helps to verify and evaluate the working of the monitoring algorithm in real-world testing cases. The results obtained during the simulation with one of the logged test data is shown below.

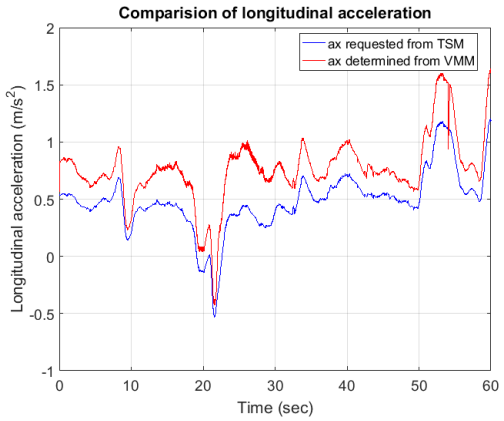

Figure 3.9: Comparison of requested and determined longitudinal acceleration

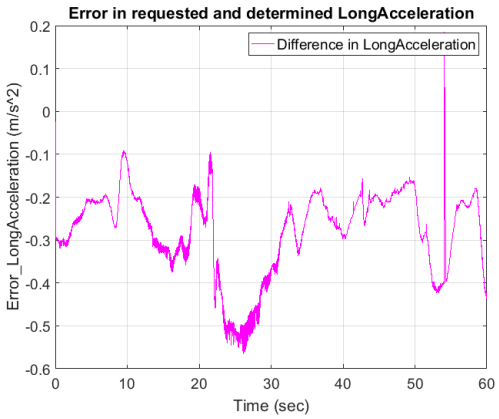

Figure 3.10: Error in longitudinal acceleration with logged data

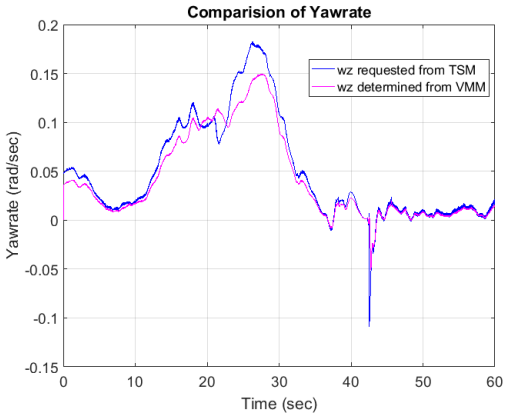

Figure 3.11: Plot representation of requested and determined yawrate

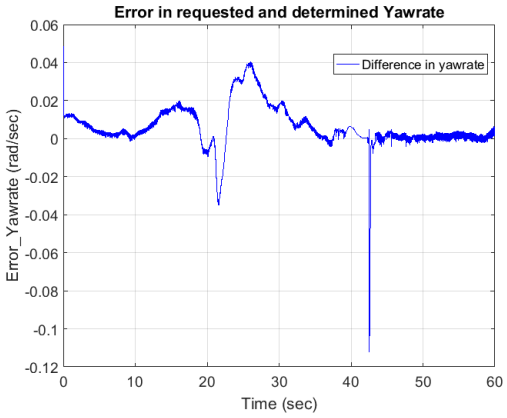

Figure 3.12: Error in yawrate with logged data

Figures. 3.9, 3.11 clearly indicates that the determined values are not equal to the values requested from the TSM. In the real-world driving condition, due to presence of noise factors such as measurement noise, transient actuator response etc. there exists a offset between the requested and determined values as shown in the figures 3.10, 3.12. To ensure safety and robustness, noise factors present in the control output of VMM should be scaled down. This can be achieved with adaptive monitoring concept, which is explained in detail under the section 3.3

3.3 Adaptive monitoring

The two factors that basically define the error threshold limit are safety and robustness. In context of safety the threshold limits have to be set low such that in case of large error the monitor should detect the fault, thus ensuring safety. On the other hand, to guarantee robustness, the error threshold value should be set high such that the monitoring does not raise the fault flag due to the combination of noise factors in worst condition, so there is a trade off between the two factors.

Since there is always an error due to noise factors, the threshold limit should be set higher than the magnitude of worst case noise. By setting the threshold value high, in some situations this may lead to hazardous event. To overcome this problem the monitor has to adapt to noise factors but not to genuine faults. . Adaptive monitoring is similar to the monitoring concept explained under the section 3.1 but with addition of an extra Adaptive block. The schematic representation of adaptive monitoring concept is shown in the figure. 3.14. Since there is no filtering of any signals, adaptive monitor is not a high pass filter. Adaptive monitor decreases the offset between requested and determined values by deleting the noise error.

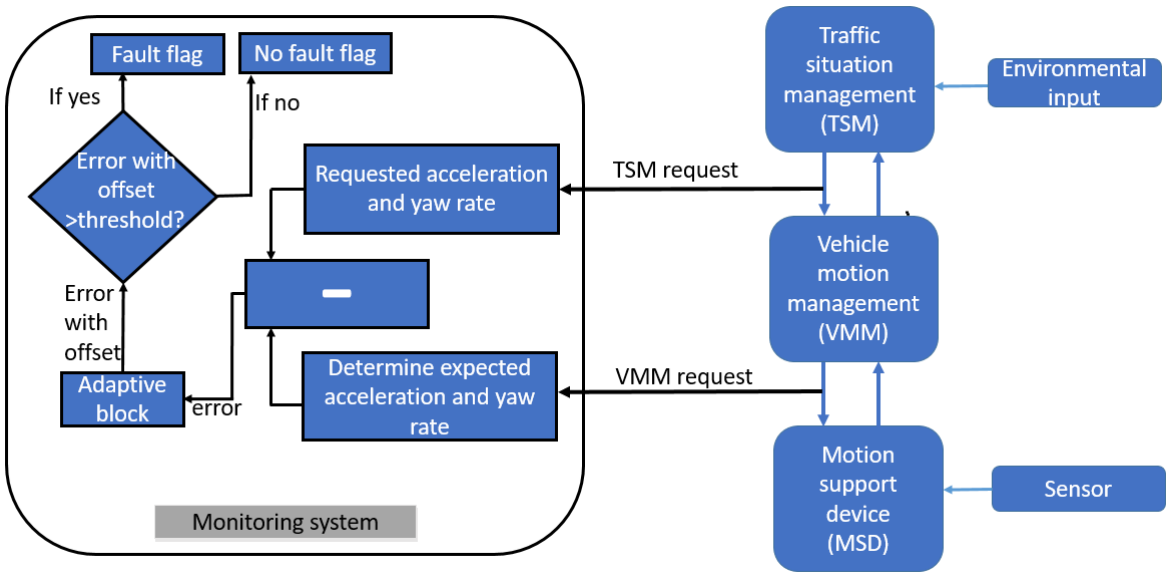

Figure 3.13: Schematic representation of Adaptive monitoring system [13]

As mentioned in the previous section 3.2, there exists an offset between the TSM (reference) outputs and outputs of the monitor. This is mainly due to various factors such as measurement noise, transient actuator response etc. These dependencies become noise factors and induce error. When all of these errors are considered over a cycle, it gives frequency based distribution as shown in the figure below.

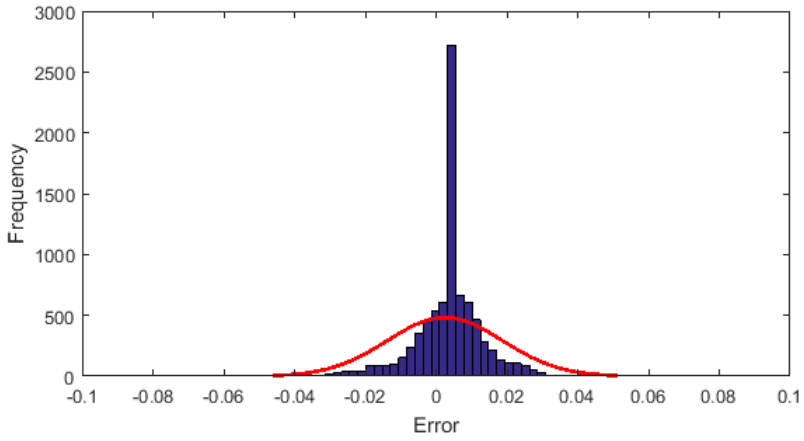

Figure 3.14: Error distribution

The figure 3.15 represents the function of Adaptive block. In order to make the monitor adaptive, few additional adaptive elements are added to the previously designed monitor. Now the monitor calculates error distribution mean from the error documented over a predefined period.

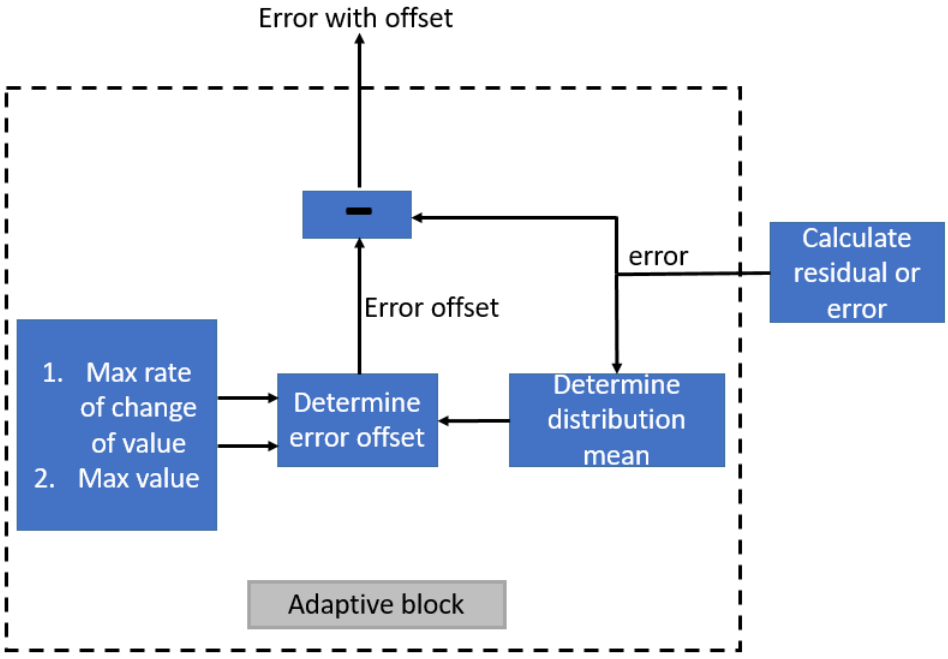

Figure 3.15: Detailed schematic representation of adaptive block

In statistics and probability theory, the distribution mean or expected value is the sum of the every possible value multiplied with its probability. If x is the possible value of random variable X and p(x) is the probability of the occurrence of that value then the equation used to calculate distribution mean is given below.

$$\mu = \sum xp(x) \tag{3.20}$$

so the monitor has to calculate real-time distribution mean as shown in the figure 3.16 and it is updated with above mentioned predefined period.

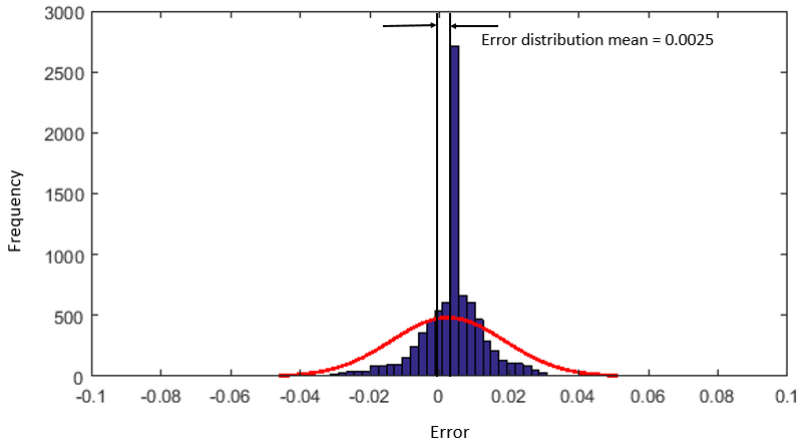

Figure 3.16: Graph representation of error distribution mean

For this application all the error values over the previous 0.1 seconds are gathered and distribution mean of these values is calculated. For future work the effects of larger sample range should be conducted. In the next step, the monitor will determine the 'error offset' by using calculated 'distribution mean'. During the finding of 'error offset', it is limited by two factors as mentioned below,

- The maximum rate of change of 'error offset'.
- The maximum value of 'error offset'.

Maximum value of error offset and maximum rate of error offset are to be set using data obtained from real world test without any fault. These values depend upon the chosen time sample range.The values for 0.1s sample range are given in table 5.15

State variables	Max Error offset	Max Error offset rate
Acceleration	0.74	2.5
Yaw rate	3.317e-2	8.733e-1

Table 3.1: Error offset and error offset rate for state variables

Finally, the 'error offset' is subtracted from original error value to obtain the 'error with offset' value which is then checked with the threshold limit to determine whether the fault flag has to be raised or not. Then the simulation is conducted again with test cycle as well as logged data, to evaluate the function of adaptive monitor. The plots obtained during the simulation indicates that the offset due to the presence of noise factors have been adapted and hence reduces error value as shown in the figure.3.18.

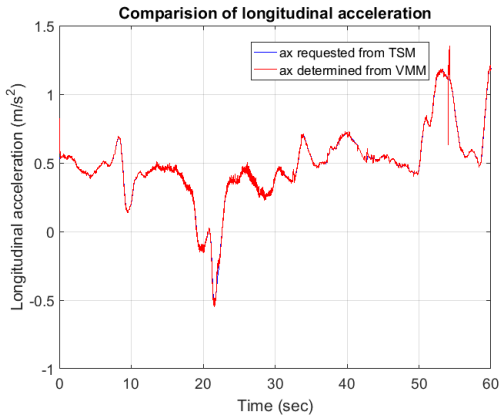

Figure 3.17: Comparison between longitudinal acceleration of TSM and VMM with adaptive monitor

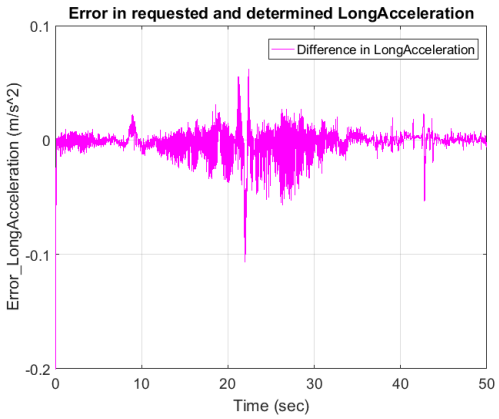

Figure 3.18: Error value between longitudinal acceleration of TSM and VMM with adaptive monitor

3.4 Threshold limits

The next important part in the methodology is to design the safety threshold limit. A threshold limit is a predefined value which is used for the fault detection task when the system does not give output as expected. The fault may occur due to the malfunctioning behavior of the complex control system, which may lead the vehicle to a hazardous event. The task is to detect malfunctioning behavior during longitudinal and lateral dynamic motion of the truck to ensure functional safety. Through literature review [2], the most common malfunction behaviors associated with a vehicle are considered in this thesis work and they are as follows,

- Sudden unintended acceleration or deceleration of the vehicle.
- Unintended steering request on the front wheel of the vehicle.

In this thesis work, the following steps are incorporated to design the most efficient safety threshold limit.

- **Safety goal**.
- **Fault injection**.
- **Deciding the threshold limit**

3.4.1 Safety goal:

The expertise based upon their knowledge will conduct a hazard analysis and risk assessment for above malfunction behavior and then specify the safety goals for each event. As mentioned under the section 1.6, in this thesis the safety goal was provided by Volvo Group they as follows,

- For longitudinal dynamics: To prevent unintended acceleration and deceleration of the vehicle i.e. $-4m/s^2 < a_x < 0.2m/s^2$.

- For lateral dynamics: The vehicle is not supposed to leave the lane by 20cm laterally.

These safety goals serve as the basic framework to determine final threshold value. By considering the above mentioned safety goals, the fault injection method is carried out, which is further explained in the next sub section.

3.4.2 Fault injection

Fault injection is a software testing method which purposely induces an error in the control output of the system. In this thesis, the control output from the vehicle motion management such as Powertrain torque, brake torque and front-wheel steering angle is injected with fault, which is represented in the figure 3.19.

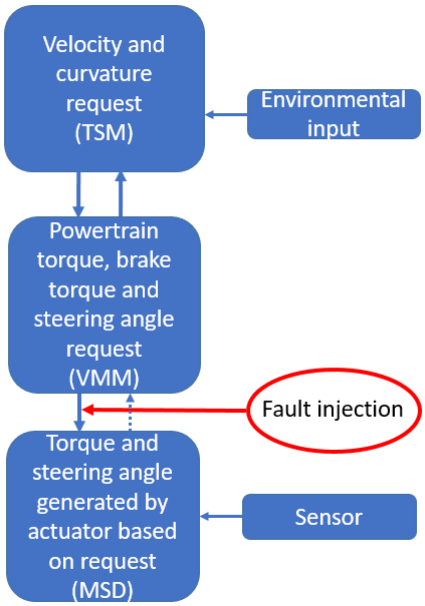

Figure 3.19: Schematic diagram representing position of fault injection.

In this thesis work the faults are injected in two different ways such as pulse fault and step fault. Pulse fault is usually injected to induce a fault with a larger magnitude for a single instance of time, whereas the step fault is injected to induce the fault with smaller magnitude for a longer duration of time.
The fault injection method is implemented to ensure,

- What size of faults can be detected
- How quickly and effectively each fault can be detected
- Whether the monitor fulfils both robustness and safety requirement.

3.4.3 Deciding the threshold limit

Finally the threshold limit is fixed by combining safety goal and fault injection process. The safety goal i.e "the vehicle is not supposed to leave the lane by 20 cm",

and the "step" fault are considered here to illustrate, how the threshold value is determined in order to detect faults quickly and efficiently.

The defined safety goal for lateral dynamics is quite challenging because one need to consider so many parameters before fixing the final threshold value such as the speed at which vehicle is travelling and current front-wheel angle. At higher speed and higher steering angle, the vehicle may violate the safety goal in a short span of time. On the other hand, for lower speed and lower steering angle, the vehicle may take a longer duration of time to violate the safety goal.

For this study purpose, the simulation has been performed in a specific driving condition. In the simulation environment, the truck was supposed to operate on a straight manoeuvre at 30kph, where the steering angle request is zero. But then an unintended step fault of magnitude 5 degree is injected to the steering angle request from vehicle motion management from 40 sec to 42 sec i.e. for a total time duration of 2 sec. Due to this, the vehicle starts to deviate laterally and it fails to follow the trajectory requested from traffic situation management as shown in the figure 3.20

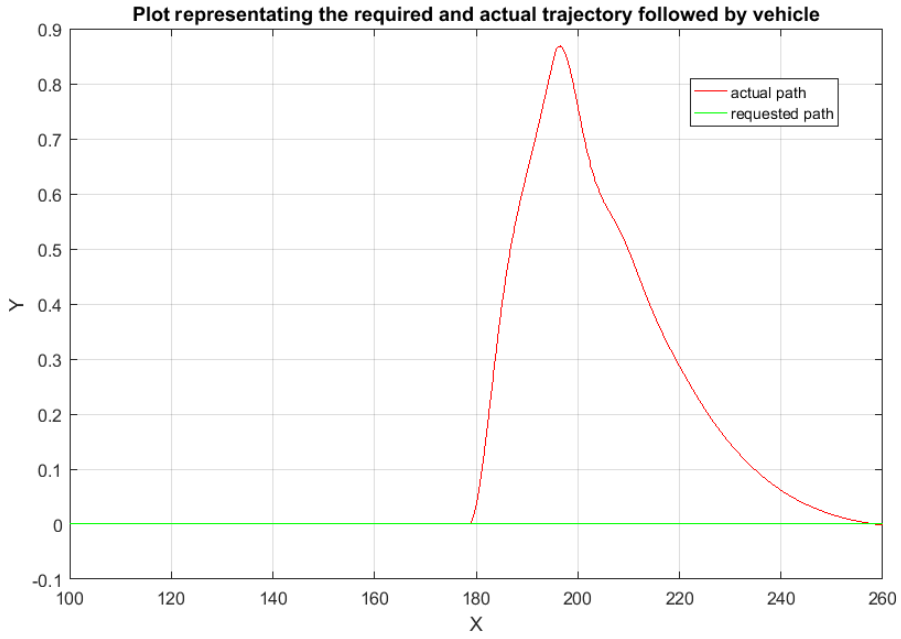

Figure 3.20: Plot representing the requested path and actual path travelled by vehicle due to injected fault

Then the deviation of the vehicle along the y axis at each time instance is plotted to determine whether the vehicle violated the safety goal, if yes, then at what time. Below shown are the time instance from the figure 3.21.

- t_i: Fault injection time
- t_d: Fault detection time
- t_v: Safety goal violation time

From the same figure 3.21, it is clearly observed that the vehicle violated the safety

goal at time t_v due to the injected fault at time t_i. Therefore, the time (Δt) required by the vehicle to violate the safety goal from the time instance at which fault is injected is given by,

$$\Delta t = t_v - t_i \tag{3.21}$$

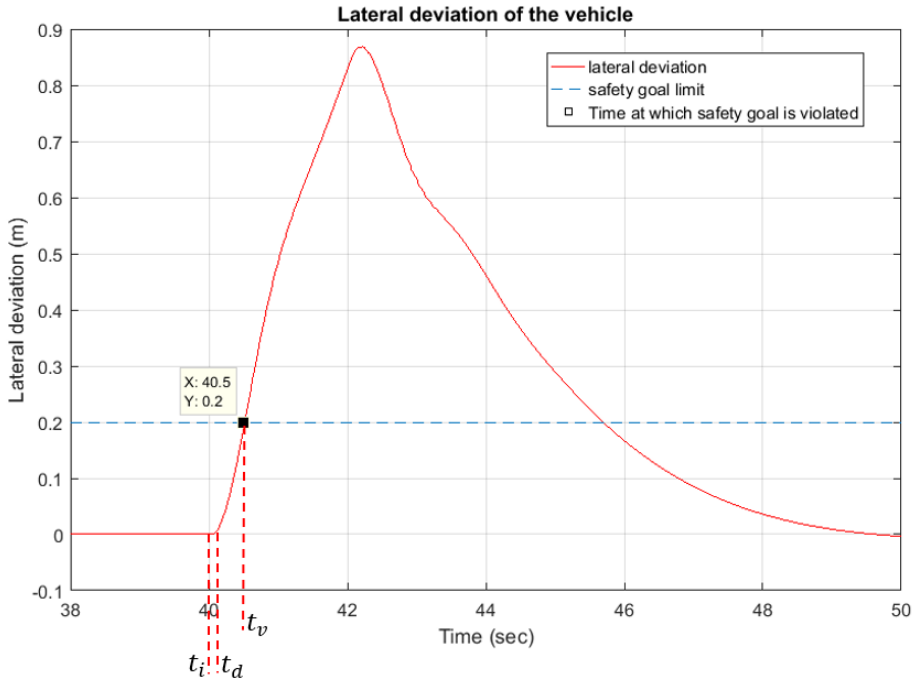

Figure 3.21: Plot representing the time required to violate the safety goal due to the injected fault

In the current example, the value of Δt is equal to 500 ms. Now the task of the monitor is to detect the fault quickly and raise the fault flag, which then provides sufficient time to carry out the necessary fallback mechanism before it leads the vehicle into a hazardous event. The fault flag is raised based on the threshold limit value. The requirement for setting up the threshold limit is that the designed monitoring algorithm should detect this fault within 20 percent of the overall time which was required by the truck to violate the safety goal from the time instance at which fault is injected. Therefore the fault detection time is determined as shown below,

$$t_d = t_i + 0.2 * (\Delta t) \tag{3.22}$$

Similarly, different magnitude of fault in steering angle has been injected at different speed. In this work, the effect of fault in the steering angle is observed as a change in yaw rate. Therefore, for lateral dynamics the unintended steering input that corresponds to the vehicle yaw rate of more than 0.05 rad/sec is considered as fault.

In case of longitudinal dynamics, it is assumed that only the sudden unintended acceleration and deceleration will lead the vehicle into a hazardous event, that is

associated with a higher level of risk. Therefore, for unintended deceleration of the vehicle, the unintended brake torque which corresponds to vehicle deceleration of more than $-4m/s^2$ is considered as a fault. For unintended acceleration of the vehicle, the power-train torque that corresponds to the unintended acceleration of more than $0.2m/s^2$ is considered as a fault.

For a given safety goal, based on the above theory the safety threshold limits required to detect the fault in the longitudinal and lateral dynamics of the vehicle are finalised and are shown in the table 3.2.

Safety goal	Type of fault injected	Safety threshold limit	Fault detection time (t_d)
1. Propulsion: To prevent unintended acceleration	Pulse fault	Acceleration error value should not exceed 0.2 $^{m}/_{s^2}$	$t_d = t_i$
2. Braking: To prevent unintended deceleration	Pulse fault	Deceleration error value should not exceed - 4 $^{m}/_{s^2}$	$t_d = t_i$
3. Steering: To prevent unintended steering angle	Pulse fault	Yaw rate error value should not exceed 0.05 $^{rad}/_{s}$	$t_d = t_i$
4. Steering: Vehicle is not supposed to leave the lane by 20 cm laterally	Step fault	Yaw rate error value should not exceed 0.05 $^{rad}/_{s}$	$t_d = t_i + 0.2 * \Delta t$

Table 3.2: Safety threshold limit for corresponding safety goals with detection time

4

Simulations

In order to validate the designed monitor model it is first simulated in virtual environment by carrying out model in loop (MIL) testing. The virtual environment consists of three parts, they are mock sensors block, application block and plant model as shown in the figure below. The application block contains models of the different layers such as TSM, VMM and MSD as mentioned in vehicle motion functional architecture. The designed monitor model is also incorporated in this block. The sensor values required to run the application block are taken from the outputs of the sensor block. The outputs of the application block are the outputs from MSD and these values are fed to the plant model. Plant model is built on simscape toolbox which is used to model the physical vehicle in order to simulate how the vehicle behaves for given inputs such as brake torques, powertrain torque and steering angle. Here the vehicle is modelled as multibody system using blocks representing bodies, joints, constraints, forces and sensors. The simscape multibody simulates the motion by solving the equations of the motion. The outputs of the plant model are the sensor values. These sensor values are fed to the sensor block with unit delay in order to simulate real life scenarios. The simulations of the monitor is carried out using different test cycles as inputs to replicate different driving scenarios.

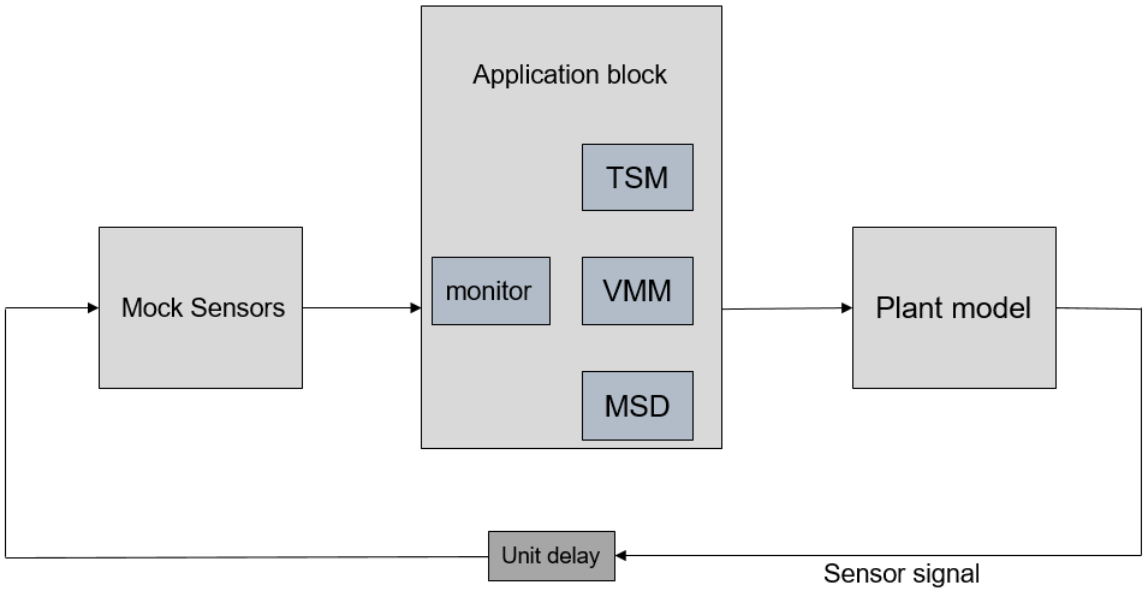

Figure 4.1: Schematic representation simulation environment

4.1 Test cyles

A test cycle is a set of data points which represents the velocity profile of the vehicle with respect to time and the curvature profile. These test cycles are designed to understand the performance of the vehicle in different driving conditions. Here the test cycle is used for the simulation of the whole vehicle model and then to validate the monitoring system. The test cycles can be designed based upon the requirement and some of them are shown in section A.2 under the appendix.

4.2 Simulation with test cycle without adaptive concept

The first designed monitoring concept without an adaptive monitoring block is simulated with different test cycles to check the performance. The results obtained during this simulation gave a satisfying result with different test cycles as shown below.

Simulation with 'braketurn'

The simulation is performed using the test cycle 'braketurn' to evaluate the function of monitor without injecting any faults. From the figures 4.6, 4.7, it is observed that the values of requested and determined state variables are almost in agreement with each other. The state variables shown here are acceleration and yaw rate.

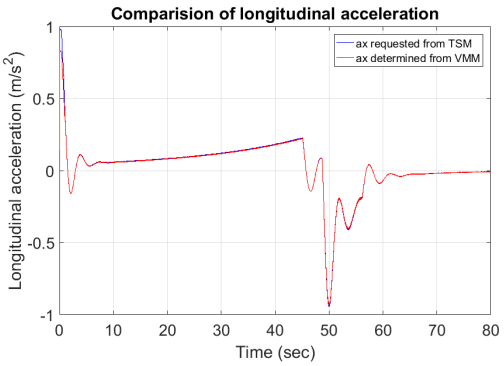

Figure 4.2: Comparison between longitudinal acceleration of TSM and VMM

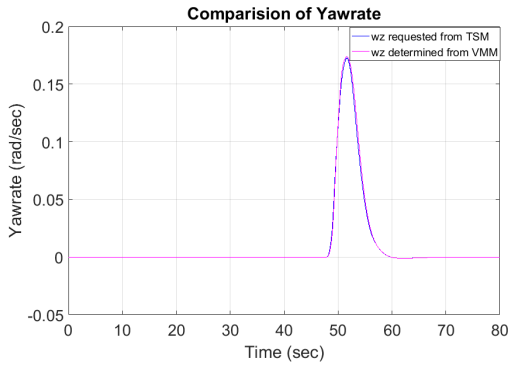

Figure 4.3: Comparison between the yawrate of TSM and VMM

Simulation with 'hook 06 ms2'

Similarly, the simulation is also performed by using test cycle 'hook 06 ms2' to check whether the monitoring algorithm is working well for different speed and curvature profiles, which are requested from TSM. As shown in the below figures 4.4, 4.5, it clearly indicates that there exists similarities between the requested and determined values.

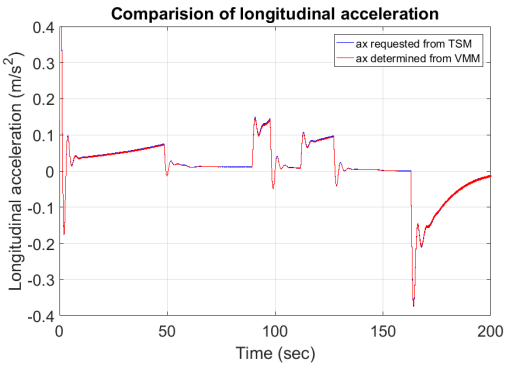

Figure 4.4: Comparison between longitudinal acceleration of TSM and VMM

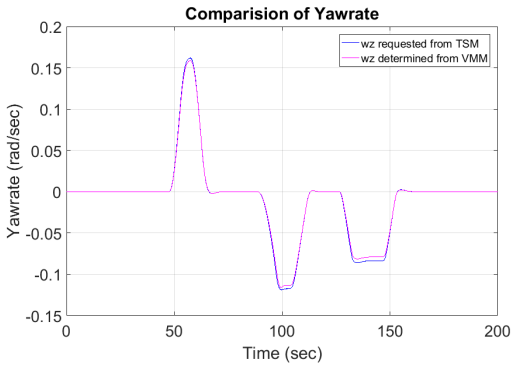

Figure 4.5: Comparison between the yawrate of TSM and VMM

4.3 Simulation with log test data

After completing the simulation with different test cycles, the designed monitoring model is simulated with the test data, logged during the real-world driving scenario. This simulation helps to validate the performance of the monitoring system for real world application.

4.3.1 Testing log data without adaptive

In this section, the simulation is carried out for test data without considering the adaptive block in the monitoring model as shown in figure 3.3. In this thesis, the requested state variable values are obtained from TSM, and the control output from the VMM are used to determine expected values.

Simulation with 'log data - test-1'

The plots obtained from the simulation with test data 'log data - test-1' shows that there exists an error value i.e. difference between the requested state variable and determined state variable values. Therefore the acceleration and yaw rate values are not in agreement with each other at some regions as shown in the figure 4.6, 4.7.

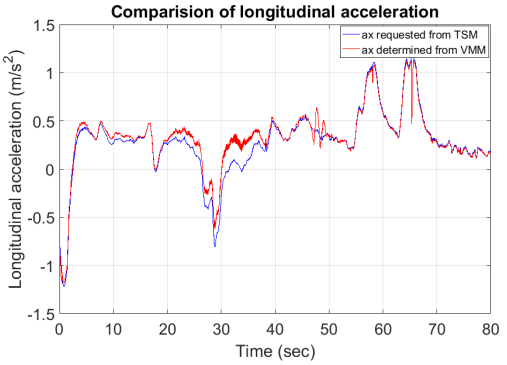

Figure 4.6: Comparison between longitudinal acceleration of TSM and VMM

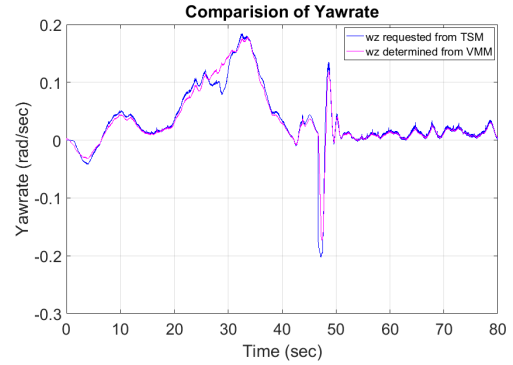

Figure 4.7: Comparison between yawrate of TSM and VMM

Simulation with 'log data - test-2'

Similarly, the simulation is carried out with another test data 'log data - test-2' to investigate whether the presence of error value. The plots obtained during the simulation confirms that there exists an error value between the requested and determined state variables when the simulation is conducted with logged test data.

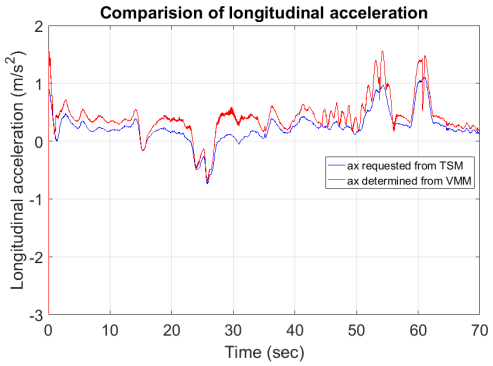

Figure 4.8: Comparison between longitudinal acceleration of TSM and VMM

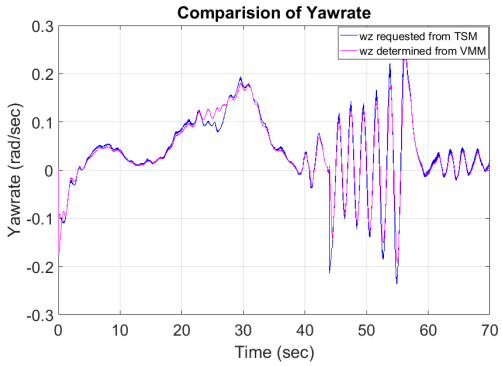

Figure 4.9: Comparison between yawrate of TSM and VMM

Based on the plots obtained under section 4.3.1, it is evident that the requested and determined values of acceleration and yaw rate are not equal, which then results in the generation of a larger error value. Due to the presence of this error value, the threshold limit should be set higher to prevent the monitor from raising the fault flag unnecessarily but, by doing so the monitor will fail to detect the small error, that occurs in the control output of the VMM.

4.3.2 Testing log data with adaptive monitor

In this session, the simulation is carried out along with adaptive block in the monitoring model. As a solution to the previous section, the monitor with adaptive reduced the error value between the requested and determined state variables. Therefore, the threshold limit value can be reduced, thus ensuring safety and robustness.

Simulation with 'log data - test-1'

By using the adaptive monitor, the simulation is performed again with test data 'log data - test-1'. The plots obtained here indicate that the error values which was present in the figures 4.6, 4.7, is reduced.

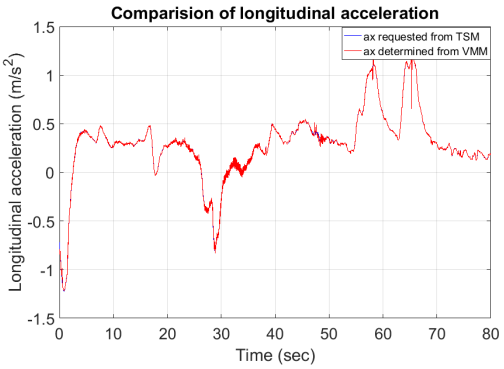

Figure 4.10: Comparison between longitudinal acceleration of TSM and VMM

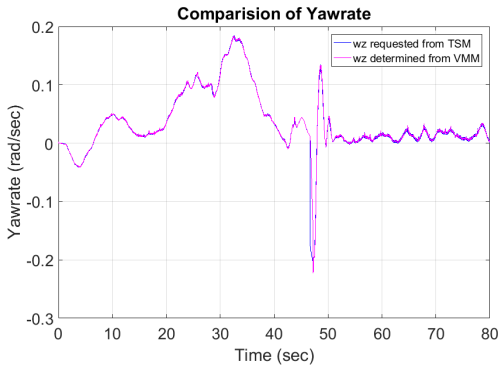

Figure 4.11: Comparison between yawrate of TSM and VMM

Simulation with 'log data - test-2'

The simulation is conducted with more test data. Once again, from the figures 4.12, 4.13, it is proved that the adaptive monitor is successful in reducing the error value between the requested and determined state variables.

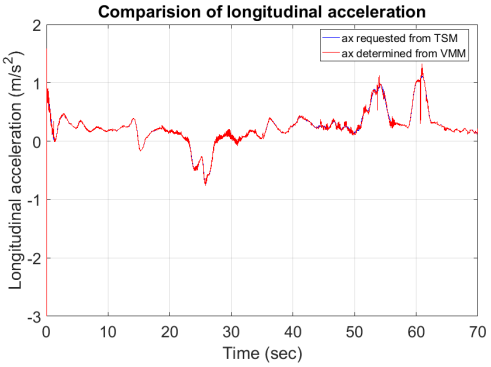

Figure 4.12: Comparison between longitudinal acceleration of TSM and VMM

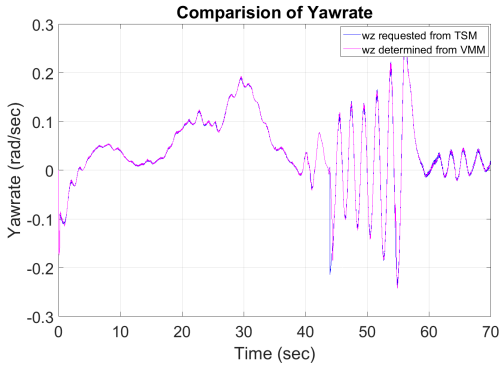

Figure 4.13: Comparison between yawrate of TSM and VMM

4.4 Simulation with test cycles with adaptive monitoring concept

The results obtained in previous section, validates the performance of adaptive monitoring algorithm with the logged data. In practice, it is not possible to inject the fault during the simulation by using the log data, therefore after completing the simulation with the log data, the monitoring algorithm with an adaptive block was used to run the simulations with different test cycles.

4.4.1 Simulation with adaptive monitor without faults

With test cycles, the simulation is first carried out without injecting any faults. Specific driving cycles are chosen for simulation to validate the longitudinal and lateral

dynamic behaviour of the vehicle. Some of them are shown below.

Simulation with 'braketurn'

For simulation purpose, the brake turn profile seemed to be the right choice because it includes both longitudinal and lateral dynamics. Both the state variables i.e. longitudinal acceleration and yaw rate are compared as shown in the figures 4.14, 4.16. Figures 4.15, 4.17, represents the error values obtained as a result of comparison between the requested and determined state variables.

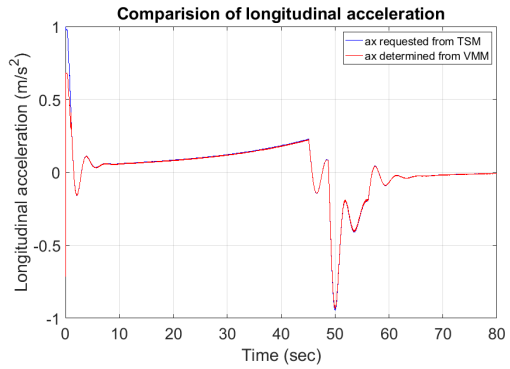

Figure 4.14: Comparison between longitudinal acceleration of TSM and VMM

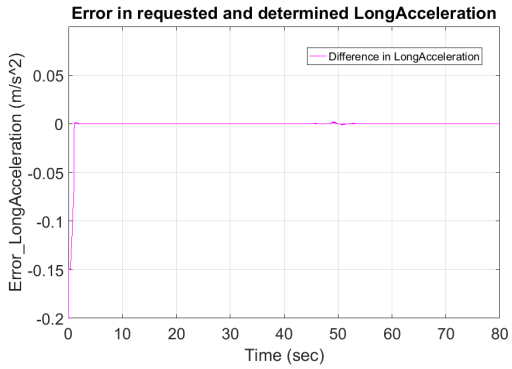

Figure 4.15: Plot representation of error in requested and determined values

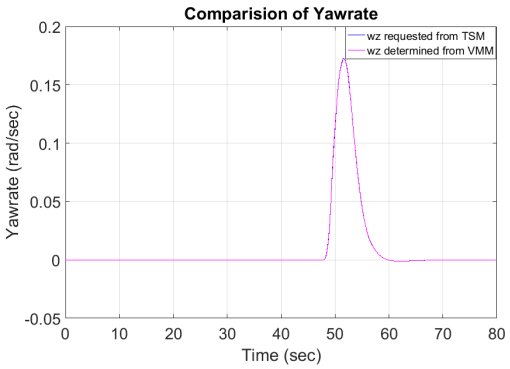

Figure 4.16: Comparison between longitudinal acceleration of TSM and VMM

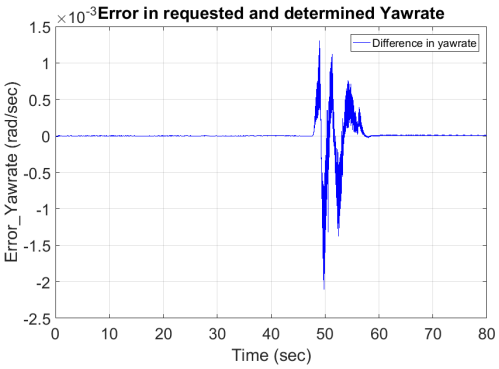

Figure 4.17: Plot representation of error in requested and determined values

Simulation with 'hook-06-ms2'

Similar to the previous test cycle, even the $hook06ms2$ looked promising test cycle to conduct the simulation for the validation purpose. The results obtained during the simulation are shown below.

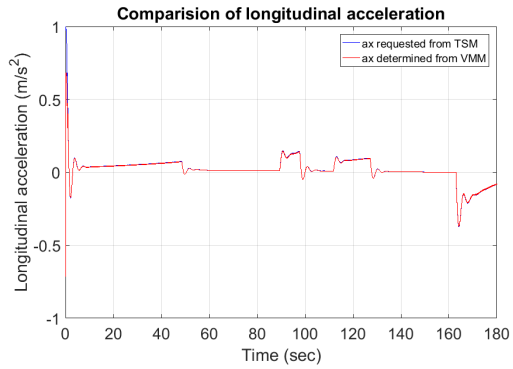

Figure 4.18: Comparison between longitudinal acceleration of TSM and VMM

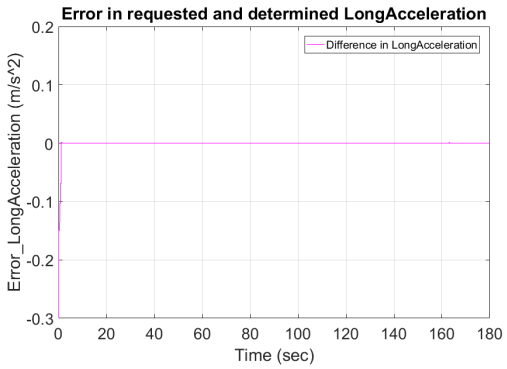

Figure 4.19: Plot representation of error in requested and determined values

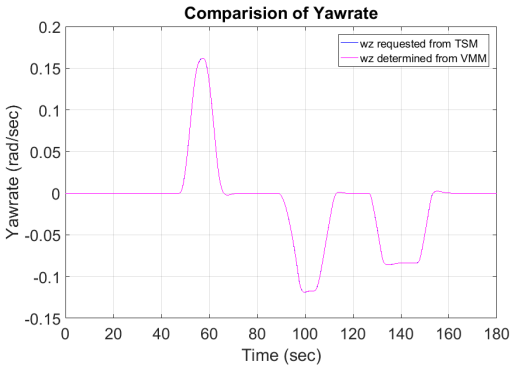

Figure 4.20: Comparison between longitudinal acceleration of TSM and VMM

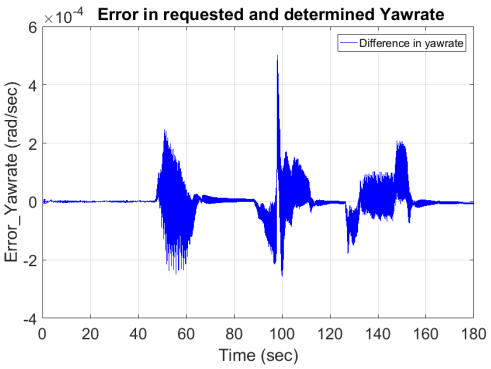

Figure 4.21: Plot representation of error in requested and determined values

From the above simulation results, the monitoring algorithm without adaptive block performed well for test cycles with the negligible value of an error present between the requested values from TSM and the determined values from the control output of VMM. In the succeeding step, the same monitoring algorithm is used to simulate the test data, logged during the real-world driving condition. It results in the error value of a larger magnitude. As a solution to minimize this error value and to tighten the threshold limit, the adaptive monitoring algorithm is designed and then simulated with the test data. The results obtained from this simulation proved that the adaptive monitoring algorithm successfully reduced the error value. Through simulations, it is discovered to be impossible to inject any fault by using test data. Therefore, the adaptive monitoring algorithm should be simulated with the test cycle for fault injection purpose as shown in the next chapter. The final fault-free simulation results with test cycles promises that with the least value of error, the adaptive monitoring algorithm is ready to detect the fault quickly and efficiently.

5
Results

The plots obtained under the section 4.3.2, 4.4.1, prove that the adaptive monitor based on forward dynamics method is working well with different driving scenarios during the fault-free simulation. This section is focused on the results obtained by simulating the model with two types of injected faults, which is further explained in coming section.

5.1 Simulation of test cycles with fault injection

Two types of faults are injected to the control output of the Vehicle motion management and checked whether the adaptive monitor detects the faults quickly and efficiently. Here faults are injected to power-train torque, Brake torque and steering angle. Different types of faults injected are given below.

- Pulse fault
- Step fault

5.1.1 Pulse Fault injection to Power-train torque

In order to detect sudden unintended acceleration, pulse fault of large magnitude is injected to the powertrain torque output of VMM. So 1000 Nm of torque is injected at time instant 20 second to check for any unintended acceleration of 0.2 m/s2. Plots given below shows that the fault is detected instantly at time 20 sec.

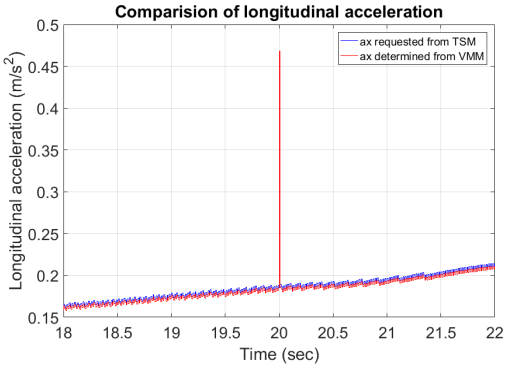

Figure 5.1: Plot representation of requested and determined acceleration

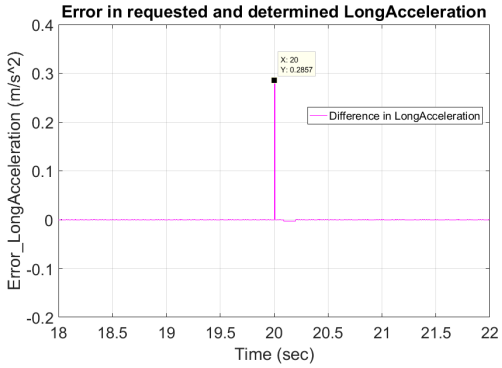

Figure 5.2: Plot representation of acceleration error

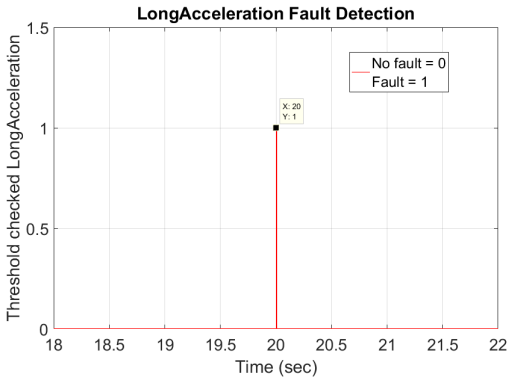

Figure 5.3: Fault detection in the power train torque request

5.1.2 Pulse fault injection to brake torque

In order to detect sudden unintended deceleration, pulse fault of large magnitude is injected to the brake torque outputs of VMM. So at time instant 20 second, torque of -4000 Nm at each wheel is injected to brake torque outputs of VMM to check for any unintended deceleration of -4 m/s2. Plots given below shows that the fault is detected instantly at time 20 second.

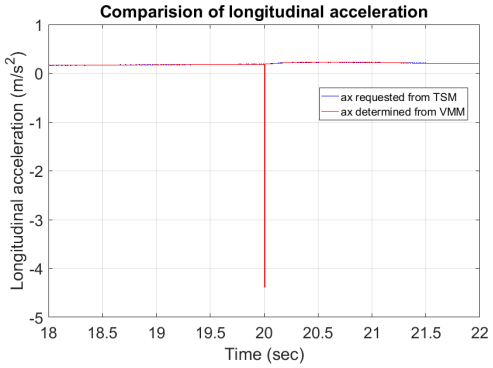

Figure 5.4: Plot representation of requested and determined acceleration

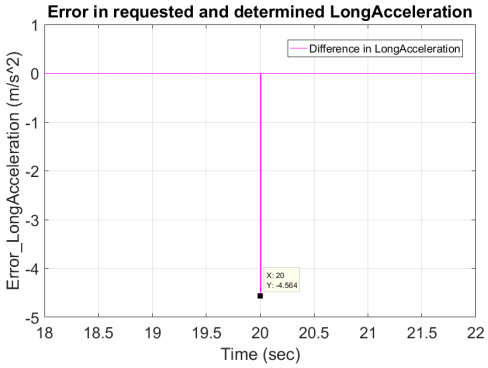

Figure 5.5: Plot representation of deceleration error

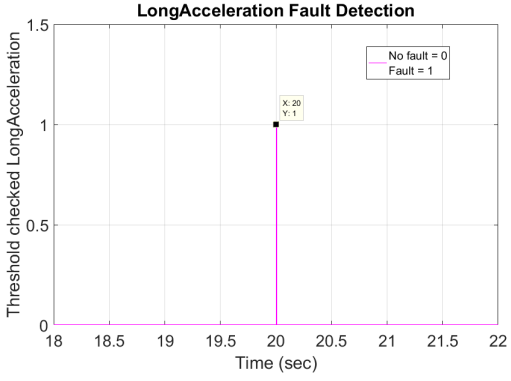

Figure 5.6: Fault detection in the power train torque request

5.1.3 Pulse fault injection to steering angle

Plots given below shows the simulation results with large pulse fault of magnitude 10 degree, which is injected to steering angle at time instance 20 second to check for yaw-rate error with the threshold value of 0.05. From the figure 5.7 it can be analysed that even if the pulse fault is injected at a time instance of 20 second, its effect on yaw rate is observed after 10 milliseconds. Hence, figure 5.9 shows that the fault is detected instantaneously.

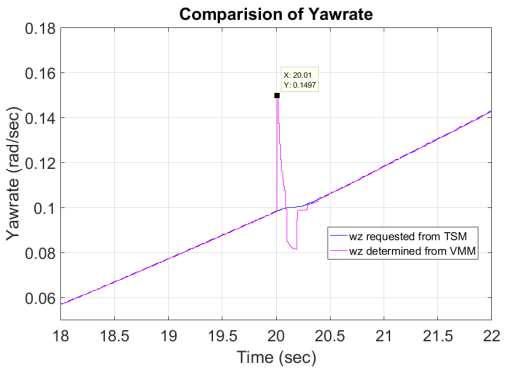

Figure 5.7: Plot representing the requested and determined yaw rate

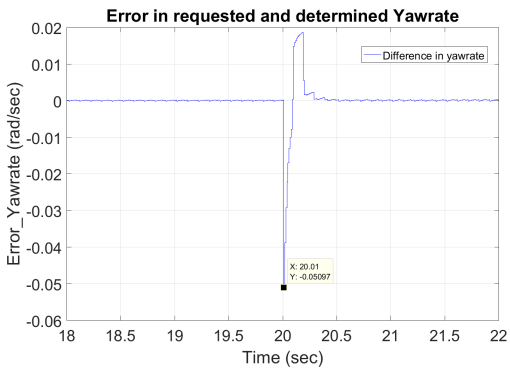

Figure 5.8: Plot representing the yaw rate error value

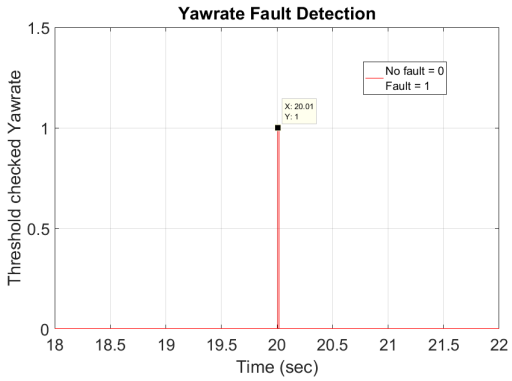

Figure 5.9: Steering angle fault detection for pulse fault 10 deg

Similarly, Here the vehicle is simulated with straight manoeuvre at a speed of 30 kph and suddenly an unintended steering angle fault of 27 degree is injected at a time instance 40 second. The figure 5.12 shows that the fault is detected instantaneously based on the explanation from previous paragraph.

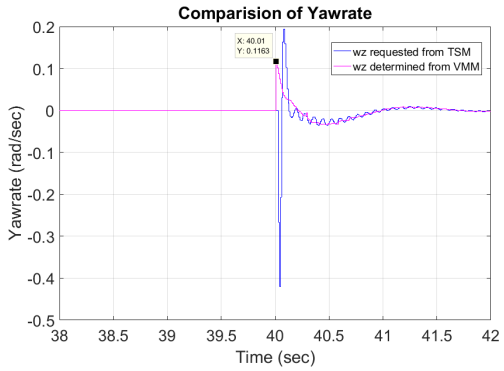

Figure 5.10: Plot representing the requested and determined yaw rate

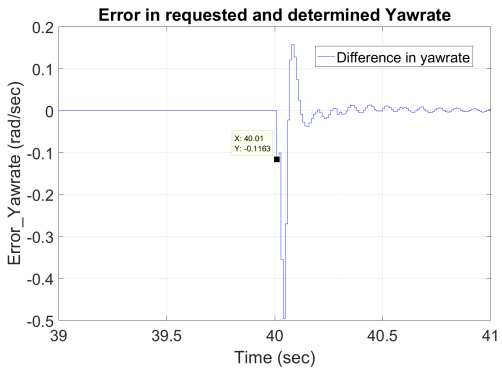

Figure 5.11: Plot representing the yaw rate error value

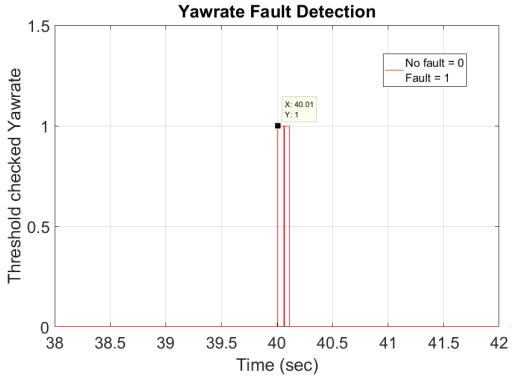

Figure 5.12: Steering angle fault detection for pulse fault 27 deg

Therefore, based on the results obtained from the simulation for pulse fault injection in the control output of vehicle motion management, it proves that the monitoring algorithm detects the sudden unintended pulse faults very quickly and thereby ensures the safety of the trucks motion. Then the monitoring algorithm is validated for step fault injections which is explained in the next section.

5.1.4 Step fault injection to steering angle

Plots given below shows the simulation results with a step fault injection of 2 degrees in steering angle at a time instance 40 second for a total duration of 3 seconds. For this simulation straight manoeuvre was chosen with a constant speed of 30 kph. The figure 5.13 shows that the vehicle violated the safety goal (not to leave the lane by 20 cm) in 1.05 seconds from the time instance at which fault has been injected. So the monitor should detect this fault within 20 percent of the total time required to violate the safety goal. The figure 5.16 shows that the fault is detected in 40 milliseconds, which is less than 20 percent of violation time.

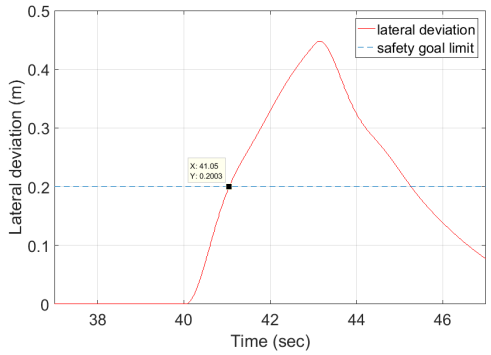

Figure 5.13: Plot representing the lateral deviation due to injected step fault

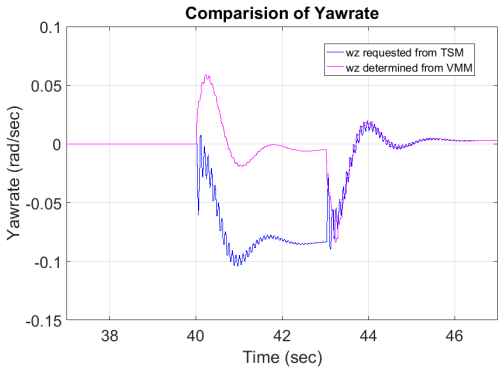

Figure 5.14: Plot representing requested and determined yaw rate

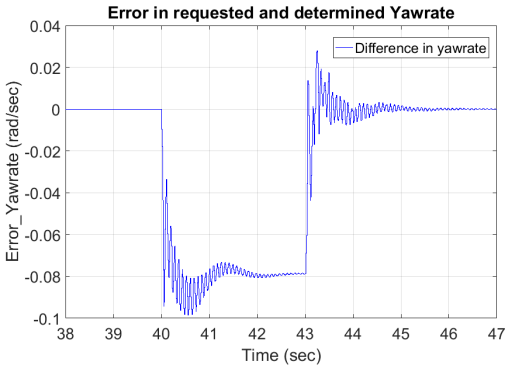

Figure 5.15: Plot representing the yaw rate error value

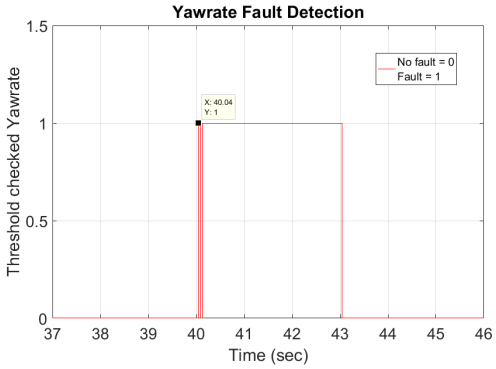

Figure 5.16: Plot representation of fault flag raised when the fault is detected

Not all the faults that occur in the control output of vehicle motion management will lead the vehicle to violate the safety goal. Therefore, in this simulation the same magnitude of step fault is injected to a control output of the vehicle traveling at same speed as mentioned in previous paragraph but the fault is injected for a duration of just 1 second i.e. from the time instance of 40 second to 41 second. The figure 5.17 shows that even though fault is injected for just 1 second, the vehicle still violated the safety goal in 1.05 seconds. The figure 5.20 shows that the fault is detected in 40 milliseconds from the time at which the step fault is injected.

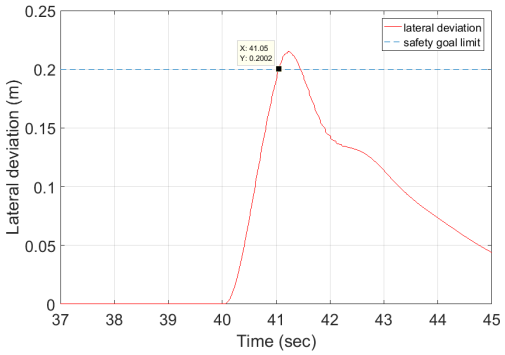

Figure 5.17: Plot representing the lateral deviation due to injected fault

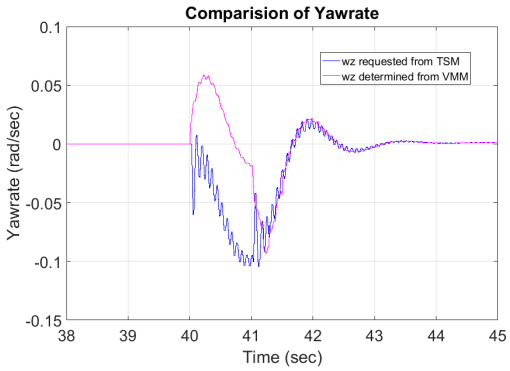

Figure 5.18: Plot representing determined and requested yaw rate

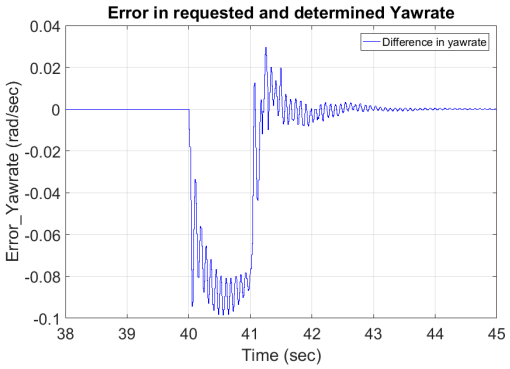

Figure 5.19: Plot representing the yaw rate error value

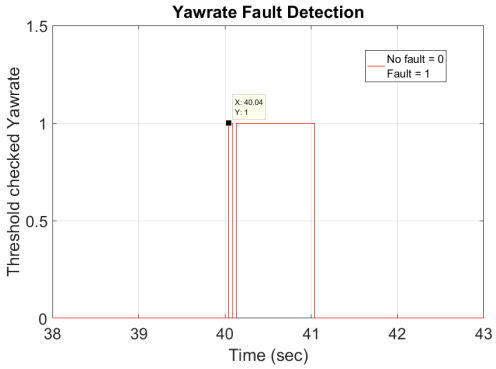

Figure 5.20: Plot representing fault or no fault condition

Similarly, simulation results with a step fault injection of 5 degrees in steering angle for 2 seconds at time instance 40 second is shown below. Figure 5.21 shows that the vehicle violated the safety goal in 510 milliseconds. Then the figure 5.24 shows that the fault is detected in 40 milliseconds from the time at which the step fault is injected.

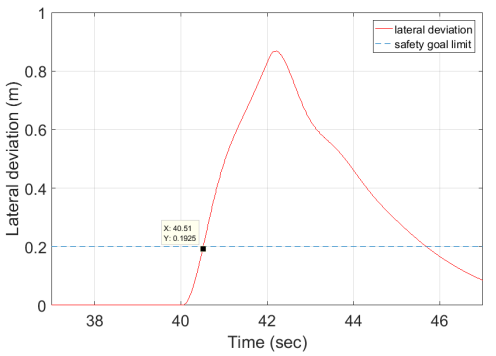

Figure 5.21: Plot representing the lateral deviation due to injected fault

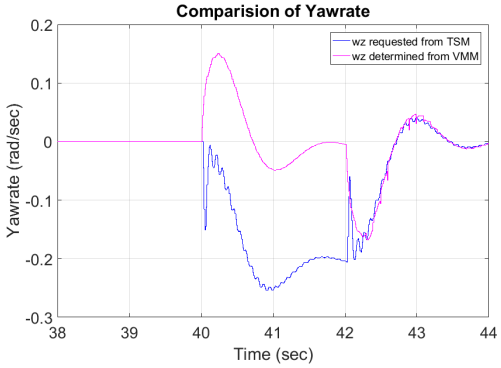

Figure 5.22: Plot representing requested and determined yaw rate

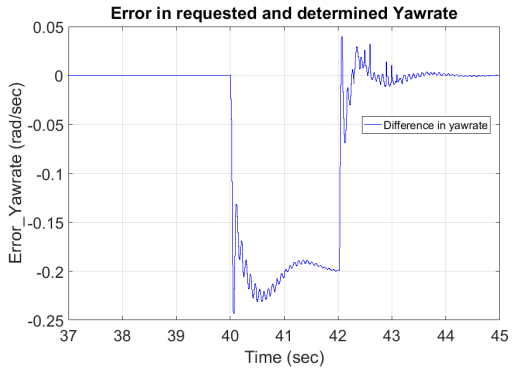

Figure 5.23: Plot representing the yaw rate error value

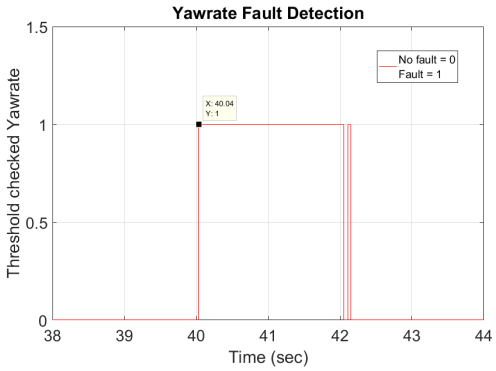

Figure 5.24: Plot representation of fault flag raised when the fault is detected

The simulation results with a step fault injection of 0.5 degrees in steering angle for 10 seconds at time instance 40 second is shown below to investigate the affect of small step fault for a longer duration of time. Figure 5.25 indicates that the vehicle did not violate the safety goal and the figure 5.27 shows that the fault flag is not raised.

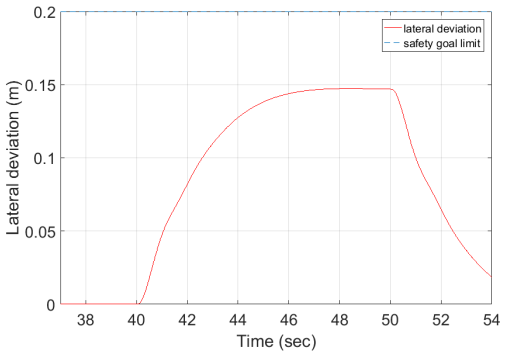

Figure 5.25: Plot representing the lateral deviation due to injected fault

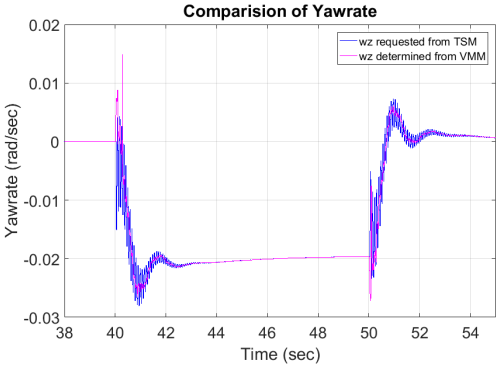

Figure 5.26: Plot representing determined and requested yaw rate

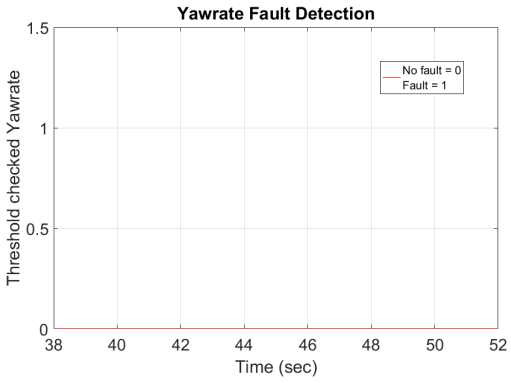

Figure 5.27: Plot representing fault or no fault condition

6
Discussion

The main requirement of the the monitor is to detect faults in VMM quickly if there are any, so the detection time should be as low as possible. The designed monitor should be simple, so it has to be computationally less complex. Another requirement was that the designed monitor should be adopted to functional safety. The monitor should detect the faults within time period such that there is enough time to carryout fallback mechanism in order to avoid any violation of safety goal.
Based on the above requirements a monitor is designed on forward dynamic approach using single track model. The designed monitor is improved by making it adaptive in order to ensure safety and robustness. The thresholds for classifying faults are derived from provided safety goals. The monitor is tested and validated in the virtual environment by injecting appropriate faults.
To monitor longitudinal dynamics, state variable longitudinal acceleration is chosen to monitor as it is found to be sensitive to torque faults than longitudinal velocity. Two cases considered to monitor longitudinal dynamics are sudden unintended acceleration and deceleration which are of highest ASIL level. In order to generate error in acceleration, pulse fault is injected to the power-train torque output of VMM to check whether there is any unintended acceleration of $0.2m/s^2$. As shown in the section 5.1.1, the monitor detects the fault instantly. Similarly in order to check for any intended deceleration of $-4m/s^2$ pulse fault is injected to brake torque outputs of VMM. As shown in the section 5.1.2, the monitor detects unintended deceleration instantly.
To monitor lateral dynamics, Yaw-rate is chosen to monitor as it is found to be sensitive enough to steering angle fault. Here two types of faults are injected, pulse fault to inject large magnitude of fault for short duration of time and step fault to simulate small magnitude of fault for large duration of time. For both the cases the yaw-rate error of 0.05 rad/s is considered as threshold limit which is derived from the provided safety goal, not to leave the lane by 20cm. When pulse fault of magnitude 10 deg is injected, as shown in section 5.1.3, the monitor detected the steering fault instantly. When step fault of magnitude 2 deg is injected for duration of 3 seconds, as shown in the section 5.1.4, the monitor detects the fault within the 20 percent of the total time required to violate the safety goal. From the results it is evident that the faults affecting the motion are detected within the required time and any violation of safety goal is prevented, thus ensuring functional safety.

7
Conclusion

The main aim of the thesis is to design an algorithm to detect faults in the VMM to check whether its out puts leads to any hazardous situations. First a literature review has been carried out regarding monitoring methods, functional safety and fault detection methods. Based on what to monitor or how to monitor different monitoring methods used in the industry were found. Some of them include signal based fault detection and structural analysis. It is found that fault detection based on signals from the sensor is slow as there is always delay in sensing. Fault detection using structural analysis is simple and effective, another advantage of the method is that it can isolates the faults easily, but it is found that this method is suitable for detecting and isolating faults in components and sensors. A new approach based on inverse dynamics and forward dynamics was introduced. Inverse dynamics had few disadvantages over forward dynamics.

After reviewing different fault detection methods it is found that a monitor based on forward dynamics is best suited for this application. So the monitor is modelled according to forward dynamics using the single track model. Out of longitudinal acceleration and longitudinal velocity, acceleration is chosen to monitor longitudinal dynamics because it is found to be more sensitive to torque fault than velocity. For monitoring lateral dynamics yawrate is chosen to monitor, as it is found to be sensitive to steering fault. The designed monitor is simulated with different test cycles. After carrying out simulation it is found that the monitor is accurate and precise, then the designed monitor is simulated with logged data of real test. It is found that the there is a offset between the requested and monitor output. In order to ensure the robustness and safety the monitor is converted to adaptive monitor by adding adoptive elements to it. The adaptive monitor is designed such it does not adapt to genuine faults ensuring safety but adapt to inherent small faults and avoid unnecessary shut down due to false positive error thus increasing the robustness. The adaptive monitor is simulated for with logged data of real test and it is found that it adapts to small faults but not to genuine faults.

Next step involved finding appropriate error threshold for longitudinal acceleration and yawrate to classify as faults. The thresholds has been composed based on provided safety goals such that the there is sufficient time to carryout necessary fallback mechanism in order to prevent any hazardous event from taking place. So the designed monitor is adapted to functional safety. In order to check whether the monitor detects the faults for the given threshold, different appropriate faults are injected. Pulse fault is injected to induce large fault in small amount of time. Step fault is injected to induce small fault for longer duration of time. Fault injection is carried out for different test cycles. From the results it is found that the monitor

detects the faults in longitudinal acceleration and yawrate quickly. It can be concluded that monitor based on forward dynamics meets all the requirements and is best suited for this application. Due to time constraint the monitor could not be tested in the realistic driving condition in a test vehicle.

8

Future scope

Due to lack of time some of tasks were not able to be carried out. Following are the recommendations for future work. Currently the monitor is designed for tractor only, but for future work the monitor should be designed for different combinations of tractor and trailers. The designed adaptive monitor has to tested for different time sample range and has to be tuned for this particular application. The designed model based monitor software should be adapted in compliance with ISO 26262 standard.Due to time constraint monitor could not be tested in the real world scenario, so the monitor should be validated in a test vehicle in the realistic driving situations. Currently thresholds are composed for truck travelling at low speed. At higher speeds, due to fault in VMM, the truck may violate the safety goals quicker when compared at low speeds, so this problem can be resolved by designing an adaptive threshold such that magnitude of threshold adapts based on speeds at which the truck is moving.Currently the monitor is designed based on single track model to monitor in normal driving scenarios. Two track model can be used in order to monitor stability functions.

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A

Appendix 1

A.1 List of parameters used in this thesis

Parameters	Value	Unit	Description
m	7000	kg	Mass of the tractor,
C_f	2*150e3	N/rad	Front axle cornering stiffness,
C_r	2*140e3	N/rad	Rear axle cornering stiffness,
l_r	2.18	m	Distance from the center of gravity to rear axle
l_f	1.52	m	Distance from the center of gravity to front axle
L	3.7	m	Effective wheel base
f_r	0.0050	-	Rolling resistance coefficient
g	9.82	m/s^2	Gravity constant
ρ	1.1840	kg/m^3	Density of air
A	7	m^2	Frontal cross sectional area
c_d	0.4	-	Air resistance coefficient
I_z	16452	kg*m^2	Moment of inertia along z axis
R	0.5	m	Effective radius of the wheel

Table A.1: List of vehicle parameters

A.2 Test cycles

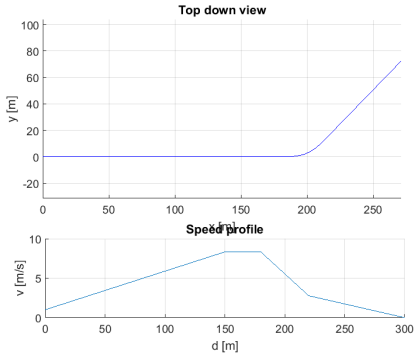

Figure A.1: Plot of trajectory 'brake turn' representing speed profile and path travelled

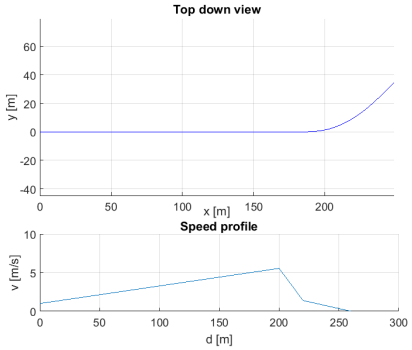

Figure A.2: Plot of trajectory 'hallered' representing speed profile and path travelled

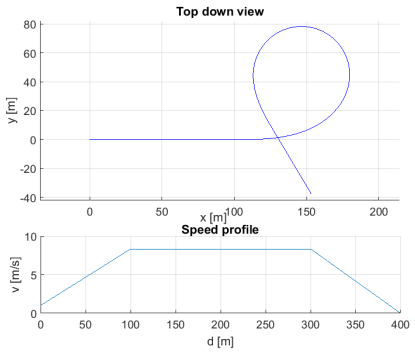

Figure A.3: Plot of trajectory 'jackknife-turn' representing speed profile and path travelled

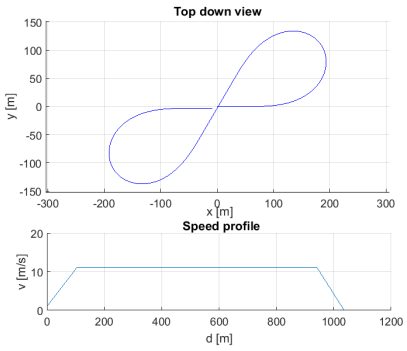

Figure A.4: Plot of trajectory 'eight' representing speed profile and path travelled