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Mathematical Modelling of Truck Platoon Formation Based on A Dynamic String Stability

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ABSTRACT

In this research, developing a Fuzzy Logic Cooperative Adaptive Cruise Control (FCACC) scheme significantly enhanced truck platooning string stability by ensuring rapid stabilization and robustness against disturbances. The mathematical model designed and implemented in SUMO/OMNeT++ simulated various scenarios, demonstrating the superiority of the FCACC over conventional CACC, PATH CACC, and Ploeg CACC controllers. Quantitatively, the FCACC achieved velocity and spacing stability within an average of 7.33 seconds and 4.39 seconds using the triangular-centroid method, outperforming the CACC, PATH CACC, and Ploeg CACC by 28.09%, 25.21%, and 22.26% for velocity stability and 31.69%, 29.96%, and 28.01% for spacing stability, respectively. Additionally, the FCACC reduced the Expected Arrival Time (EAT) deviation by 4.62% compared to the CACC, demonstrating its efficiency in handling disturbances such as truck breakdowns. The FCACC's rapid stabilization, even in the presence of impulse signal disturbances, was evident in its ability to recover within 2.3 seconds for speed and 3.6 seconds for distance, compared to 27.5 seconds and 10.1 seconds for CACC. The fuzzy-PLEXE framework further emphasized the FCACC's advantage by inducing more minor distance errors and faster stability times than other models, achieving stability in 53 seconds versus 60 seconds for Ploeg CACC. These results underline the FCACC's efficacy in mitigating unexpected disruptions and maintaining optimal string stability. However, limitations such as dependency on precise sensor data, susceptibility to communication delays, and challenges with scalability for larger platoons were observed, suggesting areas for future optimization.

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1. INTRODUCTION

Over the years, there have been increments in the number of trucks moving on the highways [1]-[5]. This is due to the high growth of freight transportation because of its flexibility and accessibility, which makes it a brilliant alternative for freight shippers [6]-[10]. Truck platooning can be defined as a connection of two or more trucks moving in a specified direction with constant close distance (constant equidistance) between each other and maintaining a steady speed, using connectivity technology and automatic driving support systems [11]-[16]. This implies a group of vehicles that use driver assistance technologies to drive at a definite velocity in a convoy or a short-distance road chain. It has been shown in the literature that truck platooning has been shown to improve safety, efficiency, and productivity, reduce travel time, and reduce traffic congestion, pollution, and stress for travelers [17]-[19]. Truck platooning can be considered a prospective approach to alleviating the adverse effects of trucks on highway traffic streams [20][21]. Transportation industries benefit

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from less fuel consumption and higher driver productivity, while the public benefits from fewer accidents and less traffic [21][22].

Truck platooning is affected by some problems such as delay of platoons, which generate traffic trying to exit a highway, the inability of the trucks to maintain a constant inter-vehicular gap and speed, and unknown uncertainties related to what would happen during a crash or accident (disturbance) along the string in the platoon (string instability) [23]. From a practical perspective, it can be referred to as uncertainties of the system states amplified along the string of vehicles, which can cause the emergence of traffic congestion. A commonly used technique in literature is the Cooperative Adaptive Cruise Control (CACC) scheme to solve the problem of string stability in truck platooning [24]-[26]. CACC scheme comprises of the adaptive cruise control (ACC) and vehicle-to-vehicle (V2V) communication. The ACC is a cruise control system that regulates the distance and relative velocity of the vehicle, while the V2V communications enable the transfer of information between the vehicles [27].

Different techniques have been used for solving truck platooning problems. These include the Distributed Model Predictive Control (DMPC) for a heterogeneous platoon by [28], where each vehicle was assigned a local optimal control problem based solely on the information received from its neighboring vehicles; a cooperative distributed approach for creating and modifying truck platooning based on consensus algorithms was developed by [29]; a Robust Distributed Proportional Integral Derivative (RDPID) control scheme for tracking the lead truck with uncertainty connected with a V2V communication delay was developed by [30]; an adaptive neuro-fuzzy predictor-based control for the CACC System was developed by [31]; a Distributed Adaptive Sliding Mode Control (DASMC) of the vehicular platoon with uncertain interaction topology by [32]; a third-order consensus approach for vehicle platoon with inter-vehicle communication was developed by [33]; a learning-based stochastic MPC design for CACC for handling vehicles affected by interferences was developed by [34], etc. However, most of these techniques are limited in their flexibility for dealing with unexpected disturbances introduced into the platooning system.

2. METHOD

A mathematical model for truck platoon formation was developed and implemented using SUMO, OMNeT++, and the PLEXE framework, chosen for their distinct advantages. SUMO's open-source accessibility and capability to simulate complex traffic scenarios made it ideal for analyzing truck platoon dynamics [35][36]. OMNeT++ was selected for its ability to simulate communication systems, enabling effective modeling of vehicle-to-vehicle (V2V) communication within the platoon [26][29]. The PLEXE framework was utilized for its specialized support for platooning scenarios, including cooperative adaptive cruise control (CACC) and string stability evaluation, ensuring comprehensive simulation of both mobility and communication aspects [37]. The step-by-step procedure for developing the mathematical model and its implementation under this framework is discussed as follows:

2.1. Create the n^{th} number of a truck in a platoon as a state variable

The number of trucks in the platoon is defined as n, and the trucks are defined as x_i
Let T be the set of trucks in the platoon, then $x_1, x_2, x_3, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots x_n \in T$ i.e.

$$T = \{x_1, x_2, x_3, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots x_n\} \quad (1)$$

($x_i \in T$; where $i=1, 2, 3, \ldots\ldots, n$
The position (p) assigned to each truck in the platoon is presented as:
Let p be a function that determines the position of a car in the platoon
$P = \{p(x_1), p(x_2), p(x_3) \ldots\ldots p(x_n)\}$ then

$$P = \{p_1, p_2, p_3 \ldots\ldots p_n\} \quad (2)$$

2.2. Obtain the equidistance between the individual trucks in the platoon

The inter-vehicular distance (spacing) between the trucks is determined as:

$$\begin{gathered} \partial = p(x_{i+1}) - p(x_i) \\ \partial = p_{i+1} - p_i \end{gathered} \quad (3)$$

The total distance covered by each truck from source to destination is presented as follows:

Truck 1: $x_1 : D_c = \hat{\partial}$

Truck 2: $x_2 : D_c = \hat{\partial} - \partial$

Truck 3: $x_3 : D_c = \hat{\partial} - 2\partial$

Truck 4: $x_4: D_c = \hat{\partial} - 3\partial$
Truck 5: $x_5: D_c = \hat{\partial} - 4\partial$

$$\vdots$$

Truck n: $x_n: D_c = \hat{\partial} - (n-1)\partial$
Where ∂ Is the inter-vehicular distance between two trucks and $\hat{\partial}$ is the distance covered by each truck thus, for any number of trucks in the platoon, the total distance covered by each truck is computed as:

$$D_c = \hat{\partial} - (n-1)\partial \tag{4}$$

Where D_c is the total distance from the source to the destination without disturbance introduced to the string, and the time taken by each of the trucks to reach the destination is recorded as t. Thus, the speed of each truck is determined by:

$$speed = \frac{\hat{\partial} - (n-1)\partial}{t} \tag{5}$$

2.3. Introduction of disturbances along with the string stability of the truck platoon and obtaining the inter-vehicular distance and the speed covered for various scenarios at a time interval (t)

A disturbance(s) was introduced into the string in the form of a truck break, which resulted in pulling the truck from the string. This translates to an increase in the inter-vehicular distance between the trucks. The total distance covered by the trucks is computed as:

$$D_c = \hat{\partial} - (2n-2)\partial \tag{6}$$

$$speed = \frac{\hat{\partial} - (2n-2)\partial}{t} \tag{7}$$

Let Δ_d^t be a desired inter-vehicular distance at time t, where $d = 1,2,\dots,n$
Therefore $\Delta_d^t = \partial$
Let Δ_a^t be the actual inter-vehicular distance at time t>0, where $a = 1,2,\dots,m$
$\forall \Delta_d, \Delta_a \in D$, where D is the total distance covered
If $\Delta_d^t = \Delta_a^t \Rightarrow E_r = 0$
Definition 1: Let $\Delta_a^t, \Delta_d^t \in D \ni \xi_{(d,a)}$
Where $\xi_{(d,a)}$ is error function defined as:

$$\begin{gathered} \xi_{(d,a)} = [\Delta_d, \Delta_a]_\xi \\ \xi_{(d,a)} = |\Delta_a - \Delta_d| \end{gathered} \tag{8}$$

Definition 2: A catch-up strategy function is defined as:

$$\xi_{(d,a)} = \begin{cases} (\Delta_d - \Delta_a), iff\ \Delta_d > \Delta_a \forall \Delta_d, \Delta_a \in D \\ 0, otherwise \Delta_d = \Delta_a \end{cases} \tag{9}$$

Therefore, the catch-up speed is defined as:

$$U_{CU} = U_{AS} + \frac{\xi_{(d,a)}}{t_i} \tag{10}$$

Where U_{CU} is the catch-up speed, U_{AS} is the actual speed and $\xi_{(d,a)}$ is the error generated between the actual and the desired spacing within a time interval t_i.
Definition 3: A slow-down strategy function is defined as:

$$\xi_{(a,d)} = \begin{cases} (\Delta_a - \Delta_d), iff\ \Delta_d < \Delta_a \forall \Delta_d, \Delta_a \in D \\ 0, otherwise \Delta_d = \Delta_a \end{cases} \tag{11}$$

.

Thus, the slow-down speed is defined as:

$$U_{SD} = U_{AS} - \frac{\xi_{(a,d)}}{t_i} \tag{12}$$

Where U_{SD} is the slow-down speed, U_{AS} is the actual speed and $\xi_{(d,a)}$ is the error generated between the actual and the desired speed within a time interval t_i.

2.4. Development of Fuzzy-PLEXE using the FCACC Scheme for Simulation and Analysis of the Truck Platoon

The fuzzy-PLEXE was developed using the FCACC scheme developed for the simulation and analysis of the truck platoon. The following procedures were carried out:

2.4.1. Vehicle real acceleration

It is essential to obtain the vehicle's actual acceleration to be able to control the vehicle effectively. Thus, the first-order lag model was used to model the engine. For any input velocity signal $x(v)$, the vehicle's actual acceleration $a(t)$ must satisfy equation (13). The fuzzy-PLEXE uses a controller acceleration class to control the desired acceleration.

$$\tau \frac{da}{dt} + a = v \tag{13}$$

Where τ is the vehicle response time constant.

2.4.2. Vehicular Lane changer

In order to control the vehicle during navigation from one lane to the other, a lane-changing class module was implemented in the fuzzy-PLEXE. The lane changes module uses the existing driving environment to change lanes and enters the weaving section before finally reaching the off-ramp. The lane change sub-modules were designed using the decision process shown in Figure 1. Lane changing is a continuous process that allows merging and diverging. It entails target lane determination, generating the intention to change lanes, evaluating acceptable gaps, and executing the lane change.

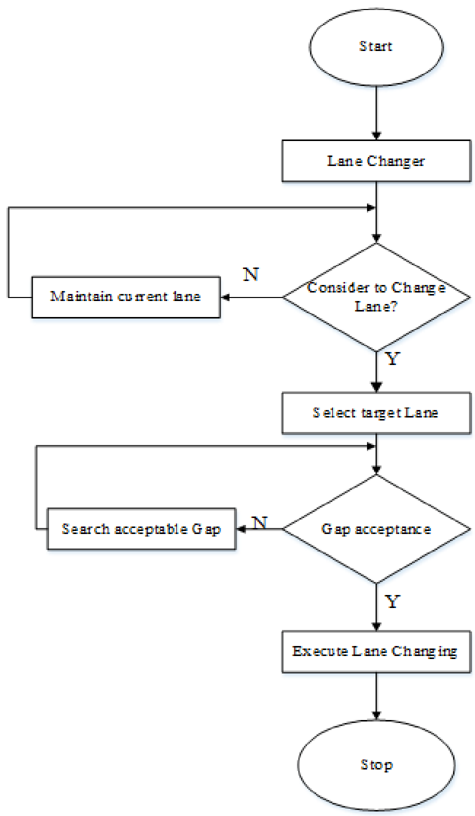

Figure 1. Flowchart of the Design for Lane Change Maneuver

2.4.3. Improved vehicular communication

To improve vehicular communications using OMNet++ network simulator and road traffic simulator SUMO, VeiNS was adopted based on its capabilities to improve the IEEE 802.11p communication stack. VeiNS allows the modeling of real node mobility, which is referred to as the mobility model. All OMNet++ nodes are associated with the network stack, IEEE 802.11p network interface, beaconing protocol, and other applications running on it. The veins update the vehicular mobility model by replicating each movement in each OMNet++ node. SUMO exposes Traci interfaces, coupled with both the traffic frameworks and network, which entails the status of the traffic (total vehicles in the platoon, speed, positions, amongst others). These interfaces from SUMO were queried, and their traffic dynamics were modified using veins. This modification involves altering the vehicle's routes and accelerations. PLEXE 3.0 was adopted and modified using a fuzzy controller to ease data interactions between the vehicles in the platoon and, as such, ease the vehicle platoon protocol applications. The extended schematic of the developed simulator is shown in Figure 2.

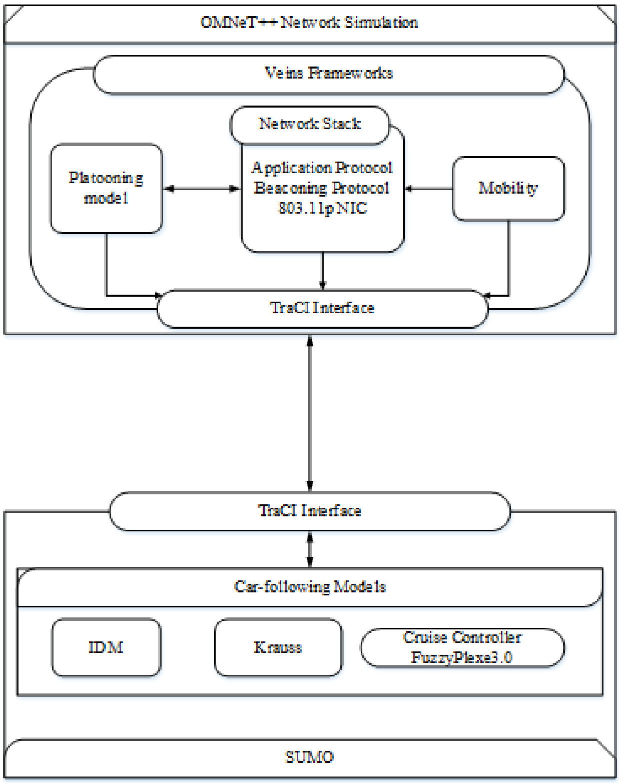

Figure 2. Extended Schematic of the Developed Simulator

3. COMPREHENSIVE THEORETICAL BASIS

3.1. Truck Platooning

Truck platooning consists of two or more vehicles traveling in a region with a short distance (regular adjustment) between them and maintaining the speed, using connectivity technology and driver support systems automatically [38][39]. Short spacing can be found between trucks using CACC. With the CACC method, there is communication between the trucks, thereby creating a platoon. Trucks in the platoon use radar and vehicle-oriented communication to interact with each other. Collaboration is important for a good distance between vehicles and safety. Besides, V2V collaboration or communication can eliminate storm surges and improve traffic [40]. Figure 3 shows an illustration of the truck platooning system.

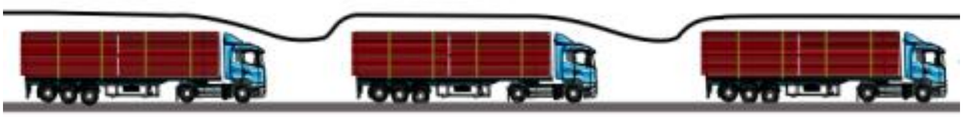

Figure 3. Illustration of Truck Platooning

3.2. String Stability

String stability is a property whereby the speeds or positions of the following vehicles will not be affected by the variances in the speed or position of the lead vehicle [41][42]. String stability could be a property that is attained through the data stream of the driving vehicle within the Constant Time Headway (CTH) approach, where the inter-vehicle communication is utilized to urge exact velocity/position data. Although the CTH uses the information flow of the leading vehicle to guarantee string stability, string stability is only achieved in a small or medium platoon. If the predecessor successor data stream is utilized, the velocities/positions of the preceding and succeeding vehicles can realize the string stability in a huge platoon. The plan of the truck platooning framework requires the integration of the spacing arrangement, data stream, and control scheme. String stability guarantees that the partition errors do not proliferate within the platoon. For that, a few strategies depend on vehicle-to-vehicle communication. Figure 4 illustrates the string along the truck platoon.

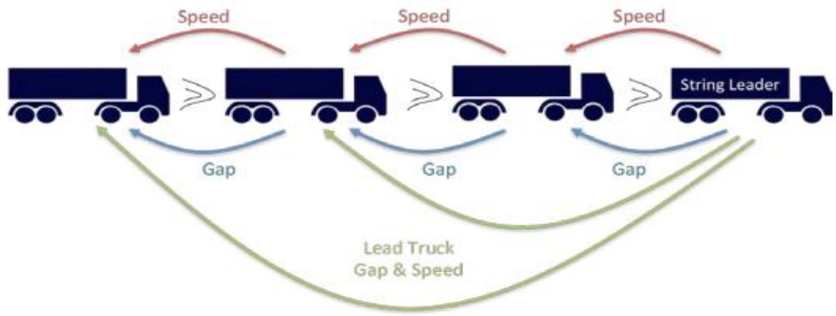

Figure 4. Illustration of the String Truck Platoon

3.3. String Instability

String instability occurs when there are disturbances and uncertainties along with the string propagation, such as a breakdown of a truck, loss of communication, and other sudden disturbances that may occur within the platoon, which can result in a collision of trucks within the platoon [43]. String instability can also be described as the amplification along the string of the response to a disturbance to the lead vehicle. If spacing errors and velocity errors amplify as they propagate upstream, this will result in string instability, which provides poor ride quality and likewise results in collisions. Disturbance is a signal that tends to affect the operation of a system either at the input, on the plant, or at the output [44]. It causes deviation (system error) from the desired or reference input signal compared to the actual output. Internal disturbance is generated within the system, while the one generated outside the system is called external disturbance. The impulse signal, as shown in Figure 5, is mainly used to test the effectiveness of the controller when a system is subjected to a disturbance.

$$\delta(t) = \begin{cases} At = 0 \\ 0t \neq 0 \end{cases} \quad (14)$$

If A=1, the impulse signal is called the unit impulse signal.

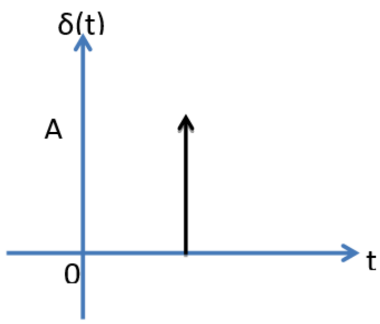

Figure 5. Impulse Signal

3.4. Adaptive cruise control system

Conventional cruise control is an example of a longitudinal controller that controls and maintains the velocity of a vehicle at a constant value. The control system cruise control works on the throttle to retain the reference velocity specified by the driver [45]. The cruise system can become useless in heavy traffic if the driver keeps setting the speed and/or disengages the control [46]. The ACC is a modified cruise control system with a distance sensor radar sensor and is equipped with an assisted braking system that regulates the distance and relative speeds between a vehicle and the following vehicle [47].

It has been noticed that most ACC users do not know about the ACC system limitations (system incapability to function at velocities below 30km/h) and have the false assumption that an ACC system would help avoid a collision. The areas suggested for the improvement of the limitations of the ACC systems are the occurrence of unsafe and uncomfortable reduction or increase in the speed and the sensitivity of the system.

The positive impact of the ACC system includes safety, comfort, and traffic throughput as well. However, the conventional ACC system suffers from the inability to enable a string-stable platoon. Also, the effect of traffic throughput is insignificant because of the significant time gap generally selected for the ACC system. Therefore, quick advances and consistent wireless communication have led to the development of the CACC.

3.5. Cooperative Adaptive Cruise Control

CACC, being one of the promising Intelligent Transport System (ITS) technologies, extends the currently available ACC technology with the addition of information exchange between vehicles through V2V and V2I wireless communication [26][48]. To overcome the sensory limitations of human- or ACC-enhanced vehicles, wireless information exchanges are provided to significantly improve the traffic flow of vehicles, especially on the highway. Information exchange between vehicles includes status and topography of the road ahead, speed and distance of the vehicle, which can have a great impact on the fuel economy of heavy-duty vehicles. By providing additional information to the controller, wireless communication can contribute to maintaining the stability of the platoon as well. For this research, the CACC was used to maintain the constant velocity and equidistance between the trucks in the platoon.

3.6. Mode of Data Transmission

There are various modes of data transmission when sending packets from the sender to the receiver [49]-[51]. However, the commonly used modes of data transmission in truck platooning include broadcast, unicast, and multicast.

3.6.1 .Broadcast mode of data transmission

In data transmission broadcast mode, packets are sent from one node to various nodes in the communication range using the bandwidth of the resources to provide the information, with a safe distribution of packets that share the usual updates, road conditions, and improved delay. The main shortcoming of this type of routing is the problem of collision overload.

3.6.2 .Unicast mode of data transmission

In unicast data transmission mode, packets are sent from one point to another. It only involves one sender and one receiver. In this case, packets have been sent from a single source to a specified destination. Unicast is the predominant form of transmission on LAN and within the internet. The major disadvantage of this protocol is that there is a delay in the transmission of data.

3.6.3 .Multicast mode of data transmission

In multicast data transmission mode, packets are sent from one or more points to a set of other points. In this case, there may be one or more senders, and the information is distributed to a set of receivers.

4. RESULTS AND DISCUSSION

The result of the developed mathematical model was presented and discussed as follows:

$$speed = \frac{\hat{\partial} - (n-1)\partial}{t} \tag{15}$$

$$speed = \frac{\hat{\partial} - (2n-2)\partial}{t} \tag{16}$$

.

$$D_c = \hat{\partial} - (n-1)\partial \tag{17}$$

Where Equations (14)-(16) represent the speed of trucks without disturbance, speed of the trucks with disturbance and the estimated distance covered by the trucks.
The catch-up strategy model is defined as:

$$U_{CU} = U_{AS} + \frac{\xi_{(d,a)}}{t_i} \tag{18}$$

The slow-down strategy model is defined as:

$$U_{SD} = U_{AS} - \frac{\xi_{(a,d)}}{t_i} \tag{19}$$

Figure 6 presents the developed CACC-enhanced trucks in the platoon without any disturbance being introduced into the system as they move to the destination from the base station. The trucks maintain a constant inter-vehicular distance and speed of 13.65m and 15m/s respectively. For smooth movement of the trucks, the lead truck (Veh0) transfers information to the follower trucks in the platoon so as to avoid crashes or collisions of trucks within the platoon and to prevent intruder vehicle(s) from coming in between the trucks.

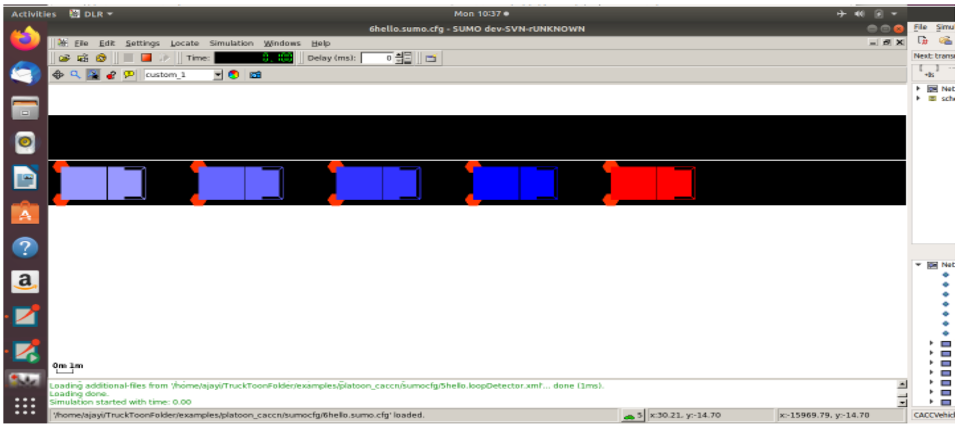

Figure 6. Developed CACC Enhanced Trucks without Disturbance in SUMO/OMNET

Figure 7 presents the developed CACC-enhanced trucks in the platoon, with disturbances introduced into the system. It can be seen that the disturbance was introduced on Truck 3, and the effect of the disturbance pulled it to the second lane. Thus creating a more considerable inter-vehicular distance between Truck 4 and Truck 2. The affected Truck 3 passes information to the preceding truck, Truck 2, at the sudden breakdown point. As Truck 3 is totally out of the platoon, it is completely out of communication range from the other trucks in the platoon. This is why it changes to yellow in the second lane.

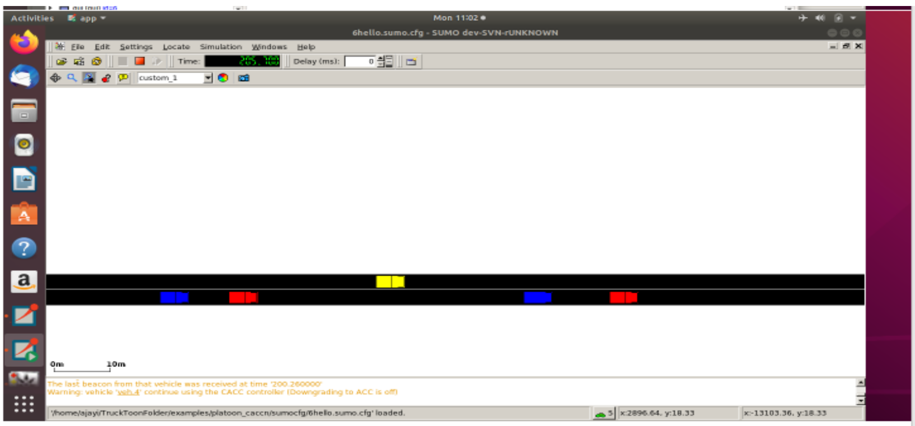

Figure 7. Developed CACC Enhanced Trucks with Disturbance in SUMO/OMNET

The response plot of the speed of the trucks as a function of time without the introduction of disturbance into the platoon system is illustrated in Figure 8. It can be seen that the initial motion of the trucks as they retardate for a period of 10s with different initial speeds to form the platoon at the take-off station (based station at 3m) with an initial spacing of 3.10m. The trucks then accelerate after 4.5s to enable each truck to take off at the base station to meet the desired speed of 15m/s and desired spacing of 13.65m. The truck platoon was restored to speed stability at about 12.2 seconds.

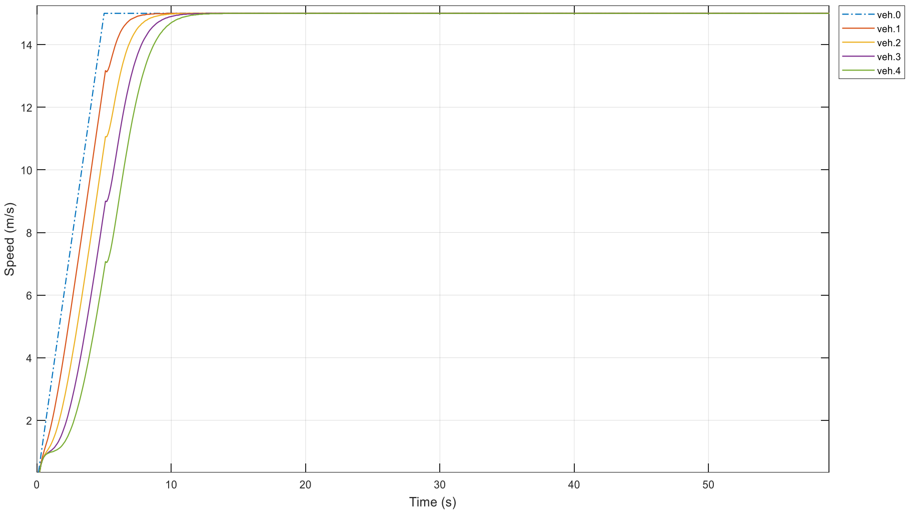

Figure 8. Speed Response Plot

Figure 9 shows that the trucks in the platoon maintain a spacing of 3.10m from each other, which increases to 13.65m as the trucks decelerate to rest. As the trucks accelerate from zero to 15m/s, the spacing increases to the desired value which is maintained until the target destination is reached. The truck platoon attains spacing stability at about 12.2secs.

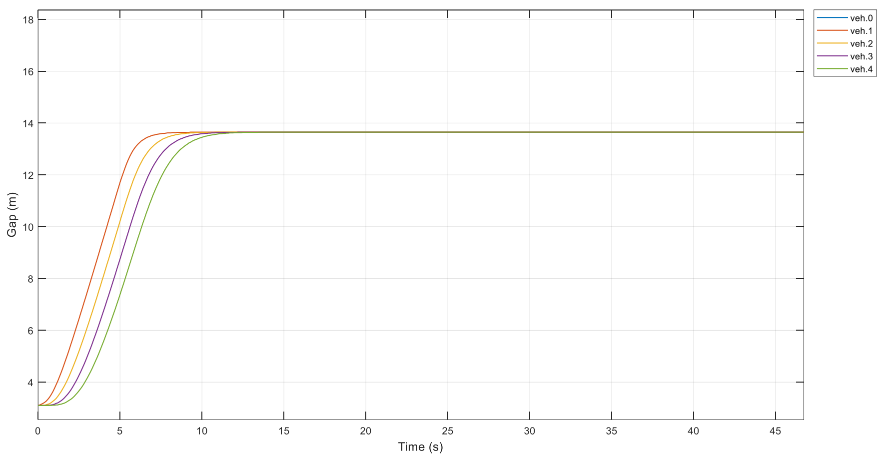

Figure 9. Spacing Response Plot

The speed response plot of the trucks in the platoon system, when an impulse signal was introduced as a disturbance on the CACC trucks (truck2 in this instance), is presented in Figure 10. From it (Figure 10), it can be seen that the disturbance was introduced after the trucks had attained the desired speed of 15m/s at 10secs. This resulted in the increase in spacing between truck1 and truck3, which is termed a spacing error. The CACC controller does not have the flexibility capacity to handle the sudden impulse disturbance on truck2, thereby resulting in the speed variation from 15m/s to 29.5m/s of the follower trucks for almost 10.1secs before attaining stability again.

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Figure 11, on the other hand, shows the effect of the disturbance after the trucks have attained the desired spacing of 13.65m, which can be seen at 10.1s. This resulted in the increase in spacing between truck 1 and truck 3. The CACC controller does not have the required flexibility to handle the sudden disturbance on truck 2, thereby resulting in the spacing variation (from the desired) for almost 10.1s. The undesired spacing and the time taken to make it up may enable another vehicle to disrupt the flow of the platoon. Thus, there is a need for a controller that can handle disturbances as fast as possible to avoid such intrusion.

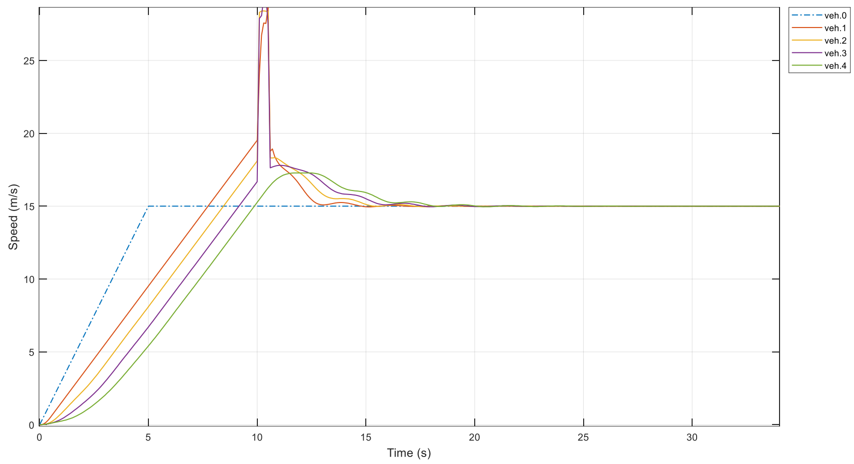

Figure 10. Speed Response Plots with Disturbance Introduced on Truck2

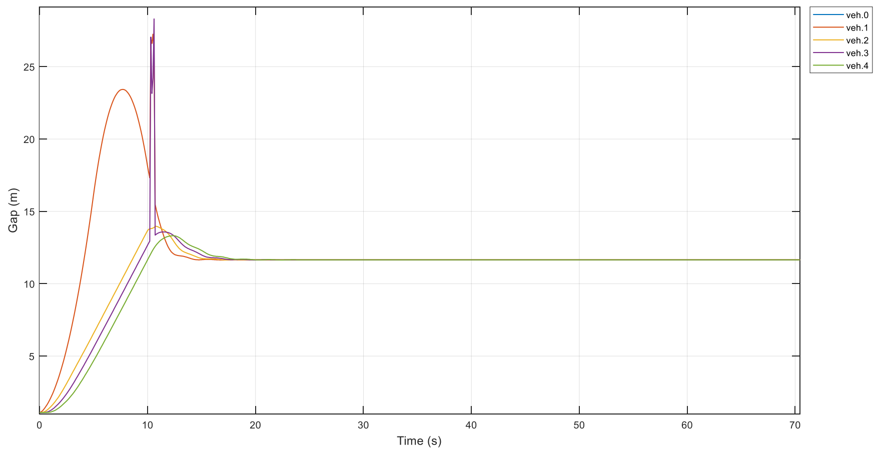

Figure 11. Spacing Response Plots with Disturbance Introduced on Truck2

The speed response plot of the trucks with disturbance into the platoon system on truck 4 is shown in Figure 12. It can be seen that the disturbance was introduced after the trucks had attained the desired speed of 15m/s, at t=15.7s. This increased spacing between truck 3 and truck 5, which is termed a spacing error. The FCACC accepts this error and implements a catch-up strategy on truck5 with a speed of 10m/s and a slow-down strategy on truck 3 until the spacing error is cleared at t=2.3s and spacing as shown in Figure 12.

It can be seen in Figure 13 that at about 15.7 seconds, truck 4 was pulled out of the platoon to the second lane, leaving four (4) trucks in the system with an error in spacing between truck 3 and truck 5. Thus, the spacing decreases due to the implementation of catch-up and slow-down strategies by the FCACC controller until the desired spacing is achieved. The controller restored the desired spacing at the time, t=0.6s, irrespective of the magnitude of the disturbance introduced.

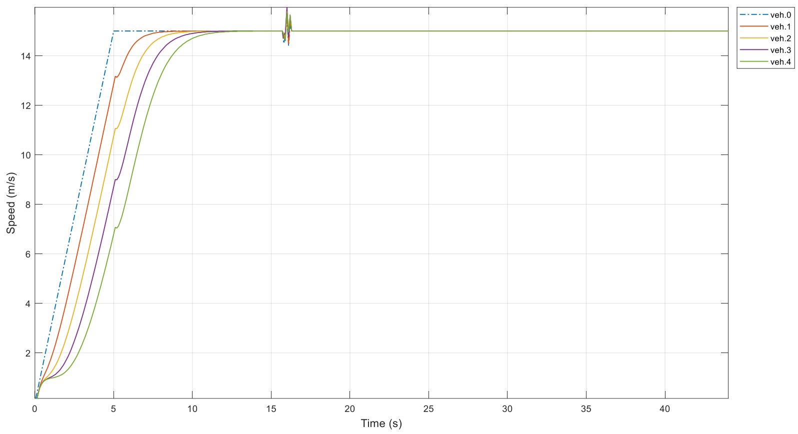

Figure 12. Speed Response Plots with Disturbance Introduced on Truck4

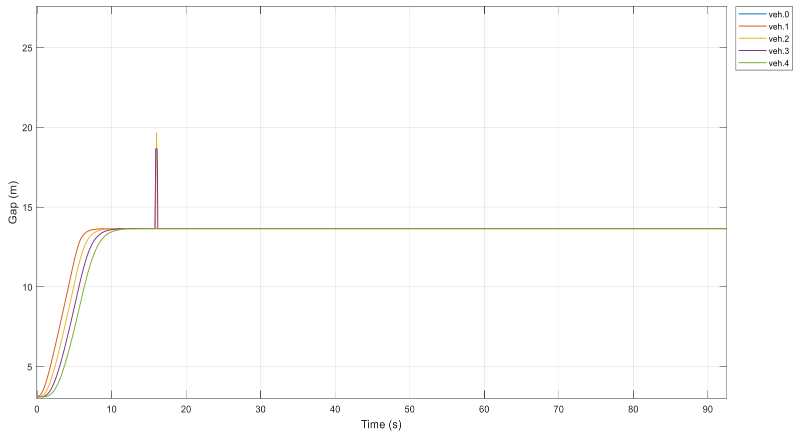

Figure 13. Spacing Response Plots with Disturbance Introduced on Truck4

5. CONCLUSION AND LIMITATION

The study aimed to develop a head gesture-controlled robot with an accelerometer sensor to assist individuals with disabilities by translating head movements into precise robotic actions. During the development and testing, the system demonstrated substantial functionality, with the accelerometer sensor accurately capturing head gestures and translating them into corresponding movements, enhancing accessibility for users with limited mobility. Quantitatively, the robot achieved a high accuracy rate in interpreting head gestures, proving reliable across different tests, and its lightweight and compact design allowed for easy navigation in confined spaces, expanding its usability in practical settings. However, several limitations surfaced, particularly concerning scalability and sensitivity. The sensor's accuracy diminished in environments with significant vibrations and external noise, indicating a potential limitation in broader, dynamic settings where such disturbances are common. Additionally, the system required recalibration for each user due to variability in individual head movements, posing a challenge for large-scale implementation. Mechanical constraints restricted the robot's speed, which could limit its application for tasks requiring rapid response times. Future research should enhance the system's robustness to external interferences like vibrations and noise by integrating noise-canceling algorithms or more sophisticated sensors. Investigating alternative sensor technologies or hybrid systems that combine multiple sensors could also improve disturbance resilience, making the robot more adaptable to diverse environments. Developing a user-independent calibration method would also simplify setup and increase accessibility, thereby addressing scalability issues. Modifying the mechanical structure to allow higher speeds could expand the robot's utility for a broader range of applications, including time-sensitive assistance tasks. Implementing these advancements could significantly enhance the effectiveness and flexibility of the robot, promoting wider adoption and encouraging further development in assistive robotics for people with disabilities.

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