Safety-based Platoon Driving Simulation with Variable Environmental Conditions

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Abstract: In platoon driving, a group of autonomous vehicles drives by forming one platoon to achieve advantages such as fuel efficiency and traffic congestion reduction. Ensuring the safety of such a platooning system is very challenging due to unexpected driving conditions e.g., adverse weather and obstacles on the road. Therefore, the safety of a platooning system should be guaranteed even in variable weather conditions. In this paper, we investigate the platooning system's unexpected behavior due to adverse weather conditions and provide safety guards to avoid potential hazards. Simulation techniques are essential to confirm that the designed safety guards work correctly, because testing such systems in a real situation can be highly expensive. Therefore, we extended VENTOS, an open-source platoon driving simulator to verify the provided safety guards, which can prevent risks under diverse weather scenarios e.g., fog, rain, snow, etc. Our simulation results show that the proposed safety guards for adverse weather conditions can enhance the safety of the platooning systems.

1 INTRODUCTION

Nowadays, autonomous vehicles have become one of the emerging technologies, and they can be a standard way of transportation in the near future (Bagloee et al., 2016). An autonomous vehicle is a type of Cyber-Physical System (CPS) that collects information about the road environment using various sensors like camera, radar, and LIDAR (Light Detection and Ranging sensors), and then actuates through actuators like engine and steering based on the information. An autonomous vehicle that drives by itself is a safety-critical system that can lead to significant hazards, such as loss of life and injury, etc., if the safety of such a safety-critical system is not ensured properly (Kalra, 2017).

Several standards are published or being developed to guide and ensure the safety of autonomous vehicles. ISO 26262 standard (ISO 26262, 2018) addresses the safety associated with the entire life cycle of all electrical-electronic equipment mounted on a vehicle. Other standard ISO/PAS 21448 (ISO/PAS 21448, 2019) was published to address the safety of the intended functionality. The other standard ISO/SAE FDIS 21434 (ISO/SAE FDIS 21434, n.d.) is under development to protect vehicles from cybersecurity attacks.

Despite these efforts, it is very difficult to achieve rigorous safety for autonomous vehicles (Koopman & Wagner, 2016). Autonomous driving in a platoon is even more difficult, in which several autonomous vehicles are driven by forming one platoon with a narrow distance between vehicles. In platoon driving, member vehicles exchange information with each other using V2X (Vehicle to Everything) wireless communication so that each vehicle can grasp surroundings and respond agilely. The platooning system, a representative example of collaborative CPS, is recently in the limelight due to several advantages such as enhanced traffic throughput, lower energy consumption, pollution reduction, and so on (Jia et al., 2015). These benefits are due to the narrow distance between member vehicles. The narrow distance can be obtained by collecting real-time data about the other vehicles in the platoon. This is achieved by using the Cooperative-Adaptive Cruise Control (C-ACC) technique (Milanés & Shladover, 2014; Xiao et al., 2017).

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A number of studies have been conducted to ensure the safety of platoon driving (Xu et al., 2014; Rahman & Abdel-Aty, 2018). In particular, variability occurred in complex road environments can have great risks due to its difficulty in predicting and reproducing the situation. The possible risks from variability like changeable weather conditions must be considered in the development phase of a platoon driving application. Although the ISO/PAS 21448 standard addresses risks that may be arisen due to environmental variability, it is hard to find relevant previous research in the platoon driving domain.

In this paper, we investigate environmental variability (e.g., fog, rain, snow, etc.) in platoon driving in order to provide safety guards to reduce the risks caused by the variability. Considering diverse scenarios, we defined a number of safety guards to ensure platoon driving safety, particularly in case of an unexpected scenario. Also, validating the safety guards with real vehicles on real roads requires high costs due to limited environments and potential accidents. Thus, it is necessary to validate them through simulation. Now, several simulators are available for platoon driving. However, they did not consider risks such as diverse environmental conditions and also did not reflect such safety requirements. Therefore, in our work, we extend an open-source platoon driving simulator, named VENTOS (VEhicular NeTwork Open Simulator) (Amoozadeh, 2015) (VENTOS, n.d.), to reflect the safety requirements for variable environmental conditions. We simulate and analyze the effects of safety guards designed to reduce the corresponding risks to the variable environments with platoon driving case study.

2 VARIABILITY AND SAFETY GUARD IN PLATOON DRIVING

The goals of platoon driving are to reduce fuel consumption and traffic congestion. However, the degree of achieving safety goals is highly dependent on the distance between member vehicles in a platoon. The smaller the distance, the more aerodynamic drag is reduced. However, the smaller distance may lead to safety challenges of stable driving and collision avoidance, and also serious risks in platoon driving can bring out the loss of life. The variable environments can have a significant impact on the safety of autonomous vehicles. In the following subsections, we first categorize possible variabilities in the autonomous platooning system that may lead to a number of uncertainties. After the classification, we focus on environmental variability with a number of variable scenarios, and define safety guards to avoid dangerous situations during runtime.

2.1 Variability in Platoon Driving

2.1.1 Variability in CPS Applications

We classified potential variabilities that may lead to uncertainties in CPS applications as below (Ali et al., 2020):

- Environmental variability
- Physical variability
- Spatial variability
- Temporal variability

Environmental variability refers to the variabilities that affect the performance of sensors and actuators of CPS, such as dense fog, heavy rain, strong sunshine, snow, etc. The physical variability can be occurred due to a diverse set of hardware devices or due to heterogeneous communication infrastructure. Spatial variability is the variability caused by spatial interference of CPS by other CPS or other near objects. And temporal variability is the variability caused by unexpected time differences in systems like response time delay, the overhead of the system etc.

Table 1 lists typical examples of applying the above classification of variability to platoon driving.

Table 1: Examples of variability in platoon driving.

Variability Type	Examples
Environmental variability	Fog, Ice, Heavy rain, Snow, Strong wind, and Sunshine.
Physical variability	Battery aging, Tire wear, and LIDAR power degradation.
Spatial variability	Distance from another vehicle, and Garbage dumped on the road.
Temporal variability	Communication response delay, and Overhead of ECU in the vehicle.

2.1.2 Environmental Variability in Platoon Driving

Environmental variability was included in the scope of the ISO/PAS 21448 standard published in 2019. This standard, also named SOTIF (Safety of the Intended Functionality), is established to reduce the risks that can be occurred without functional failure. Table 2 shows the topics covered by the ISO/PAS 21448 standard.

Table 2: Safety relevant topics addressed by the ISO/PAS 21448 standard (ISO/PAS 21448, 2019).

Source	Causes of the hazardous event
System	▪ Performance Limitations or insufficient situation awareness, with or without reasonably foreseeable misuse. ▪ Reasonably foreseeable misuse, incorrect human-machine interfaces.
External factor	▪ Impact from car surroundings (other users, 'passive' infrastructure, environmental conditions: weather, Electro-magnetic interference, ...)

Although several factors are involved in environmental variabilities, our investigation focuses on the following variable elements to ensure safety in platoon driving:

- **Cloud:** Cloud reduces the light intensity, which can cause performance limitations on the camera sensor.
- **Rain:** The road may be slippery, increasing braking distance by rain. It reduces the perception of the vision systems in object recognition.
- **Fog:** Fog affects the camera vision system, making it difficult to distinguish road conditions and other objects.
- **Snow:** Snow increases braking distance by freezing the road and hinders the correct steering of the vehicle. Also, piled snow can disturb the vision system by covering its lens.
- **Cold Weather with Rain:** Cold weather with rain can make black ice (a.k.a. an assassin on the road).
- **Heatwave:** Overheated Engines can cause a fire.
- **Strong Wind:** Strong wind interferes with vehicle controls especially when crossing bridges or high-level roads.
- **Strong Sunshine:** Strong sunshine hinders the detection of forwarding objects. And it can cause performance limitation in vision systems.

2.2 Safety Guards for Platoon Driving

2.2.1 Types of Safety Guards for CPS Applications

CPSs are a safety-critical system that requires safety guards to prevent dangerous situations. These safety guards can be classified into two; safety guards for pre-identified hazardous situations and safety guards for unidentified hazardous situations (Wu et al., 2017). The first one is reflected in the system specification and then becomes part of the intended functionalities in the system. The ISO/PAS 21448 standard suggests continuous modification of functions to avoid identified risks. However, it is impossible to identify all possible risks at the design time of the system. Thus, as the second one, we provide the safety guards for the potential risks which are unknown at design time or training time.

2.2.2 Safety Guards and Its Roles

Representative safety guards and their roles applied to platoon driving are given as below:

- **Slowdown:** Slowdown of vehicle speeds is an essential safety guard in almost cases under all members slowdown simultaneously.
- **Speed Up:** In certain situations, speeding up may be necessary to avoid rear-end collision.
- **Lane Change:** In certain situations, an accident can be avoided by lane changing from a hazardous lane.
- **Distance Gap Adjustment:** Increasing or decreasing the distance gap between vehicles in the platoon can help to get more safe distance or achieve the goal of platoon driving.
- **Platoon Splitting:** In the case of a large size platoon, communication can be a problem due to signal coverage. Therefore, splitting the platoon into smaller sizes can increase the stability of the platoon.
- **Dissolution:** In certain situations, it can be difficult to maintain platoon driving (e.g., malfunction of a participant vehicle in the platoon). In this case, the platoon can be dissolved to promote safety at the individual vehicle level.
- **Distance Expansion with Outsiders:** Increasing the distance between a platoon and another platoon (or other vehicles) is an essential task to ensure safety in platoon driving.
- **Propagation of Hazardous Situation:** Platooning vehicles can receive information from RSU (Road-Side Unit) or other vehicles. Meanwhile, vehicles can transmit traffic information to other vehicles and RSU using V2X communication.
- **Emergency Alert Signal Operation:** Sending alert and blinking signals to surrounding vehicles can prevent an additional hazardous situation.

The real world is dynamic, therefore, predicting all hazardous situations is impossible. Although state machine is considered to design and analyze each safety guard for the hazardous situation, it can cause state explosion and further increase the complexity of the system (Kress-Gait, 2011). Therefore, it is efficient to design the safety guards in advance without considering hazardous situations, then select and apply appropriate safety guards in order to counteract the specific situation.

3 EXTENSIONS OF VENTOS

3.1 VENTOS Platoon Driving Simulator

VENTOS is an open-source simulator developed by UC Davis University to support platoon driving. VENTOS simulator is a combination of two open-source simulators; the road traffic simulator SUMO (Simulation of Urban Mobility) (Behrisch, 2011) (SUMO, n.d.) and the network simulator OMNET++ (Objective Modular Network Testbed in C++) (Varga, 2010) (OMNET++, n.d.). In the VENTOS simulator, many kinds of platoon driving strategies such as platoon merging, platoon splitting, and leaving from the platoon are implemented well. In particular, the TraCI (Traffic Control Interface) included in SUMO provides a convenient interface for simulation control from external.

However, VENTOS had been developed primarily with considering functional requirements only for platoon driving. Safety of platoon driving was not considered in VENTOS development. Therefore, it is inappropriate to simulate possible risks and safety guards in the development of platoon driving application, as it had been constrained that no risks occur during platoon driving. Hence, this paper extends the VENTOS by modifying its source code so that it can be used for verifying the safety of platoon driving. Such extensions should be utilized the scenario-based verification for hazardous events presented in the ISO/PAS 21448 standard.

3.2 Implementation of the Effects of Variability

For the realization of our scenarios for safety guards, the source code of VENTOS were modified, and some other modifications were made to SUMO. This subsection briefly explains every implementation or modification that is performed to SUMO.

In VENTOS, each vehicle determines its behavior through the *planMove* function. These determined results of the *planMove* function are executed in the *updateState* function for the actual run. The risk imposed by environmental variability cannot be considered to determine the motion of the vehicle. Therefore, implementing variability in the *updateState* function can lead to unexpected movements of vehicles by external influences. In particular, sensor problems can lead to unusual values delivery to the ECU of the vehicle. In this case, the vehicle makes unreasonable decisions that are not suitable for the actual environment.

Determining acceleration and deceleration is the most important action for platooning vehicles. The acceleration or deceleration of a platooning vehicle is decided in the function *followSpeed* within the *carFollowingModel*. We added the unexpected acceleration or deceleration by modifying the source code of the function *followSpeed*.

3.3 Implementation of Safety Guards in Platoon Driving

Safety guards for abnormal situations can be implemented in the function *planMove* in SUMO that determines the behavior of platooning vehicles. Otherwise, it is also possible to implement safety guards in VENTOS itself and provide it to SUMO simulation via TraCI. This allows for the implementation of more appropriate and diverse safety guards, especially in the context of platoon driving.

4 SCENARIO VALIDATION

To demonstrate that our simulation approach is useful to verify the safety of platoon driving, we prepare a scenario in which environmental variability factors are considered as follows.

4.1 Definition of the Scenario

We define a scenario to validate our approach. As shown in Figure 1, the eight same vehicles are driving by forming a platoon on the expressway which has two lanes in one direction. The red-colored vehicle is the leader of the platoon and member vehicles of the platoon are shown in gradational blue color. The platoon is driving in the first lane of the highway with a target speed of 25 m/s (90 km/h) and a time-gap of 0.7 seconds. The first lane is occupied for autonomous vehicles or platoons recommended by the Automated Highway System (AHS) (Fenton &

Mayhan, 1991). The configuration of this platoon is shown in Table 3.

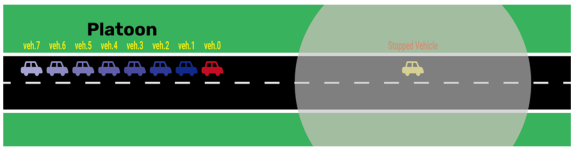

Figure 1: Simulation Map.

Table 3: Platoon Configuration.

Vehicle ID	veh.0	veh.1	veh.2	veh.3	veh.4	veh.5	veh.6	veh.7
Depth	0	1	2	3	4	5	6	7
Roll	Leader	Followers						
Color	Red	Deep Blue – – – – – – – – – – Light Blue						

In our scenario (Figure 1), a vehicle in the dense foggy area marked with a gray circle has low visibility of the distance about 50 meters. Also, in the middle of the foggy zone, there is a yellow vehicle that has stopped due to a malfunction. This scenario poses a serious safety concern if the leader could not recognize the stopped car in the foggy zone. In this case, an appropriate safety guard should be applied to the leader vehicle to avoid the risks from the dense fog.

4.2 Implementation and Results of Hazardous Scenario

4.2.1 Implementation of Variability

To simulate the hazardous scenario, we inject the dense fog effect into the VENTOS. The variable *frontGap*, which means the distance to the preceding vehicle, and used in the vehicle's speed determination algorithm, is modified to recognize the presence of foggy situation. An object laid more than 50 meters away will be not recognized by the vision system of the vehicle in our scenario.

4.2.2 Results and Evaluation of Hazardous Scenario

Results: After implementing dense fog in VENTOS, the results of the simulation are shown in Figure 2. The explanation of each scene are as follows:

(1) Vision systems without fog recognition do not identify any vehicle ahead. Until the distance to the forward vehicle reaches up to 50 m, the platoon leader continues to drive at a speed of 25 m/s without recognition of the yellow vehicle that has stopped at the front location.
(2) As the leader vehicle approaches the broken-down vehicle, the vision system suddenly recognizes the vehicle and starts to suddenly brake.
(3) However, due to not enough time to stop safely, a collision has happened between the platoon leader and the broken vehicle (Figure 2, marked by white dots).
(4) Because of this accident, a series of five rear-end collisions happened. However, the fifth vehicle in the platoon succeeded in stopping without a collision.
(5) After series of collisions, the platoon initiates the platoon splitting maneuver for member vehicles. The fifth vehicle acquires a roll of new platoon leader, three following vehicles of the new leader join the new group.
(6) The new platoon moves to the second lane for continuous driving.
(7) The new platoon passes by the accident location.
(8) The new platoon returns to the first lane again to continue platoon driving on the recommended lane for platoon driving.

Figure 3 shows the analysis results of the above scenario. The speed graph represents that the platoon leader encounters the first collision in 42.6 seconds. The front space gap graph represents zero distance from the vehicle ahead at that moment. The leader of the newly formed platoon begins to accelerate again by changing lanes in 56.6 seconds, as shown in the scenario of Figure 2 (6).

Evaluation: The dense fog caused a series of five collisions by continuing to drive at high speeds without recognition of the object in a dense foggy area. Therefore, safety mechanisms are needed to avoid potential collisions in such changeable weather conditions on roads. In section 4.3, we implement the safety guards for such kinds of scenarios and show the avoidance of potential collisions.

4.3 Implementation and Results of Safe Scenario

4.3.1 Implementation of Safety Guard

We implemented the safety guards for dense foggy situations. The variable environmental situations such as dense fog can be recognized by the enhanced vision systems of the autonomous vehicle. Once the dense fog is recognized, the safety mechanisms should be initiated to avoid risks like collisions. We provide a safety guard *Slowdown* that decreases the speed of the leader vehicle to a safe speed. The speeddown vehicle can stop at a short distance within detection coverage of the radar sensor. Additionally, if dense fog is recognized, a message is sent to the platoon members via V2V communication in order to turn on the emergency alert signal.

Algorithm 1 is implemented for the safety guards in the VENTOS framework.

Algorithm 1: Safety guard for dense foggy situation.

```
1  if (fogRecognition):
2      fogWarn = true
3      turnOnEmergencyAlertSignal()
4      sendMsg(turnOnEmergencyAlertSignal)
5      setTargetSpeed(15)
6  else:
7      fogWarn = false
8      turnOffEmergencyAlertSignal()
9      setTargetSpeed(25)
```

The detailed explanations of Algorithm 1 are as below:

From lines 1 to 5 of Algorithm, line 1 means the actions that a foggy situation is recognized by the vision system of the platoon leader. In line 2, it sets the variable `fogWarn` to be true.

In lines 3 and 4, the leader turns on its emergency alert signals. Then it makes all follower vehicles in the platoon turning on the emergency alert signals to warn other vehicles via V2X communication.

In line 5, the platoon leader decelerates its target speed to 15 m/s (54 km/h). It makes follow vehicles in the platoon also decelerate accordingly.

The lines from 6 to 9 mean the actions of the leader after escaping the foggy zone. When the leader goes out of the foggy zone, it sets the variable `fogWarn` back to false, and turns off emergency alert signals, and returns the target speed to 25 m/s, then accelerates to the target speed.

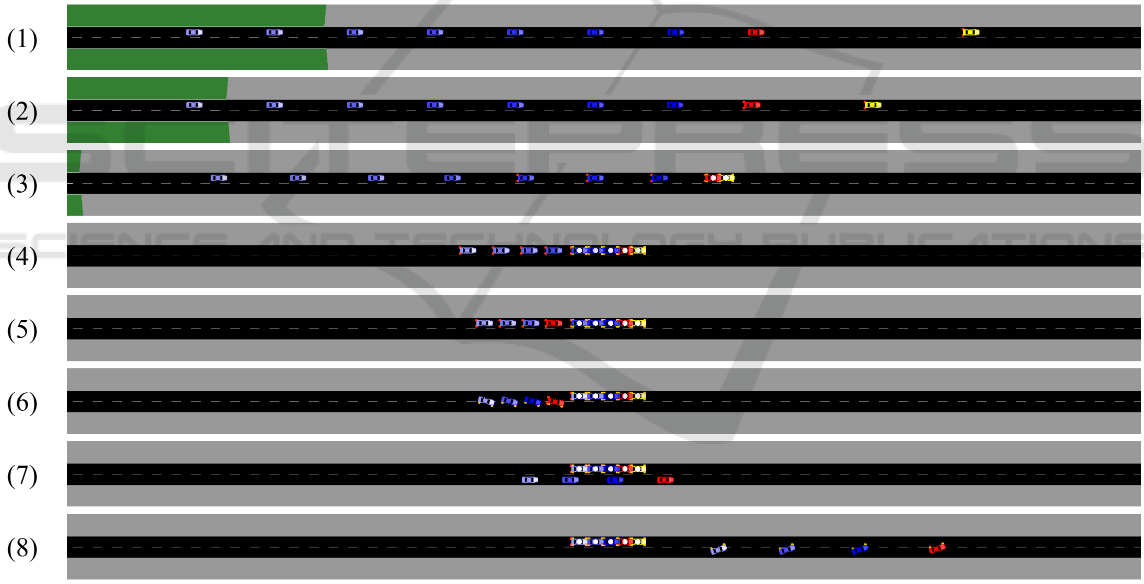

Figure 2: Simulation Scenes of Hazardous Scenario.

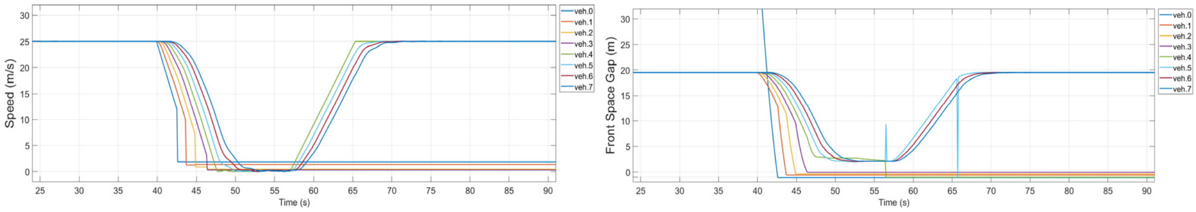

Figure 3: Simulation result of speed (left) and inter-vehicle distance (right) for hazardous scenario.

4.3.2 Results and Evaluation of Safe Scenario

Results: Simulation results with safety guards are shown in Figure 4. We explain each scene one by one as follows.

(1) When the vision system of the platoon leader recognizes the fog, it turns on its emergency Alert signal and decelerates to a low speed that can be safely stopped in a short distance.
(2) Despite the sudden appearance of a broken-down vehicle, the leader vehicle was able to stop safely with a sufficient distance.
(3) After identifying the surrounding conditions of the road, the entire platoon changes the lane to the second one.
(4) The platoon bypasses the broken vehicle.
(5) The platoon returns to the first lane to keep the platoon driving.
(6) After escaping the dense foggy zone, the platoon begins to perform normal driving again as shown in Figure 4 (6).

Figure 5 shows the analysis results of the vehicle movement in the safe scenario. At the time 34.2 seconds, the platoon leader recognizes that it encounters a foggy zone and begins to decelerate. The platoon leader then maintains a low speed of 15 m/s and then stops safely even if the broken vehicle appears ahead suddenly. The platoon then changes lanes in 51.7 seconds by identifying the surrounding situation. Then the leader vehicle increases the speed again to 25 m/s after escaping the foggy zone from 68.5 seconds.

Evaluation: The designed safety guards *Slowdown* and *EmergencyAlertSignalOperation* were able to conduct properly to prevent accidents occurring in hazardous scenarios (dense fog). Such safety guards can be used to avoid potential risks in a variable environment.

5 CONCLUSIONS

In our work, we investigate how to reduce the risks that may arise due to environmental variability in platoon driving. For this purpose, we first investigate environmental variability in platoon driving and analyze the characteristics of safety guards to reduce potential hazards. We also utilize VENTOS, an open-source platoon driving simulator, to simulate diverse scenarios reflecting environmental variability (e.g., fog, snow etc.) and proposed safety guards to avoid the potential hazards at runtime. The findings in this

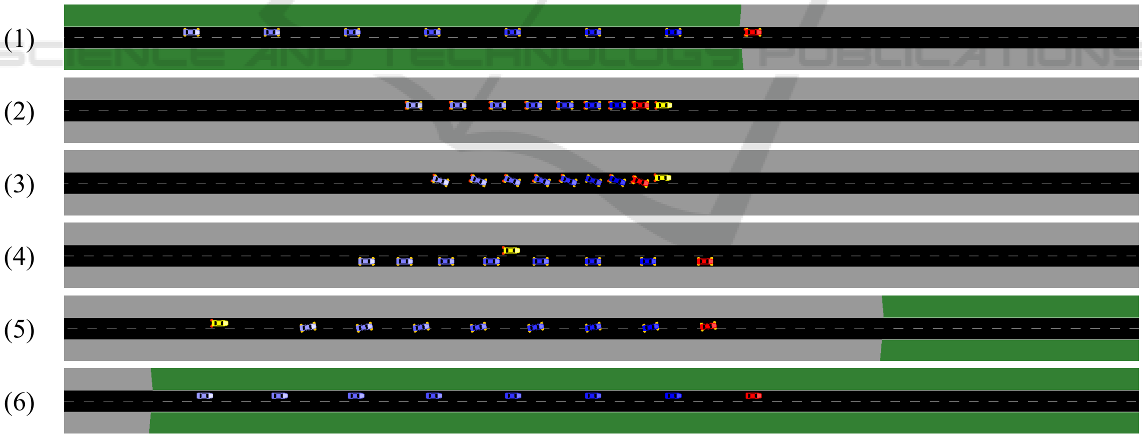

Figure 4: Simulation Scene of Safe Scenario.

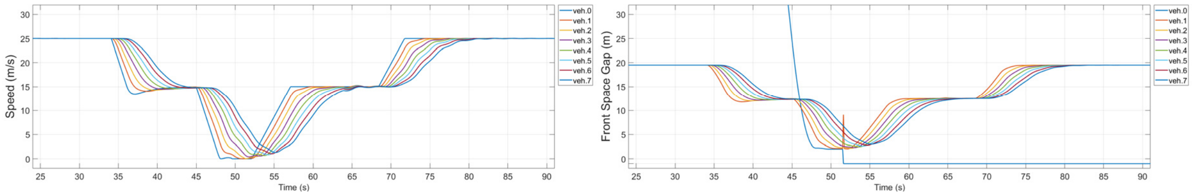

Figure 5: Simulation result of speed (left) and inter-vehicle distance (right) for safe scenario.

paper will greatly help to analyze the impact of environmental variabilities on the safety of autonomous platoon driving. And it can also support safety engineers to develop realistic platoon driving techniques.

In the future, we will conduct a study about the real-time properties of safety guards. It is very critical to satisfying the real-time constraints to support spatial and temporal variabilities as well as environmental variability in autonomous (platoon) driving. Thus, we will research and develop time-constrained safety guards based on simulation techniques.

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