공학석사 학위논문

UGV 효과성 및 운용적합성 측정을 위한 시험평가 방안

Study on the Operational Test Scenarios for Assessment of Unmanned Ground Vehicle's Operational Suitability

2023년 2월

서울대학교 대학원

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Study on the Operational Test Scenarios for Assessment of Unmanned Ground Vehicle's Operational Suitability

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In recent years, the Korean Army has been actively carrying out research to adopt autonomous driving technology into their weapons and transportation systems. A key point to note is that most training and actual war-time scenarios require mobility in unpaved and off-road scenarios, hence there is a need to assess the performance of autonomous driving systems in such situations. As an example, severe vibrations arising from these unpaved roads may result in the degradation in performance of on-board perception sensors. Therefore, scenarios that fit the environmental characteristics of the Korean Army need to be defined in order to accurately assess the applicability of autonomous vehicles.

This paper presents a series of test scenarios and evaluation metrics to evaluate the applicability of autonomous driving systems for the Korean Army. The scenarios were developed based on the 6-Layer format adopted from the Pegasus Project, in conjunction with various accident cases from the Korean Army. Depending on their level of abstraction, the scenarios were categorized into three types: Functional, Logical and Concrete Scenarios. Within these scenarios, specific traits regarding the road surface were also included to more accurately represent the use-cases within the Korean Army. As a measure for performance, the vehicle's stability, ride comfort, and autonomous driving capabilities were evaluated using the following metrics. For stability, lateral error, lateral acceleration, longitudinal acceleration and the vertical force on each wheel were used. For ride comfort, vertical acceleration of the vehicle was utilized. Finally for the autonomous driving capabilities, the steering wheel angle was observed.

Furthermore, a simulation environment was developed in TruckSim and MATLAB to assess the aforementioned performance measures of autonomous vehicles. Simulation results have shown a significant degradation in lane-keeping abilities for high-speed, unpaved, curved roads, further reinstating the need for such scenarios.

The proposed scenarios and evaluation metrics are expected to play a significant role in improving the applicability of autonomous vehicles into the Korean Army's weapons and transport systems, as well as provide a framework for transport safety regulations in the near future.

Keywords : Unmanned Ground Vehicle, Autonomous Driving, Pegasus Project, 6-Layer Format, Operational Test Scenario, Army

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Chapter 1. Introduction

1.1. Research Motivation

Due to the steep decline in birthrate over the past few years, the Korean Army has been experiencing a reduction in manpower [1]. Despite the gradual decommissioning of various sectors, Army forces are only maintained at 80% capacity. For non-frontline troops, the situation is more severe. A reduced priority in dispatching manpower to the troops at the rear, filling vacancies take up extended periods of time. To combat this issue, the Korean Army has been placing increasing interest in autonomous and unmanned technologies [2]. For example, the K9 self-propelled Howitzer has been developed to support 1-man operations, allowing for its operation in limited manpower situations [3]. Additionally, due to its relatively simple operability, it provides an outstanding platform for the implementation of autonomous driving technologies [4]. Development is also currently underway for autonomous implementation with unmanned ground vehicles, drones, and CCTV systems [5].

As a counter measure to the decreasing manpower, the Korean Army has begun the process of adopting autonomous technology into their weapons systems [6]. To date, most autonomous driving systems have been developed to accommodate transport over paved roads, and are not fit for operations during training and actual war-time scenarios. The high speed, mobile, tactical vehicle (Humvee) and unmanned ground vehicles stand as a representative example. While such vehicles have been successfully adopted by some troops, the implemented autonomous driving algorithms are only designed to operate on paved roads or other limited driving conditions [7]. For unpaved or off-road scenarios, control is transferred to the driver for manual operations [8]. Following this, there are currently plans to adopt UGVs that are capable of autonomous driving on unpaved roads and war-time scenarios within the next 5 years [9].

However, the current state of evaluative facilities and scenarios for autonomous driving within the Army still show significant room for improvement. In order for an effective implementation of autonomous driving into the weapons systems, proper facilities and scenarios that accurately represent the operation environment of these vehicles are crucial. Without proper validation, adopting autonomous driving technologies in actual scenarios are bound to be severely limited. As such, there is a need for the development of scenarios for military specific uses.

Current scenarios developed to assess the applicability of autonomous driving in various scenarios only cover situations for paved roads, i.e., there is a lack in literature for unpaved roads. Understandably, paved roads have a smooth surface and clear markings for lanes, making them the ideal environment for autonomous driving systems. Conversely, to cover unpaved roads, these systems are required to navigate over rough terrain. The case for South Korea is more severe in that 70% of the land area is classified as mountainous terrain. Furthermore, most routes for military vehicles are unpaved roads, which may possibly degrade driving or detection performance of autonomous vehicles. Therefore, there is indeed a need for evaluation scenarios that tackle autonomous driving on unpaved roads.

For the scenarios developed in this paper, the UGV has been selected as a base model. Plans for a wide variety of UGVs currently exist, ranging from armored vehicles to small detection robots, all with the primary purpose of being operated either remotely or autonomously. Since actual military vehicles are unavailable for testing, computer simulations have been adopted for this study.

1.2. Previous Research

There has been a significant number of studies conducted regarding scenario design for the applicability of autonomous vehicles on paved roads. However, such studies on unpaved roads were difficult to find, with only a few related studies being available for literature reviews on the subject.

Firstly, regarding scenario development for applicability on paved roads, 6 scenarios were proposed by H.S. Chae [10]. The 6 scenarios proposed are as follows: single lane driving, congested single lane driving, following a preceding vehicle, driving in response to a cut-out vehicle, driving in response to a cut-in vehicle, and lane changing. The scenarios were developed based on a number of evaluation factors consisting of lane keeping, vehicle speed, longitudinal acceleration, lateral acceleration, and distance between vehicles, all of which were parameters set in advance with reason for the selection of such factors. On a similar note, S.H Park [11] proposed 6 scenarios for the safety evaluation of control take-overs on highway environments: The 6 scenarios were developed by analyzing common highway accident cases and categorizing them into 6 types: entering a highway, driving through a tollgate, blurry lane markings, entering construction zones, entering congested/accident zones, and autonomous system failures. For each scenario, a total of 36 variables were defined with acceptable ranges based on factors such as vehicle and environmental faults. S.M. Park [12] developed 24 scenarios through the 5-layer format proposed by the Pegasus project, where variables of each scenario could be easily altered to further develop a larger number of scenarios.

While no studies tackled the issue of evaluating the applicability of autonomous vehicles on unpaved roads, similar studies could be found. Y.H. Lee [13] proposed an algorithm which analyzed camera data to determine the outer edges of a road, through which the Kalman filter was utilized to estimate the heading angle and offset of a vehicle. H.J. Ma [14] developed an algorithm which could determine the heading direction of a vehicle and detect surrounding obstacles through various Vision based sensors and a neural network. J.W. Park [15] proposed a localization algorithm based off map-matching techniques, using a vehicle model and a LiDAR. Through this, a proof-of-concept on stable autonomous driving in outdoor environments was provided. Kolski [16] developed an autonomous driving algorithm through an existing Global Map, improving autonomous vehicle accessibility on unpaved roads.

As shown above, a number of studies have suggested methods that can potentially improve autonomous driving performance on unpaved roads. However, none could be found regarding the development of scenarios for evaluating the applicability of autonomous driving on unpaved roads. The lack of research in this field can be explained by the fact that in autonomous driving, unpaved roads are a problem that can be solved by handing control back to the driver.

1.3. Thesis Objective and Outline

The primary goal of this paper is to develop and analyze scenarios for the applicability of autonomous driving of UGV operations in the Korean Army. To assess the applicability, the safety, autonomous driving performance, and ride comfort were set as the main metrics. In operating a vehicle, the single most important factor is, without a doubt, safety. Above all else, safety has to be guaranteed before the vehicle can be operated. Furthermore, since the main utility of the vehicle is unmanned operations, satisfactory autonomous driving performance also needs to be guaranteed. Lastly, while ride comfort may not be too closely related to UGV operations, the metric has been added to account for vibrations sent to the on-board sensors and other hardware.

As previously explained in the research background section, the present research has been conducted to better the current standard for evaluating autonomous driving weapons systems for the Korean Army, not to mention the lack of research in unpaved and off-road scenarios.

In chapter 2, the 6-layer format of the Pegasus project, the basis for this research, will be explained in greater detail, along with scenario development based on reported accident cases on highways and the Korean Army.

In chapter 3, the aforementioned scenarios will be applied to the Pegasus 6-layer format to be further developed into Functional and Logical Scenarios by defining required variable types and their acceptable ranges. Values for the variables will be contained within preset ranges to develop the Concrete Scenarios.

In chapter 4, the simulation environment and metrics to assess safety will be presented. To better describe the simulation environments, 3 factors, roughness, coefficient of friction, and road frequency will be utilized as alterable variables. To assess the operational safety, data for lateral error, lateral acceleration, longitudinal acceleration, and vertical force on each wheel will be analyzed. For ride comfort, vertical acceleration was set as the main metric. Finally, the autonomous driving performance will be assessed through the steering wheel angle data.

In chapter 5, results of the simulations carried out will be discussed, with chapter 6 showing the overall conclusion and current limitations of this research.

Chapter 2. Scenario Background

2.1. Pegasus Project Scenario

The Pegasus project is a set of standards that has been developed to determine whether high level autonomous driving systems are suitable for authorization. The project, developed by the German Federal Ministry of Economy and Energy in partnership with manufacturers such as BMW, AUDI, and OPEL, provides standards for quality. Experimental methods and setups, and many others. It has been meticulously designed over the period of 4 years (Jan 2016 ~ June 2019) to ensure that their proposed experimental methods and setups are generally accepted to guarantee high-level autonomous driving capabilities [19].

According to the Pegasus project, scenarios hold different contents and expressions depending on the stages of the development process. Scenarios are mainly categorized into 3 types, the Functional Scenario, the Logical Scenario, and the Concrete Scenario, following the level of abstraction. Figure 1 shows each category and their relation to each other. Firstly, the Functional Scenario describes the road network, static and dynamic factors, environmental factors and situations explained in the natural language, ultimately showing the general direction of each scenario. Next, the logical scenario, used for developing and testing the autonomous systems, is developed to determine an acceptable range for all variables used within the developed scenarios. Finally, the concrete scenario is developed where all values for the variables in each scenario are preset and used for actual testing purposes. As scenarios are developed from a Functional Scenario to a Concrete Scenario, more

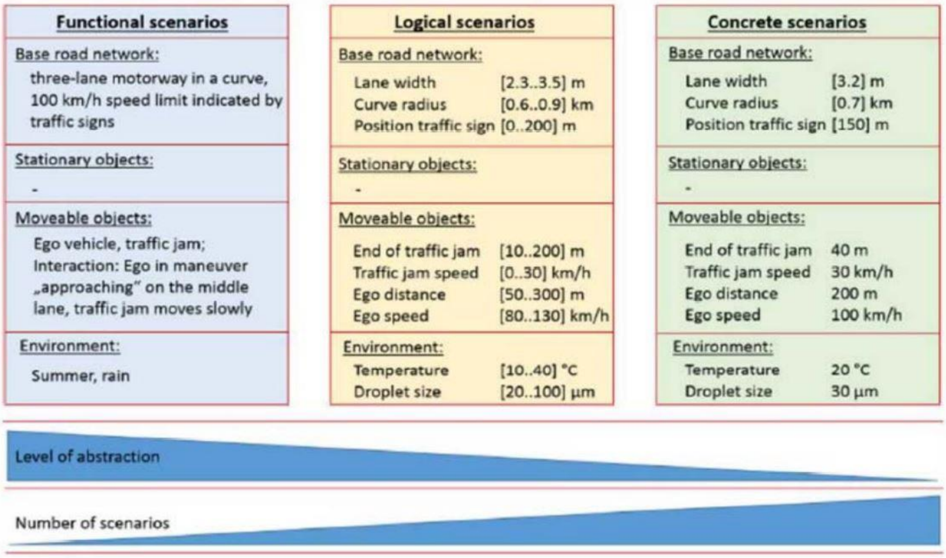


Figure 1. Scenario Abstraction Level based on Pegasus Project Terminology

scenarios are developed as the original scenario becomes increasingly more detailed.

To obtain the above scenarios, the Pegasus project defined a 6-layer format for scenarios. As shown in Figure 2, as the layer number increases, the scenario becomes increasingly more detailed, ranging from a simple geometric road shape to V2X and

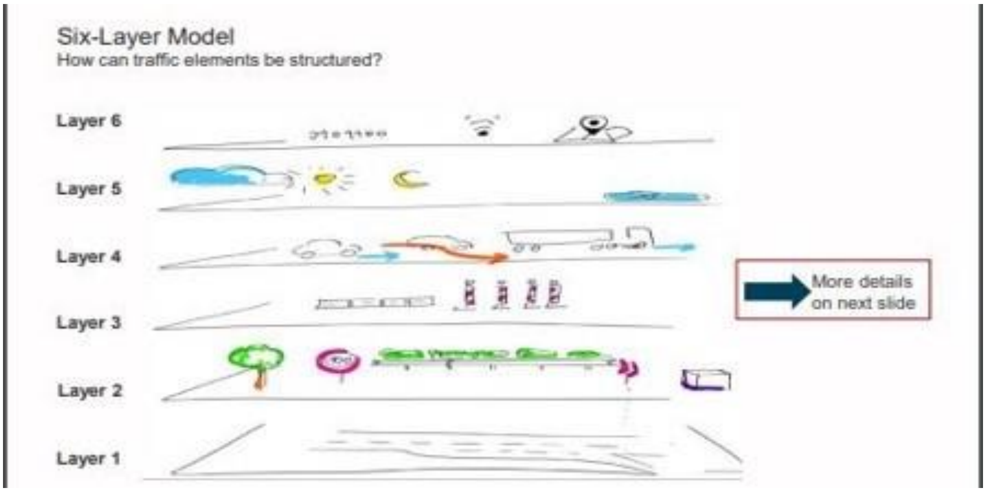


Figure 2. Pegasus Project 6-Layer Format

communications information obtained from the surrounding infrastructures. Factors such as static / dynamic obstacles, illumination, weather, and temperature are included in these layers. Further details regarding the layers are given in Table 1. Therefore, the 6-layer format provides a structured platform on which a detailed and utilizable scenario can be developed. While the 6-layer format may have its limitations in complex traffic situations, the present study only involved with unpaved roads and hence, the limitations do not apply, making the Pegasus 6-layer format a suitable standard for development.

On the other hand, specifications of an Operational Design Domain (ODD) can be used instead for developing autonomous driving scenarios, within which the Object and Event Detection and Response (OOER) shows significant similarities to the Pegasus 6-layer format. In an ODD, physical road geometries, static / dynamic obstacles, environmental conditions, communication systems, and even school zones are all included as shown in Table 2. However, the scenarios are not categorized based on their level of abstraction and additional details that an ODD provides are typically unrelated to military vehicles. Hence the Pegasus 6-layer format was ultimately selected [20].

Table 1 Specifications of experimental components

Layer	Component
Layer 1	Road geometry, Road unevenness, etc.
Layer 2	Traffic signs, Railguards, Lane markings, Bot dots, Police instructions
Layer 3	Road construction, Lost cargo, Fallen trees, Dead animals
Layer 4	Vehicles, Pedestrians moving relatively to ownship
Layer 5	Light situation, Weather (rain, snow, fog…), Temperature
Layer 6	V2X information on traffic signals, Digital map data

Table 2 Components of Operational Design Domain (ODD)

ODD Elements	**Detailed Components**
Physical Infrastructure	Road type, Roadway surface, Roadway edges & markings, Roadway geometry
Operation Constraints	Operational speed limits, Traffic conditions
Objects	Signage, Roadway users, None-roadway users, Traffic equipment
Environmental Conditions	Weather, Weather-induced roadway conditions, Illumination
Zone	Traffic management zone, School zone, Construction zone, Interference zone
Connectivity	Demonstration vehicle, Infrastructure sensors, Digital infrastructure

2.2. Accident Cases

Before starting off with the development of Functional scenarios, literature on representative accident cases on paved and unpaved roads were first reviewed.

Based on a 2021 presentation given by the Samsung Traffic Research Institute, accidents on highways can be categorized as shown in Figure 3, depending on their frequencies [21]. Collisions while driving in a single lane were the most common. Collision cases for lane changing, overtaking, and road narrowing all represent accidents arising from improper cut-in responses. Accidents from merging may also be classified as cut-in response accidents, however, since a separate road exists for the merger, this case was classified separately. The third most common case (collisions from stationary vehicles) can be thought of as an accident arising from an improper cut out. Additionally, accident cases reviewed in 2020 through the Traffic

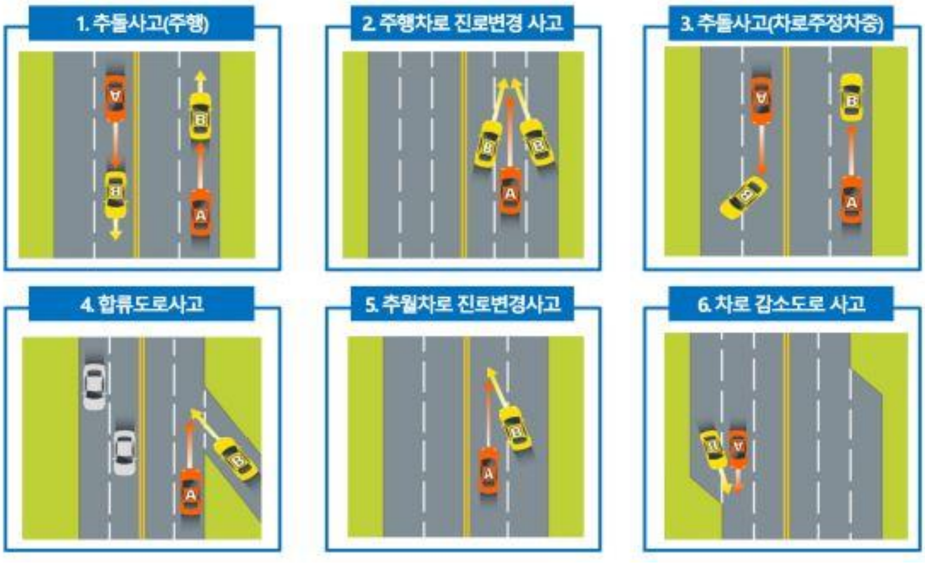


Figure 3. Ranking of Highway Accidents (Samsung Research Institute)

Accident Analysis System showed that accidents were the most common in intersections, representing 49.8% of all cases [22]. Keeping this in mind, intersection scenarios can be included as well.

To evaluate the basic applicability for autonomous driving in various situations, a single lane driving scenario was first developed. Next, to observe collisions while driving, a congested single lane driving scenario was set up. Scenarios to evaluate cut-in and cut-our vehicles were then developed, followed by a merging scenario and an intersection scenario. These 6 scenarios make up the set of scenarios for driving on paved roads.

Next, for the unpaved roads, a review was carried out for accident cases that occurred during Army transportation operations in 2021. A total of 20 cases were reviewed, of which 7 represented accidents on unpaved roads. The causes for the 20 cases are summarized in Table 3. Within the 7 cases for unpaved roads, 5 of them represented cases where vehicles were overturned while driving on narrow, unpaved roads. The causes include, falling into a ditch while turning, falling into a ditch while reversing, falling off a bridge, and a small sinkhole forming on the ground beneath the front left tire. From this, a scenario for driving in a narrow unpaved road could be developed. The review also included cases where a collision with a pole

Table 3 Analysis of 2021 Army Transportation Accidents

Types	The number of cases
Accidents caused by military-environmental	7
Accidents caused by inexperience in driving	6
Accidents caused by road ice in winter	3
Accidents caused by equipment flaws and lack of understanding	3
Other accidents	1

occurred in an evasive maneuver to avoid a rock, and a case where a guardrail collision occurred to avoid a cat. These cases were referred to when developing scenarios to observe cases of rapid steering wheel movements made while avoiding static and dynamic obstacles.

Overall, to evaluate autonomous driving on unpaved roads, a total of 4 scenarios were developed as follows: driving on a narrow, straight, unpaved road, driving on a narrow, curved, unpaved road, evading a static obstacle, and evading a dynamic obstacle.

Chapter 3. Scenario Configurations

3.1. Functional Scenarios

A Functional Scenario contains brief and general information regarding the road network, static and dynamic obstacles, environmental factors, and a specified situation in the natural language.

The first scenario is driving on a single lane. In this scenario, the ego-vehicle is required to drive on a regular paved road maintaining the center of the lane without changing lanes. The vehicle speed, lateral acceleration, and longitudinal acceleration values will be observed to see if they remain within specified acceptable ranges. For the road, the narrowest standard regulation road was used, and the vehicle width was set to be equal to a large semi-truck or a bus.

The second scenario describes driving on a congested single lane. The conditions are identical to the first scenario with the exception that a target vehicle exists in front of the ego vehicle. In this scenario, the ego vehicle follows the preceding vehicle and the vehicle speed, lateral acceleration, longitudinal acceleration, distance from the lanes, and the distance between the ego vehicle and the preceding vehicle will be observed to see if they remain within specified acceptable ranges.

The third scenario shows driving in response to a cut-in vehicle. Again, the conditions are identical to the first, with the exception that a vehicle in the next lane performs a sudden cut-in maneuver. In other words, the scenario is designed to observe whether the ego vehicle can successfully convert from the first scenario to the second scenario after a sudden cut-in maneuver. Similarly, the distance from the lanes and the distance between the ego vehicle and the cut-in vehicle will be observed.

The fourth scenario depicts driving in response to a cut-out vehicle. Conditions for this scenario are identical to the second scenario with the exception that the preceding target vehicle performs a sudden cut-out maneuver. Conversely to that of the third scenario, this scenario observed whether an ego vehicle can shift from the second scenario to the first after a cut-out maneuver.

The fifth scenario describes merging situation. While similar to that of a cut-in scenario, a merging case shows significant differences in the surrounding road structure which may potentially cause significant disturbance to detecting lanes, hence requiring a separate scenario. Furthermore, collisions during mergers also represented the 4^{th} leading cause of accidents on highways. This scenario ultimately observes whether the ego vehicle can switch from the first scenario to the second after a merging maneuver by a target vehicle.

The sixth and last scenario for paved roads represents driving through intersections. This scenario also presents some similarities to that of the cut-in scenario. While the ego vehicle is driving straight behind a target vehicle, the target vehicle slows down to perform a right turn maneuver. At this point, the ego vehicle will be assessed in its performance to convert to a congested straight driving scenario. While the measurements for the metrics are similar, the difference lies in that there are no lanes next to the ego lane.

The seventh scenario shows straight driving in a narrow, unpaved road. In this scenario, the ego vehicle will be assessed on its ability to maintain virtual lanes along with the risk of flipping over through the lateral and longitudinal acceleration values.

Similar to that of the first, the road width was set to the narrowest standard regulation road and the vehicle width was set to match that of a large semi-truck or a bus

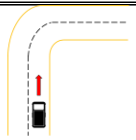
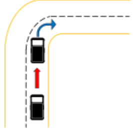
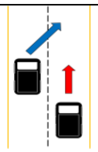
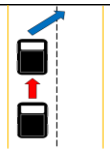
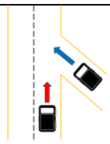
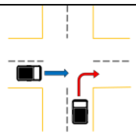
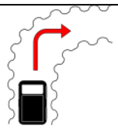
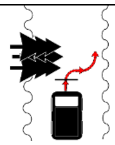
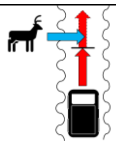
The eighth scenario represents driving on a narrow, curved, unpaved road. Unlike the previous scenario, the road width was set to be comparatively large. Performance measure will be similar to that of the seventh scenario where the lane keeping performance of virtual lanes and the risk of flipping over will be assessed.

The ninth scenario depicts driving in response to a static obstacle. To ensure that there is enough room for an evasive maneuver, the road width has been set to be relatively large. At the point where the vehicle swerves, the ego vehicle will be assessed on its ability to either stop or perform an evasive maneuver in response to a static obstacle intruding the lane. The risk of collision and flipping over will be evaluated.

The tenth scenario describes driving in response to a dynamic obstacle, which intrudes the lane suddenly from an unobservable area. In such a scenario, sudden swerving may result in a secondary accident, hence the scenario was designed such that the vehicle performs an emergency braking maneuver. Since the scenario does not present any risks associates with swerving, only the risk of collision will be assessed.

The above scenarios have been categorized with abbreviated names for the ease of reference. The names are classified in Table 4. The first part of the abbreviation represents the vehicle movement, either going straight or turning right. The middle part represents information regarding the road environment and the scenario which includes: solo driving, congested driving, cut-in, cut-out, merging, intersections, static obstacles and dynamic obstacles. In Table 4, the “Sort” column shows GS, TR, P, N, F, CI, CO, MR, and CR, which represents Going Straight, Turning Right, Paved, Normal, Following, Cut-in, Cut-out, Merging Road, and Crossroad respectively. For the unpaved roads, the abbreviations U, SO, and DO represent Unpaved, Static Obstacle and Dynamic Obstacle respectively.

Table 4 Functional Scenarios

Title	Image	Description
TR-P-N		A solo drive in own lane
TR-P-F		Driving in congested lane
GS-P-CI		Driving corresponding to cut-in vehicle
GS-P-CO		Driving corresponding to cut-out vehicle
GS-P-MR		Driving corresponding to merging road
TR-P-CR		Driving corresponding to crossroad
GS-U-N		A solo driving in a narrow and straight unpaved road
TR-U-N		A solo driving in a narrow and circular unpaved road
GS-U-SO		Static obstacle avoidance maneuvering in unpaved road
GS-U-DO		Stop when dynamic obstacle occurs

3.2. Logical Scenarios

In the Pegasus project, Logical scenarios are used for developing and testing the autonomous driving systems, where the acceptable ranges of all variables are presented. Therefore, its composition must be more detailed than that of the Functional Scenarios. Each scenario contained identical layers; the Logical Scenarios will be developed in accordance to each layer, not each scenario.

The first layer contains information regarding the road, such as road geometry and irregularities. Hence the geometric form of the road has to be checked beforehand. However, since all scenarios mentioned in section 1 (Functional Scenarios) do not differ significantly from each other, Layer1 has been categorized as a single class applicable to all the aforementioned scenarios. Further details are provided in Table 5, where each acceptable range values have been designed based on the road design specifications provided by the Ministry of Land, Transport and Maritime and the Army Transport Field Regulations.

Layer 2 contains information regarding road infrastructure and other norms

Table 5 Logical Scenario (Layer1)

Layer	Component	Parameter	Range
Road Layer (Layer1)	Road geometry	Planning Speed	60km/h or less 40km/h or less
		Road Width	3m ~ 3.5m
		Cross-fall Grade	1.5% ~ 2% / 3% ~ 6%
		Road number	1 ~ 4 lane road
		Roadway radius of curvature	0~∞
		Maximum braking factor	0.3~1
	Others	In case of necessity	

such as traffic signals, guardrails, lane markings, and traffic signs. The presence of infrastructure, type of lanes, lane specifications, lane color, and lane guides are checked in this layer, as shown in Table 6. The range for each variable has been referred from the road design specifications provided by the Ministry of Land, Transport and Maritime Affairs.

Layer 3 handles general facilities and temporary static obstructions such as construction sites, parked vehicles, and fallen trees. For example, in GS-U-SO, the scenario assumes a fallen tree intruding the ego lane, which is included in Layer 3 to represent temporary static obstacles. Further details are provided in Table 7.

Table 6 Logical Scenario (Layer2)

Layer	Component	Parameter	Range
Road furniture and Rules (Layer2)	Road Geometry	Structure	Bridge / Tunnel
	Road markings	Types of traffic lane	White / Orange / Blue / X
			Single / Dotted / Double / X
		Specification of traffic lane	Dotted Lane Painting 10m
			Lane Gap 10m
			Lane Width 10~15cm
		Reflective performance of lane painting	White / Yellow / Blue (150mcd)
		Guide Lane	O / X
	Others	In the case of necessity	

Table 7 Logical Scenario (Layer3)

Layer	Component	Parameter	Range
Temporal modifications and events (Layer3)	Roadside Facilities	Bus-only Lane	O / X
		Shoulder Lane	O / X
	Protection Facilities	Traffic cone	O / X
	Others	Types	Telephone Pole, Fallen tree, etc.
		Range (Lateral)	1~2m

Layer 4 provides information on dynamic obstacles such as other vehicles and pedestrians. For this layer, the components differ depending on whether the road is paved or unpaved and has therefore been divided accordingly. Ranges for parameters such as vehicle acceleration, initial distance to target vehicle, and Time to Collision (TTC) with the target vehicle was set at a later time after some evaluations were carried out with simulations. The Layer 4 classification for paved roads and unpaved roads are shown on Table 8 and Table 9 respectively.

In Layer 5, information regarding the surrounding environment such as illumination, weather, and temperature are given. As for the weather, the most general types, clear, rain, and snow, were selected and their corresponding windspeed and temperatures were set accordingly. The illumination state of the road can be divided simply into daytime and night time. As for the illumination state for night time scenarios, an illumination level between M2 and M4 were set, referred from the Road Safety Infrastructure Installation Regulations. Further details are

Table 8 Logical Scenario (Layer4-Paved Roads)

Layer	Component	Parameter	Range
Moving Object (Layer4)	Default Setting	Number of vehicles required	Actor, Ego, Neighbor
		Initial intercar distance	In the case of necessity(2~10m)
	Actor 1	Velocity of Vehicle	40km/h~60km/h
		Acceleration	Experimental Definition
		Target intercar distance to ego vehicle	In the case of necessity(2~10m)
		Time to Collision	Experimental Definition
	Ego	Velocity of Vehicle	40km/h~60km/h
		Acceleration	Experimental Definition
		Target intercar distance to ego vehicle	In the case of necessity(2~10m)
		Time to Collision	Experimental Definition

provided in Table 10.

The last layer, Layer 6, contained information regarding V2X from traffic signals and other digital signals such as sensor data. While layer 6 is not expected to affect performance, related variables and their acceptable ranges have been defined nevertheless. Further details are provided in Table 11.

Table 9 Logical Scenario (Layer4-Unpaved Roads)

Layer	Component	Parameter	Range
Moving Object (Layer4)	Default Setting	Number of vehicles required	Actor, Ego, Neighbor
	Actor 1 (Static Obstacle)	Types	Fallen tree, Rock, etc.
		Range (Width)	1~2m
	Actor 2 (Dynamic Obstacle)	Types	Pedestrian, Wildlife, etc.
		Initial Speed	40km/h or less
		Distance to ego vehicle	30m or less
	Ego	Initial Speed	40km/h or less
		Distance to actor vehicle	30m or less

Table 10 Logical Scenario (Layer5)

Layer	Component	Parameter	Range
Environmental Conditions (Layer5)	Whether	Types	Clear, Rain, Snow
		Temperature	Clear, Rain : 5~40 Snow : -10 ~ 5
		Maximum Windspeed	0m/s ~ 5m/s
	Intensity of Illumination	Types	Day / Night
		Minimal Surrounding Illumination	Day : 2000 ~ 5000 Night : 500 ~ 2000
		Night Road Illumination Grade	M1 ~ M3 M2 ~ M4

Table 11 Logical Scenario (Layer6)

Layer	Component	Parameter	Range
Digital Information (Layer6)	Sensor Performance	Communication Delay	O / X
		Communication Error	O / X
		Localizing Error	O / X
	Others	Others	In the case of necessity

3.3. Concrete Scenarios

The Concrete Scenarios are obtained from the Logical Scenarios by setting proper values instead of ranges for the defined variables.

The Concrete Scenarios for the paved road show similar conditions with regards to the road geometry, infrastructure, general facilities, environment, and communications systems, corresponding to layers 1,2,3,5 and 6. While some roads show differences in road geometry and infrastructure, significant portions of the scenarios overlap with each other and were hence summarized together in Table 12. For other conditions, each layer was classified depending on the scenario.

Firstly, designing the TR-P-N scenario was comparatively simple as the scenario only describes driving along a single lane. Further details regarding the variables are summarized in Table 13. Since the ego vehicle travels along a single lane, there is no need to design any other lanes. The curvature of the road was set to 60m, a rather gentle 90 degree curved road.

The TR-P-F scenario describes a congested driving scenario where a target vehicle ahead of the ego vehicle travels at the same or slower speed than the ego vehicle. Most factors of TR-P-F share similarities with TR-P-N with the exception of an additional target vehicle. The roads were designed to be regular roads, hence the safety distance (Distance between the ego vehicle and the target vehicle) was set as 35m. With and initial speed of 40km/h for the ego vehicle, the TTC was calculated to be 4.2 seconds. Assuming that the target vehicle travelled at a slower speed than the ego vehicle, the corresponding values for the scenario variables were set as shown in Table 14.

GS-P-CI describes driving in response to a cut-in vehicle and has overlapping portions with TR-P-F. However, for GS-P-CI, the cut-in occurs during the scenario, not at the start. Hence the objective for this scenario is to observe whether the ego vehicle shows similar metric values to that of TR-P-F after the cut-in. When a slower

Table 12 Common Concrete Scenario Variables (Paved Roads)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Planning Speed	40km/h
		Road Width	3.5m
		Cross-fall Grade	1.5%
		Maximum Braking Coefficient	0.8
Road Furniture and Rules (Layer2)	Road markings	Types of Traffic Lane	Orange(line) / White(dotted)
		Specification of Traffic Lane	Dotted Lane Painting 10m
			Lane Gap 10m
			Lane Width 15cm
		Reflective Performance of Lane Painting	Yellow / White (150mcd)
		Guide Lane	X
	Others	In the case of necessity	-
Temporal modifications and events (Layer3)	Roadside Facilities	Bus-only Lane	X
		Shoulder Lane	X
	Protection Facilities	Traffic Cone	X
	Others	Type	-
Environmental Conditions (Layer5)	Whether	Type	Clear
		Temperature	10
		Maximum Windspeed	0m/s
	Intensity of Illumination	Type	Day
		Minimal Surrounding Illumination	4000
Digital Information (Layer6)	Sensor Performance	Communication Delay	X
		Communication & Localizing Error	X
	Others	Others	-

Table 13 Concrete Scenario (TR-P-N)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	One-lane Road
		Roadway Radius of Curvature	60m
	Others	In the case of necessity	-
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	-
	Others	In the case of necessity	-
Moving Object (Layer4)	Default Setting	Required Vehicles	Ego
	Ego	Initial Speed	40km/h

Table 14 Concrete Scenario (TR-P-F)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	One-lane Road
		Roadway Radius of Curvature	60m
	Others	In the case of necessity	-
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	-
	Others	In the case of necessity	-
Moving Object (Layer4)	Default Setting	Required Vehicles	Actor, Ego
		Initial V2V distance	35m
	Actor1 (Target Vehicle)	Vehicle Speed	30km/h
		Acceleration	-
	Ego (Ego Vehicle)	Vehicle Speed	40km/h
		Acceleration	Experimental Definition
		Target V2V distance	35m
		Time to Collision	4.2s

vehicle performs a sudden cut-in maneuver, the ego vehicle is expected to slow down and maintain the preset safety distance from the cut-in vehicle. Details regarding the scenario variables are provided in Table 15.

GS-P-CO shows driving in response to a cut-out vehicle, where the objective is to observe whether the ego vehicle successfully switches to measurements that are

Table 15 Concrete Scenario (GS-P-CI)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	Two-lane Road
		Roadway Radius of Curvature	Straight
	Others	In the case of necessity	-
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	-
	Others	In the case of necessity	-
Moving Object (Layer4)	Default Setting	Required Vehicles	Actor, Ego
		Initial V2V distance	50m
	Actor1 (Target Vehicle)	Vehicle Speed	30km/h
		Acceleration	Experimental Definition
		Moving Direction	Second Lane → First Lane
	Ego (Ego Vehicle)	Vehicle Speed	40km/h
		Acceleration	Experimental Definition
		Target V2V distance	35m
		Time to Collision	4.2s

similar to TR-P-N. The ego vehicle is expected to accelerate to the desired speed of 40km/h once the slower cut-out vehicle exits the lane. Values for the scenario variables are depicted in Table 16.

GS-P-MR describes a merging scenario, where the ego vehicles movement is similar to that of GS-P-CI. However, the scenario was developed nevertheless to account for the possibility of the ego vehicle not recognizing the merging vehicle, or incorrectly perceiving the surrounding infrastructure due to the difference in road geometry. Similar to the scenarios mentioned above, the objective of this scenario is to observe whether the ego vehicle shows similar measurements to that of TR-P-F after the merging maneuver. Further details regarding the scenario variables are

Table 16 Concrete Scenario (GS-P-CO)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	Two-lane Road
		Roadway Radius of Curvature	Straight
	Others	In the case of necessity	-
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	-
	Others	In the case of necessity	-
Moving Object (Layer4)	Default Setting	Required Vehicles	Actor, Ego
		Initial V2V distance	50m
	Actor1 (Target Vehicle)	Vehicle Speed	30km/h
		Acceleration	Experimental Definition
		Moving Direction	First Lane → Second Lane
	Ego (Ego Vehicle)	Vehicle Speed	40km/h
		Acceleration	Experimental Definition
		Target V2V distance	35m
		Time to Collision	4.2s

summarized in Table 17.

TR-P-CR shows a scenario where a target vehicle preceding the ego vehicle travels straight through an intersection, follow by the ego vehicle turning right. This scenario is designed to observe whether the ego vehicle returns to a state similar to that of TR-P-F after the right turn. Details of the scenario variables are shown in Table 18.

Up until TR-P-CR, the scenarios mentioned covered the concrete scenarios for paved roads. The remainder of this section discusses the Concrete Scenarios for unpaved roads. Similar to the paved roads, overlaps in layers 1,2,3,5, and 6 exist for the Concrete Scenarios for unpaved roads. The overlapping variables have been

Table 17 Concrete Scenario (GS-P-MR)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	Two-lane Road
		Roadway Radius of Curvature	Straight
	Others	In the case of necessity	Merging Road
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	Guardrails
	Others	In the case of necessity	Merging Road
Moving Object (Layer4)	Default Setting	Required Vehicles	Actor, Ego
		Initial V2V distance	50m
	Actor1 (Target Vehicle)	Vehicle Speed	30km/h
		Acceleration	Experimental Definition
		Moving Direction	Merging → First Lane
	Ego (Ego Vehicle)	Vehicle Speed	40km/h
		Acceleration	Experimental Definition
		Target V2V distance	35m
		Time to Collision	4.2s

Table 18 Concrete Scenario (GS-P-CR)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Number	Two-lane Road
		Roadway Radius of Curvature	Straight
	Others	In the case of necessity	Crossroad
Road Furniture and Rules (Layer2)	Road Infrastructure	Structure Types	
	Others	In the case of necessity	Crossroad
Moving Object (Layer4)	Default Setting	Required Vehicles	Actor, Ego
		Initial V2V distance	50m
	Actor1 (Target Vehicle)	Vehicle Speed	30km/h
		Acceleration	Experimental Definition
		Moving Direction	First Lane(South-North) → First Lane(West-East)
	Ego (Ego Vehicle)	Vehicle Speed	40km/h
		Acceleration	Experimental Definition
		Target V2V distance	35m
		Time to Collision	4.2s

summarized in Table 19, and the remaining variables have been summarized according to each scenario. Unlike the paved roads, the initial speed of the vehicle was set to 30km/h and the maximum braking coefficient was set to 0.5, representing the frictional coefficient of a dry, unpaved road. On unpaved roads, the lane keeping capabilities of a vehicle become substantially more important with regards to safety. Therefore, the width of each road has been set to a safe value separately, dependent on the scenario. For unpaved roads, road infrastructure has been omitted as infrastructure is rarely present on unpaved roads. Environmental conditions and communication systems were also set identically to that of the paved roads as they do not present any real difference depending on the road type.

Firstly, the GS-U-N scenario shows driving straight along a narrow, unpaved road, resulting in a relatively simple scenario design as well, with variables defined in Table 20, and the road width was set to the narrowest, reasonable value of 3m sine

Table 19 Common Concrete Scenario Variables (Unpaved Roads)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Planning Speed	30km/h
		Cross-fall Grade	3%
		Road Number	One-lane Road
		Maximum Braking Coefficient	0.5
Road Furniture and Rules (Layer2)	Whether	Type	Clear
		Temperature	10
		Maximum Windspeed	0m/s
	Intensity of Illumination	Type	Day
		Minimal Surrounding Illumination	4000
Digital Information (Layer6)	Sensor Performance	Communication Delay	X
		Communication & Localizing Error	X
	Others	Others	In the case of necessity

Table 20 Concrete Scenario (GS-U-N)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Width	3m
		Roadway radius of curvature	Straight
	Others	In the case of necessity	-
Scenario Objects (Layer4)	Default Settings	Required Vehicles	Ego
		Initial Speed	30km/h

the ego vehicle only travels straight.

As for TR-U-N, the scenario depicts driving on a narrow, curved, unpaved road. The simplicity of the scenario results in a relatively simple scenario design as well, with variables defined in Table 21. The road width was set to 4m in consideration of the curvature of 60m, a rather gentle 90degree curve. All other layers are identical to GS-U-N

GS-U-SO is a scenario where the ego vehicle performs evasive or braking maneuvers in response to a static obstacle (a fallen tree in this case). To allow space for evasive maneuvers, the width of the road in GS-U_SO has been set to 8m, considerably wide compared to that of GS-U-N. The intrusion depth of the obstacle has been set to 3m from the start of the lane, resulting in the remaining portion of the lane to be narrow when performing an evasive maneuver. Further details are provided in Table 22.

Table 21 Concrete Scenario (TR-U-N)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Width	3m
		Roadway radius of curvature	60
	Others	In the case of necessity	-
Scenario Objects (Layer4)	Default Settings	Required Vehicles	Ego
		Initial Speed	30km/h

Table 22 Concrete Scenario (GS-U-SO)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Width	8m
		Roadway radius of curvature	Straight
	Others	In the case of necessity	-
Scenario Objects (Layer4)	Default Settings	Required Vehicles	Ego
	Actor1 (Static Obstacle)	Type	Fallen Tree
		Range (Lateral)	3m
		Distance to Ego	30m
	Ego	Initial Speed	30km/h
		Distance to Actor	30m

GS-U-DO describes a vehicle evading a dynamic obstacle such as wild animals, pedestrians and cyclists in the case of lane intrusion. The size of the dynamic obstacle was set to be the same of that of a typical deer as it is the most widely spotted wild animal in the Korean Army. Since the top speed of deer generally hover around 40km/h, the speed of the dynamic obstacle was set as 30m in consideration of the vehicle’s braking distance and response time. Details regarding the scenario variables are provided in Table 23.

Table 23 Concrete Scenario (GS-U-DO)

Layer	Component	Parameter	Variable
Road Layer (Layer1)	Road Geometry	Road Width	8m
		Roadway radius of curvature	Straight
	Others	In the case of necessity	-
Scenario Objects (Layer4)	Default Settings	Required Vehicles	Ego
	Actor2 (Dynamic Obstacle)	Type	Wild Animal
		Initial Speed	40km/h
		Distance to Ego	30m
	Ego	Initial Speed	30km/h
		Distance to Actor	30m

Chapter 4. Simulation Environment

4.1. Designing the Simulation Environment

First off, it is to be noted that scenarios for paved roads have already been researched and developed to a significant degree. Applying these scenarios to fit the Korean Army is not expected to yield any significantly differing results and have hence been omitted from the simulation tests. Because the simulation environment only reflects unpaved roads, the characteristics of these roads must differ from that of regular roads. In this paper, roads have been characterized with 3 variables: roughness, frictional coefficient, and road frequency. The roughness factor affects the vibration amplitude of the vehicle. Under severe vehicle vibrations, its on-board sensors will experience increased vibrations as well which may potentially affect sensor data accuracy. As mentioned in a lecture provided by Stanford, winner of the 2005 DARPA GRAND CHALLENGE, bumps in the road affect the location of the scan line as shown in Figure 4. This may result in small obstacles such as rocks and animal carcasses to be perceived as larger than they are, causing the autonomous driving systems to malfunction. The road roughness stands as one of the largest causes of incorrect perception results and was hence added as a road characteristic.

The frictional coefficient determines how slippery a road is, potentially causing wheel-slip. Therefore, frictional coefficient between the road the tires of the ego vehicle stand as an important variable that affects whether the ego vehicle can be controlled or not in various road conditions. Furthermore, roads generally contain too many variables to be classified by roughness alone.

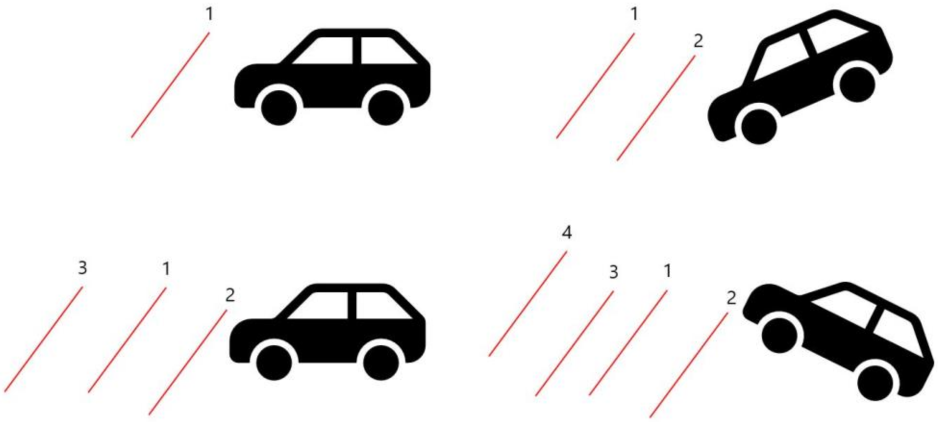


Figure 4. Vehicle Recognition Scan Line on Unpaved Road

The road frequency determines how often a bump is placed on a road, thereby determining how often a vehicle shakes. If roughness is a measure of how hard a vehicle shakes or vibrates, the road frequency shows how often the vehicle shakes or vibrates.

4.1.1. Roughness

The roughness parameter utilized in this study was referred to from the International Roughness Index (IRI). While there are multiple methods available for measuring and determining roughness, IRI has been specially selected for its accurate representation of roads, reliability and that it can be used with a variety of estimators. Additionally, since IRI represents overall roughness, integration into TruckSim becomes a relatively simple process.

IRI is measured by installing a displacement meter within the suspension system of a vehicle. As the vehicle travels along a road, vertical displacement of the tires is accumulated and divided by the total distance travelled. While the derivative of IRI values (representing the ratio between the suspension velocity and vehicle velocity) do not match a specific vehicle exactly, most related studies have shown a reasonable correlation.

The roughness conditions for unpaved roads most commonly experienced in the Korean Army can be classified as one of the following: Maintained unpaved roads, Damaged pavements, Rough unpaved roads. Details regarding the classification are given in Figure 5. In the event of an actual war, artillery strikes on roads will most likely result in roads with much high roughness values that of rough unpaved roads. The corresponding IRI values that fit the aforementioned scenarios are estimated to be between 4 ~ 20.

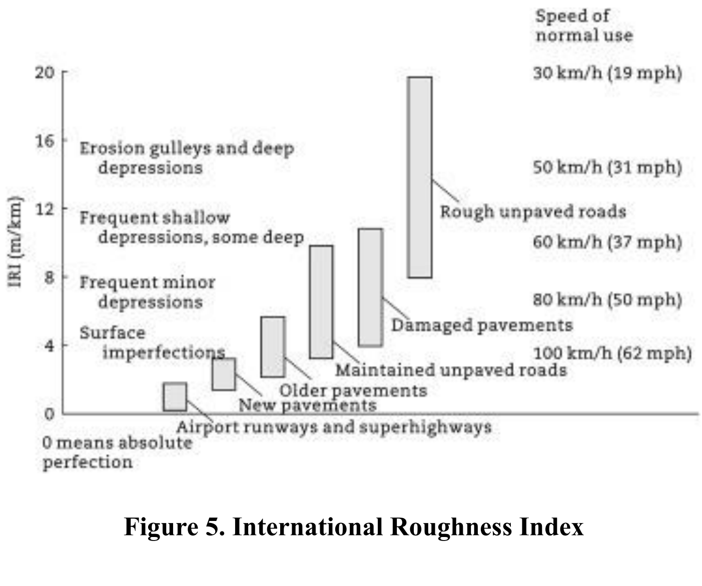


Figure 5. International Roughness Index

4.1.2. Frictional Coefficient

The frictional coefficient was referred from an available dataset. According to Table 24, the frictional coefficient for unpaved roads differ depending on the weather, where a regular unpaved road as a coefficient of 0.5 when dry, 0.3 when wet, and 0.2 when frozen. Furthermore, data from the Traffic Institution at Northwestern University suggests that a dry, pebble road has a frictional coefficient ranging from 0.35 to 0.8, depending on the fineness of the pebbles [25]. Therefore, the frictional coefficient that best fits the current unpaved road scenarios can be estimated to be between 0.5 to 0.3.

4.1.3. Road Frequency

A Power Spectral Density (PSD) functional is typically used to determine the road frequency. ISO, MIRA, and Wong, have all suggested a classification index depending on the roughness of a road, which has been represented via based on a PSD standard for ISO, better depicted in Table 25. Based on this data, a vehicle with a velocity of 30km/h is expected to have a road frequency of 0.83Hz.

Table 24 Friction Coefficient for Different Types of Roads

	Dry	Little Humid	Very Humid	Freezing
Asphalt	0.8	0.7	0.6	0.3
Concrete	0.8	0.6	0.4	0.3
Block	0.7	0.4	0.3	0.2
Unpaved Road	0.5	0.4	0.3	0.2

Table 25 Road Surface Roughness Index (ISO Standards)

Road Class	Degree of Roughness $S_g(\Omega_0)$,$10^{-6}m^2$/cycles/m	
	Range	Geometric mean
A(Very Good)	< 8	4
B(Good)	8 ~ 32	16
C(Average)	32 ~ 128	64
D(Poor)	128 ~ 512	256
E(Very Poor)	512 ~ 2048	1024
F	2048 ~ 8192	4096
G	8192 ~ 32769	16384
H	> 32768	

4.1.4. Simulation Ego Vehicle

The Simulation vehicle for this study has been selected as the "Military: Armored Combat Vehicle, 8x8(ii_ii)" option available in MATLAB TruckSim, which shows the highest similarity to the Unmanned Ground Vehicles defined by the Korean Army. Parameters for tires and the powertrain have also been selected as the base option given in TruckSim. Further details are given in Figure 7 and Table 26. An interesting point to note is that the armored vehicle model has a steering ratio of 25 deg/deg due to the high gear ratio, a significantly higher value than that of regular commercial vehicles which typically have a steering ratio of 15 deg/deg.

As for the autonomous driving algorithm, the P control option available in TruckSim was selected, which proportionally alters the control inputs depending on the current error values for various states of the vehicle. Proper operation of the algorithm can be checked through the steering angle data.

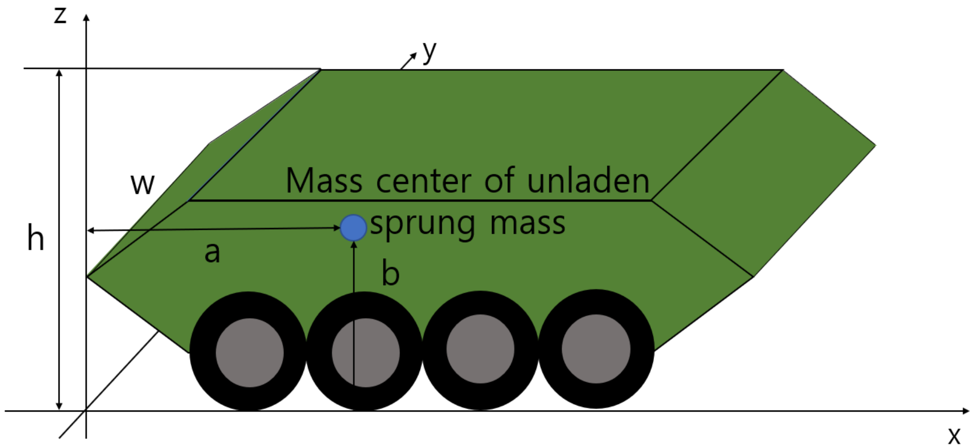


Figure 6. Specifications of Military: Armored Combat Vehicle, 8x8(ii_ii)

Table 26 Specifications of Military: Armored Combat Vehicle, 8x8(ii_ii)

Sprung mass	10,000kg	Rx	0.837m
Roll inertia	7,000kg/m2	Ry	2.000m
Pitch inertia	40,000kg/m2	Rz	2.449m
Yaw inertia	60,000kg/m2	A	1,800mm
Width(w)	2,650mm	B	1,200mm
Height(h)	1,430mm	Steering ratio	25deg/deg

4.2. Metrics for Evaluating Applicability

In order to accurately assess the applicability of autonomous driving for UGVs on various scenarios, the safety, autonomous driving performance, and ride comfort have been set as performance indexes. For safety, the lane keeping capabilities, ACC performance and contact state of each wheel were selected as the specific metrics for measurement. For autonomous driving performance, the steering angle data was analyzed. Finally for ride comfort, vertical acceleration of the vehicle was selection. The range of values for which safety can be guaranteed for each metric have been obtained from the ISO regulations.

Moving onto more specific details, the lane keeping performance of the vehicle can be assessed by observing its lateral error and lateral acceleration. Assuming that the yaw angle of the ego vehicle is sufficiently small, measurements for lateral error (l_y), and lane width ($l_{vehicle}$), and lane width (l_{road}) can be used to evaluate whether the vehicle is maintaining its lane to a satisfactory extent. If the condition presented in Equation 1 is fulfilled, the lane keeping performance of the vehicle can be said to be satisfactory [27].

$$l_y \le \frac{l_{road} - l_{vehicle}}{2} \qquad (1)$$

Additionally, lateral acceleration values are also required to evaluate the lane keeping performance of a vehicle. ISO regulations state that safe values of lateral accelerations should not exceed 3.0m/s^2.

As for Adaptive Cruise Control (ACC) performance, the longitudinal acceleration of a vehicle is used as a measure. Similarly for this case, ISO regulations state that safe values for longitudinal acceleration should not exceed 3.5m/s^2 when decelerating from speeds exceeding 20m/s, and not exceed 2.0m/s^2 when accelerating for speeds exceeding 20m/s.

As for the contact state of each wheel, the vertical force on each wheel can be measured to observe whether each tire is grounded or not, i.e., a measure for assessing the safety of the vehicle. If the vertical force on any wheel reaches 0, it can be implied that the wheel no longer has contact with the ground, which is a safety concern.

In order to assess the autonomous driving performance, steering angle data was used. If the autonomous driving algorithm was working as intended, steering inputs will be made to the vehicle, resulting in changes in the steering angle.

Finally, vertical acceleration values can be used as a measure for ride comfort. As a reference, traversing a speed bump at a vehicle speed of 30km/h results in a peak vertical acceleration value of 2.9 m/s^2. Since the scenarios are made for military vehicles on unpaved roads, ride comfort in itself is not an important factor. However, vibrations may cause deterioration in sensor performance and hence the ride comfort index will only be used as a reference.

Chapter 5. Simulation Results and Discussion

5.1. GS-U-N

To reemphasize, it is to be noted that simulations for paved roads have been omitted in this study due to the widely available resource and literate on paved roads. To evaluate the applicability of autonomous driving systems for UGVs on unpaved roads, 3 main indexes have been selected for assessment, safety, autonomous driving performance, and ride comfort, which will be discussed in the given order. For safety evaluation, lane keeping performance, ACC performance, and contact states of each tire will be observed.

First, the GS-U-N scenario will be discussed. From the data shown in Figure 7, lateral error values for satisfactory lane keeping performance need to be smaller than 0.175m, as per Equation 1. Simulation results for GS-U-N showed a maximum value of 0.027m, satisfying the above-mentioned constraint. For lateral acceleration, values should be below $3 m/s^2$. From Figure 8, the ego vehicle showed a maximum value of $0.0619\ m/s^2$ in this regard, satisfying the lateral acceleration constraint. Overall, metrics for measuring lane keeping performance was well within the specified range constraints.

For satisfactory ACC performance, longitudinal acceleration values were required to be kept within the range of $-3.5\ m/s^2$ to $2\ m/s^2$. Simulation results depicted in Figure 9 showed that acceleration values did not exceed $0.155\ m/s^2$, again satisfying the constraints.

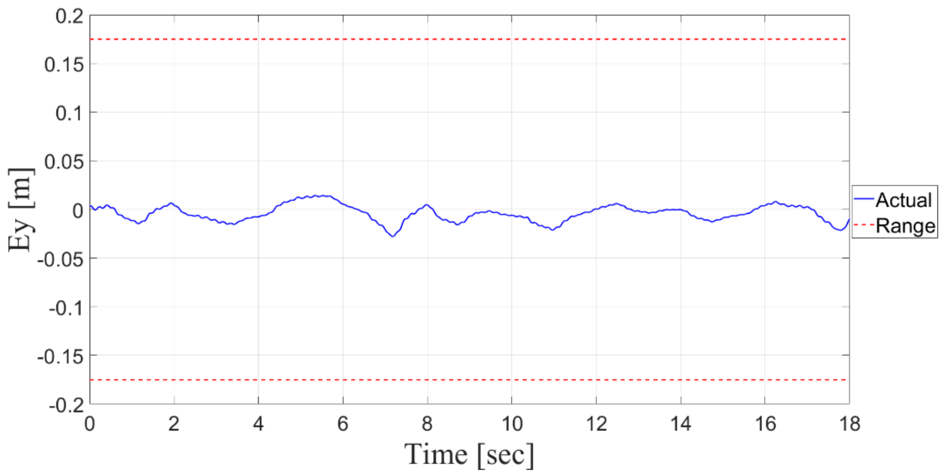


Figure 7. Lateral Error (GS-U-N)

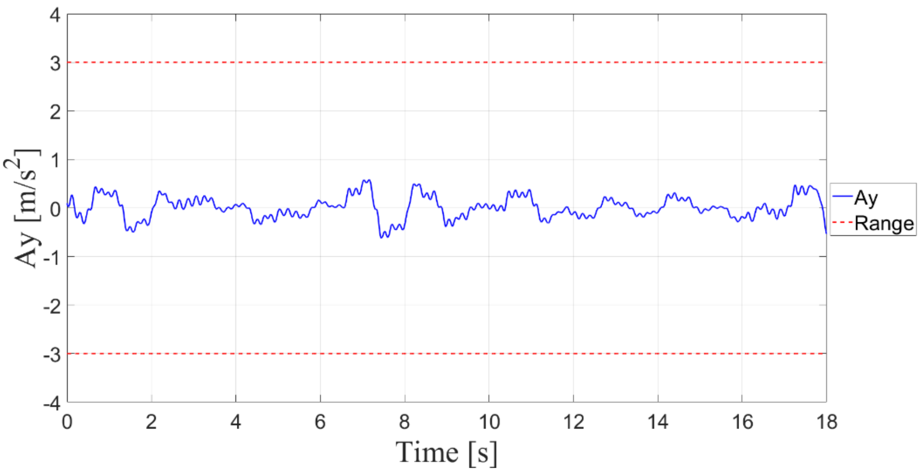


Figure 8. Lateral Acceleration (GS-U-N)

Figure 10 shows that at no point in time, the vertical force on each wheel reached 0N. This implies that all wheels kept adequate contact with the ground at all times. Overall, safety for GS-U-N can be guaranteed.

Comparing steering angle values from Figure 11 and lateral error from Figure 7 shows that the steering angle inputs were given proportionally to the lateral error,

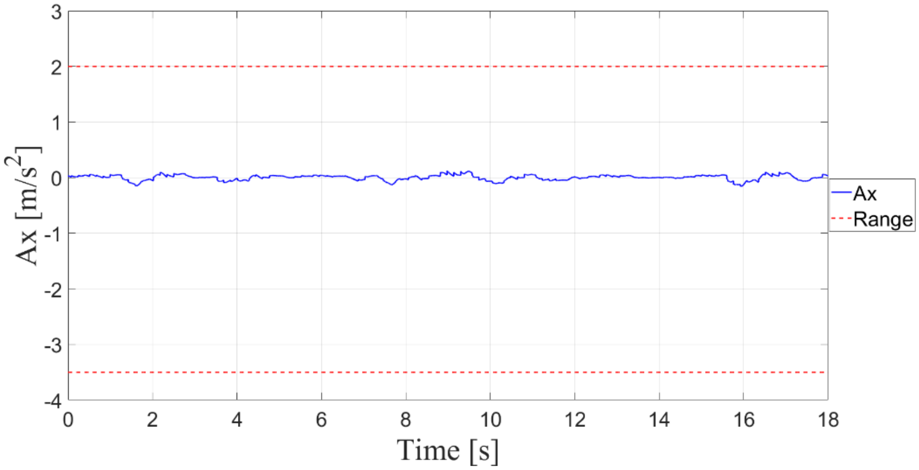


Figure 9. Longitudinal Acceleration (GS-U-N)

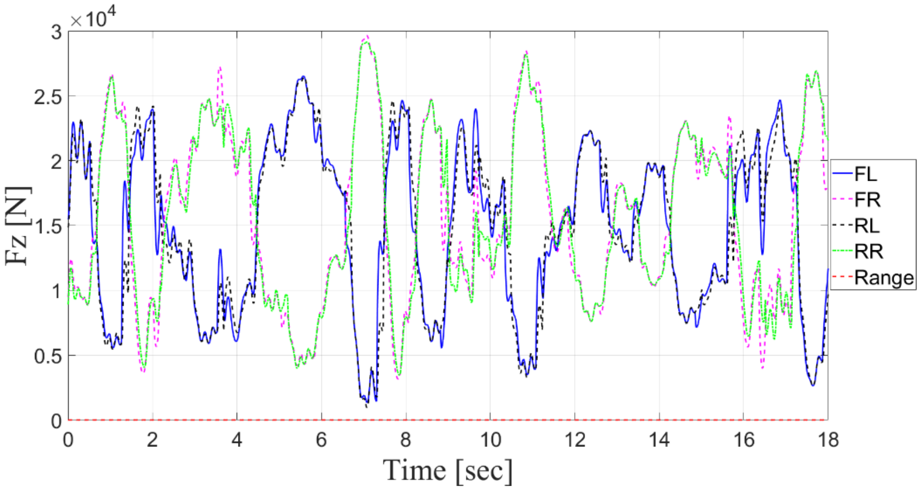


Figure 10. Vertical Force of Each Wheel (GS-U-N)

proving that the autonomous driving algorithm was working as intended.

The ego vehicle showed a maximum vertical acceleration value of 1.471 m/s^2, depicted in Figure 12. Therefore, the vehicle showed better ride comfort than travelling over a speed bump at a vehicle speed of 30km/h, implying that on-board sensors and hardware are not expected to show significant performance degradations.

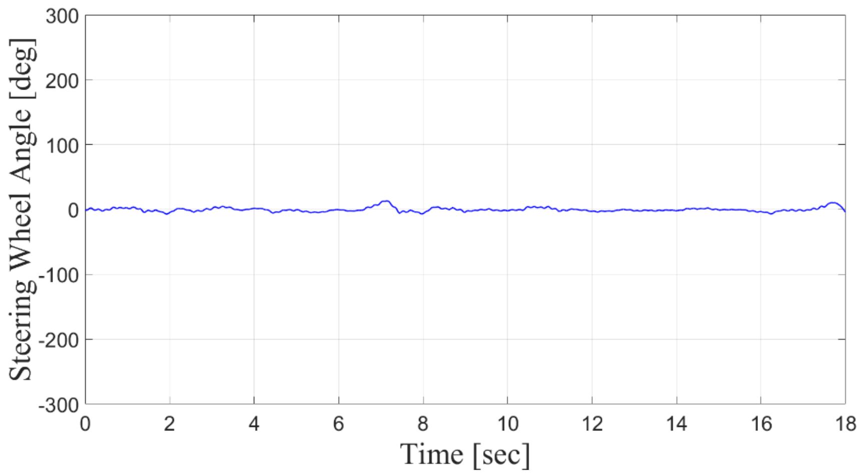


Figure 11. Steering Wheel Angle (GS-U-N)

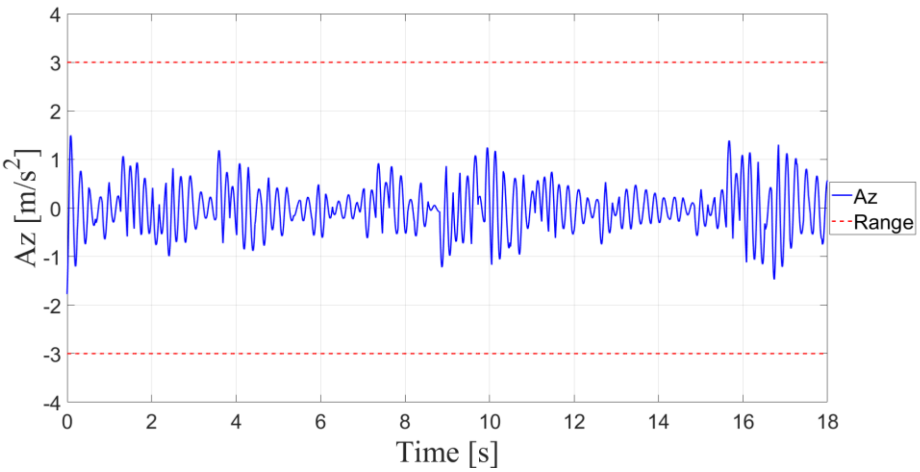


Figure 12. Vertical Acceleration (GS-U-N)

5.2. TR-U-N

TR-U-N describes traversing a curved, unpaved road. Analyzing the lane keeping performance, lateral error results in Figure 13 shows a maximum value of 0.227m, which is significantly lower than the 0.425m constraint based on Equation 1. Lateral acceleration values in Figure 14 shows that values did not exceed 1.972m/s^2, again satisfying the 3m/s^2 constraint. Overall, lane keeping performance is satisfactory for TR-U-N.

Longitudinal acceleration values, depicted in Figure 15, did not exceed the range of -3.5m/s^2 to 2m/s^2. Simulation results showed a maximum longitudinal acceleration value of 0.199m/s^2, satisfying the ACC performance constraint.

Figure 16 shows the vertical force on each wheel for TR-U-N. Again, vertical force did not reach 0N for any tire at any point in time. This implies at all wheels were kept in contact with the ground throughout the scenario. Overall, the safety

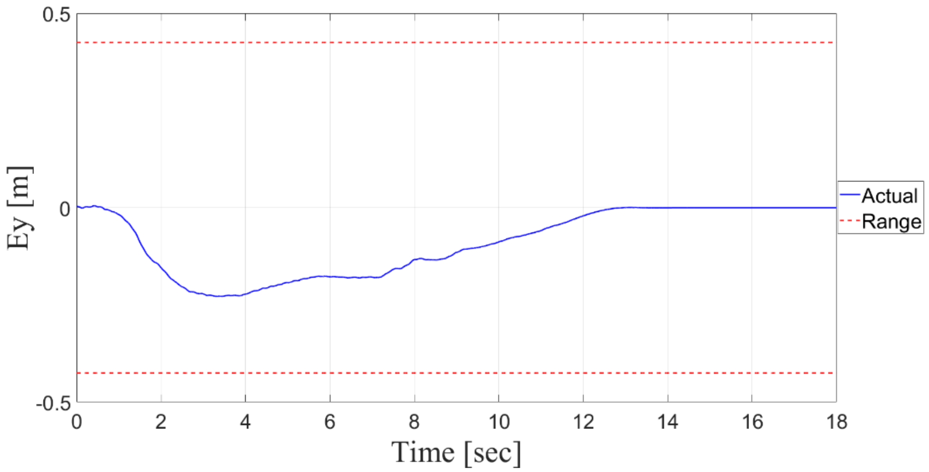


Figure 13. Lateral Error (TR-U-N)

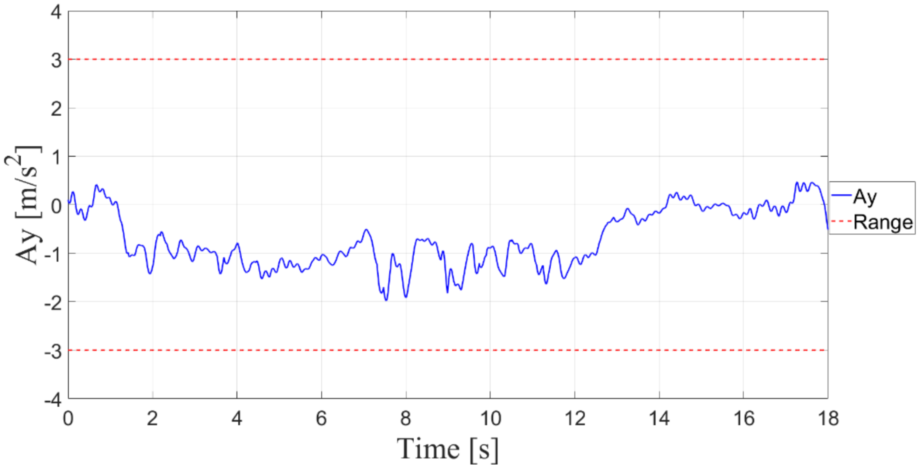


Figure 14. Lateral Acceleration (TR-U-N)

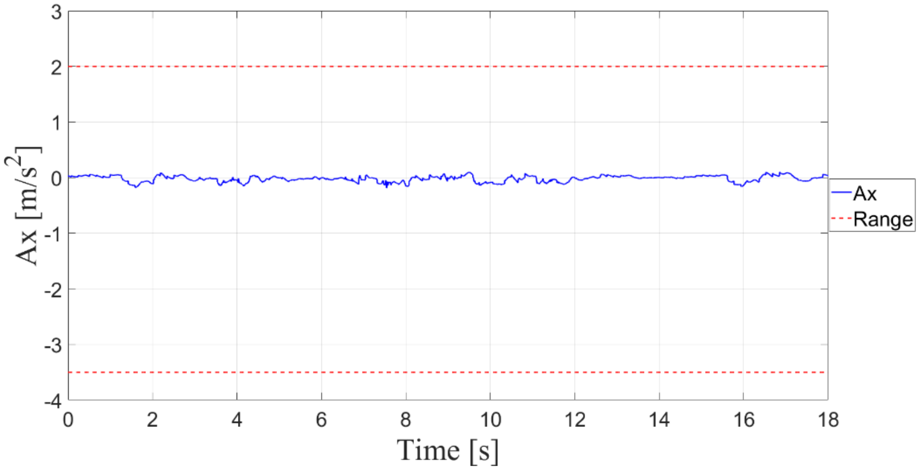


Figure 15. Longitudinal Acceleration (TR-U-N)

assessment for TR-U-N is satisfactory.

From Figure 17, it can be observed that larger steering inputs are given as compared to the previous case, which is again expected as the previous scenario describes straight line driving, whereas the current scenario depicts driving along a curved road. Nevertheless, comparisons with Figure 13 shows that proportional

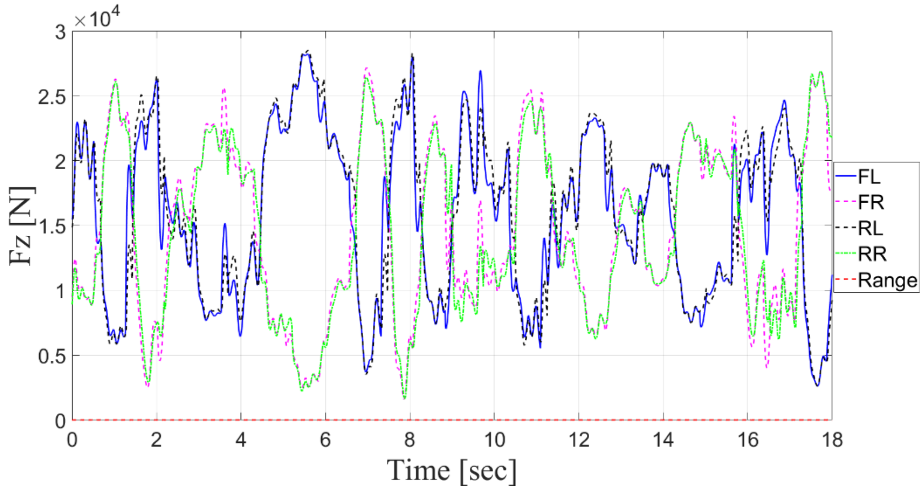


Figure 16. Vertical Force of Each Wheel (TR-U-N)

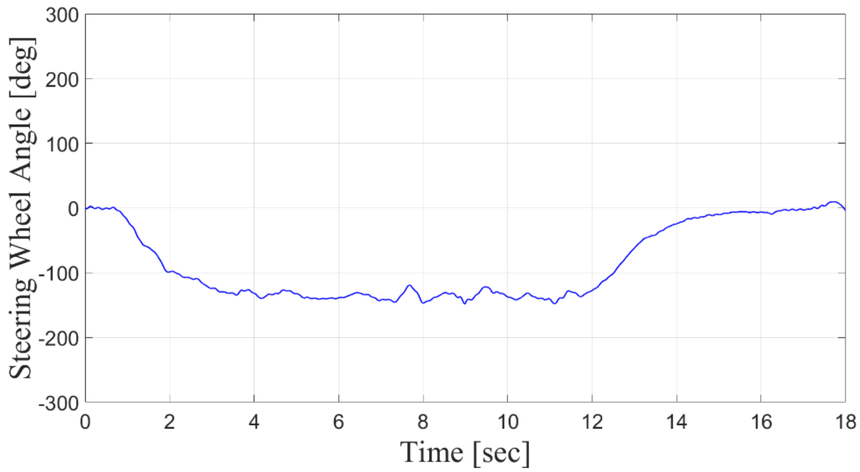


Figure 17. Steering Wheel Angle (TR-U-N)

steering inputs were given to the vehicle, showing that the autonomous driving algorithm worked as intended throughout the scenario.

Vertical acceleration values shown in Figure 18 did not exceed 1.482m/s^2. Therefore, TR-U-N shows a rather stable ride and such scenarios are not expected to loosen or shake-off any on-board hardware.

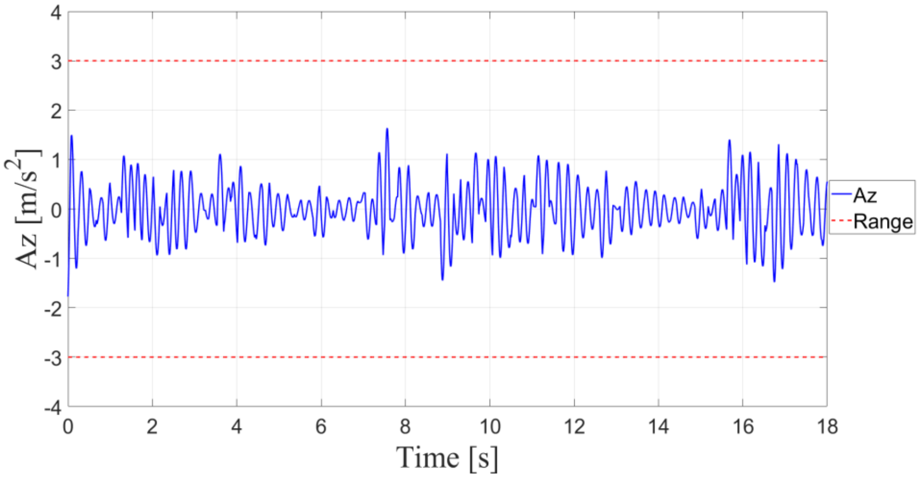


Figure 18. Vertical Acceleration (TR-U-N)

5.3. GS-U-SO

GS-U-SO describes a scenario where an evasive maneuver is made to avoid a static obstacle on an unpaved road. Lateral error values in Figure 19 shows that the maximum lateral error did not exceed 0.156m, which the 0.5m constraint set by Equation 1. Lateral acceleration values shown in Figure 20 did not exceed 2.286m/s2 as well, satisfying the 3m/s2 constraint. Overall, a conclusion can be made that GS-U-SO simulations do not significantly affect the lane keeping capabilities of the vehicle.

From Figure 21, longitudinal acceleration values showed a peak of 0.211m/s2, satisfying the ACC performance constraint as well.

Vertical force on each wheel also does not show any point where the force become 0N. Figure 22 shows that all wheels stay on the ground at all times. Overall, safety for this scenario can be guaranteed.

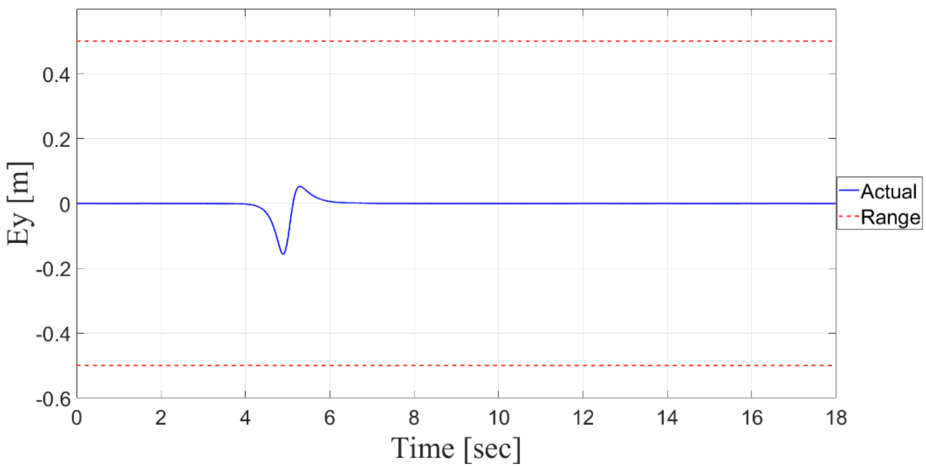


Figure 19. Lateral Error (GS-U-SO)

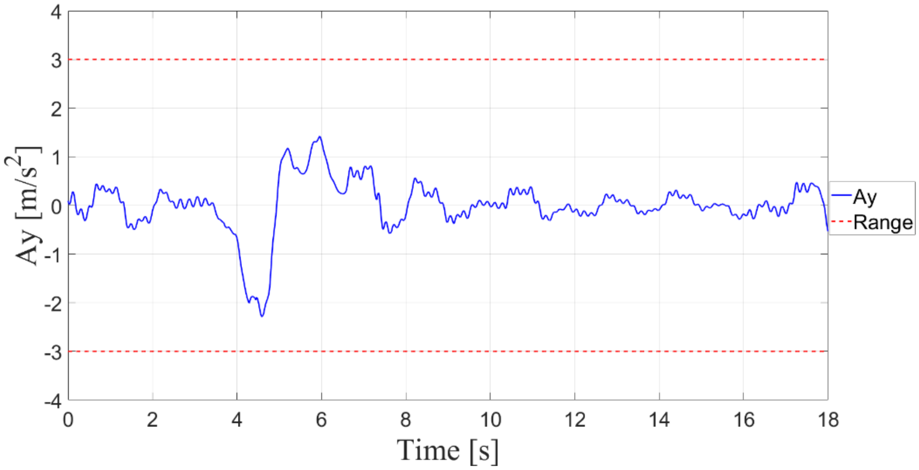


Figure 20. Lateral Acceleration (GS-U-SO)

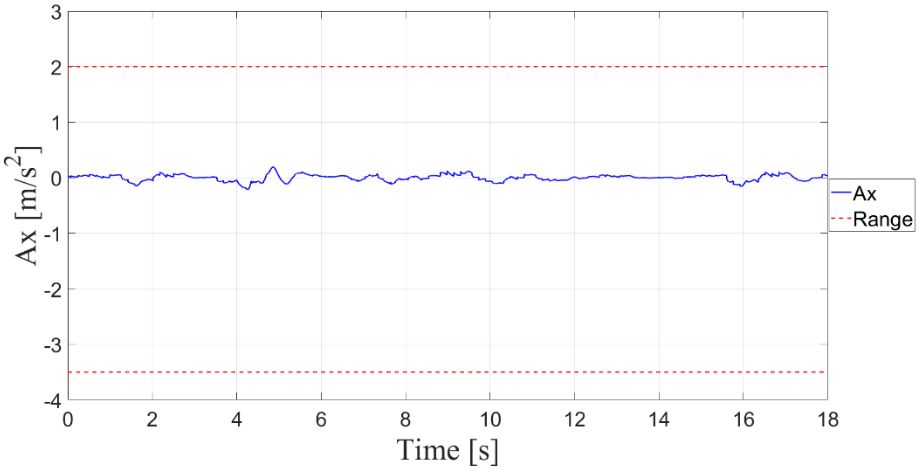


Figure 21. Longitudinal Acceleration (GS-U-SO)

As expected, Figure 23 shows a sharp change in value for the steering angle. However, one thing to note is that in the current scenario, the vehicle did not slow down before performed the evasive maneuver, which will likely be the case for real scenarios. Furthermore, despite the sharp change in steering angle, the values are kept within the specified acceptable ranges. Additionally, it can be observed that the

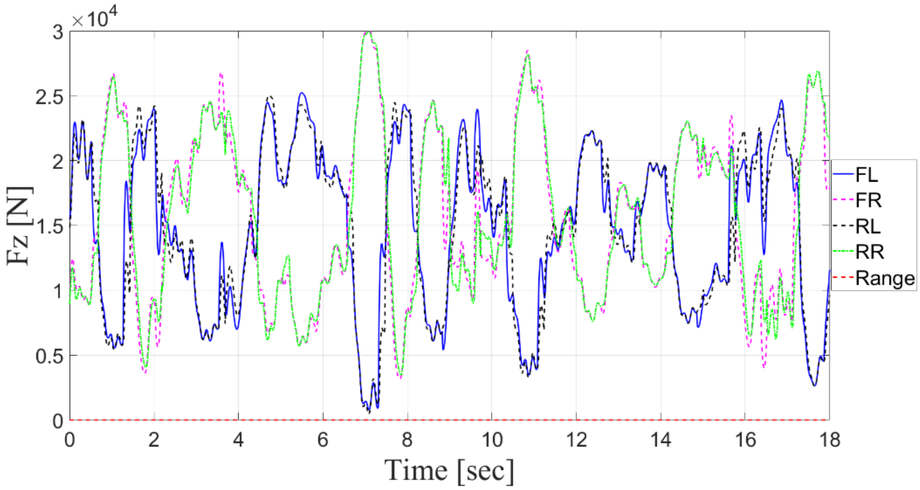


Figure 22. Vertical Force of Each Wheel (GS-U-SO)

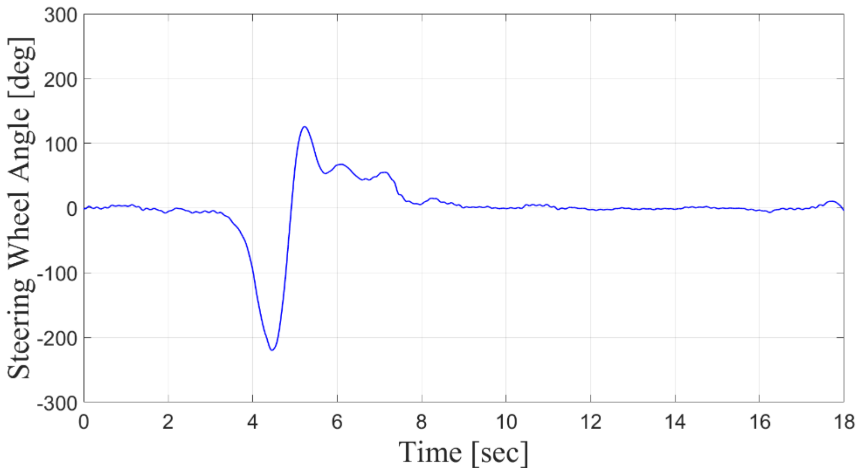


Figure 23. Steering Wheel Angle (GS-U-SO)

autonomous driving algorithm performed as intended.

Lastly for this scenario, vertical acceleration of the vehicle peaked at 1.470m/s^2 as shown by Figure 24. Hence, no significant effect is expected on the on-board sensors and hardware.

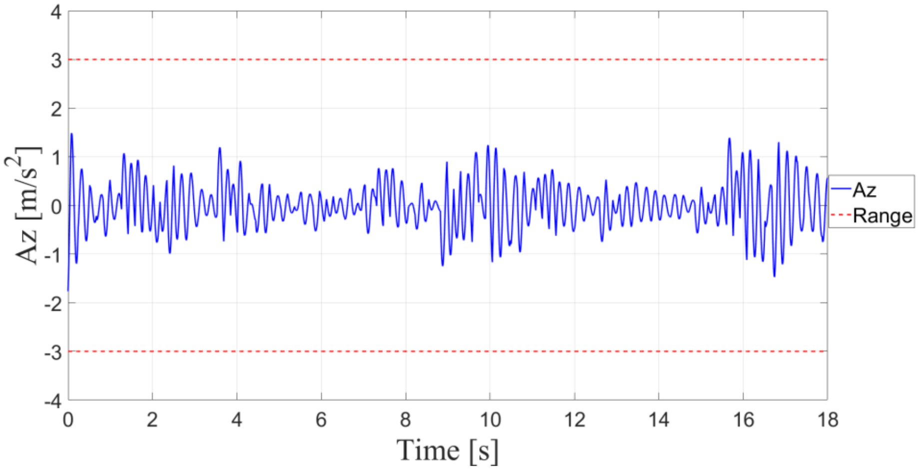


Figure 24. Vertical Acceleration (GS-U-SO)

5.4. GS-U-DO

GS-U-DO describes a scenario where a dynamic obstacle suddenly intrudes the driving lane. The scenario environment is identical to that of GS-U-N. Within this identical scenario, since there is no meaningful change in steering angle, the lane keeping performance of the vehicle is already proven to be satisfactory. But, to reiterate, Figure 25 shows that lateral error values did not exceed 0.015m and were kept within the range of 0.175m set by Equation 1. The vehicle stopped after 5 seconds of the simulation. Lateral acceleration values shown in Figure 26 also shows a peak of 0.499m/s^2, implying that no adverse effects to lane keeping performance was present.

Figure 27 shows the longitudinal acceleration values, which peaks at -2.678m/s^2, again within the specified acceptable ranges. Therefore, no adverse effects to ACC performance was present as well.

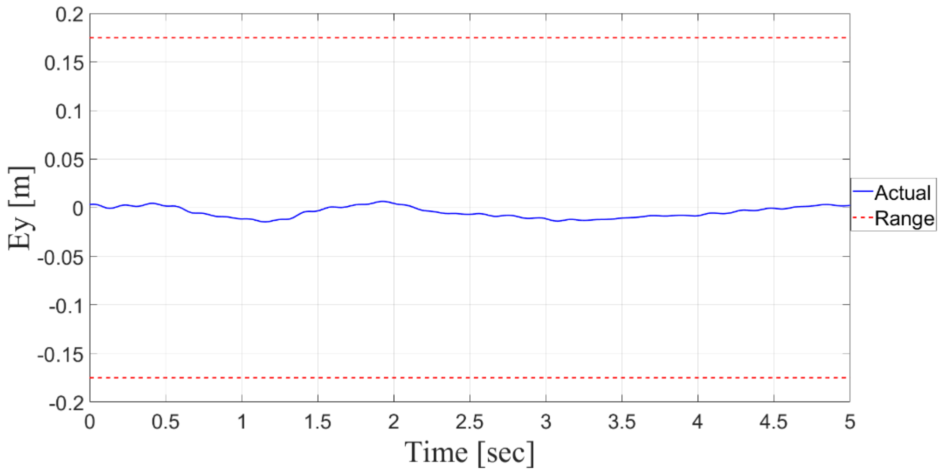


Figure 25. Lateral Error (GS-U-DO)

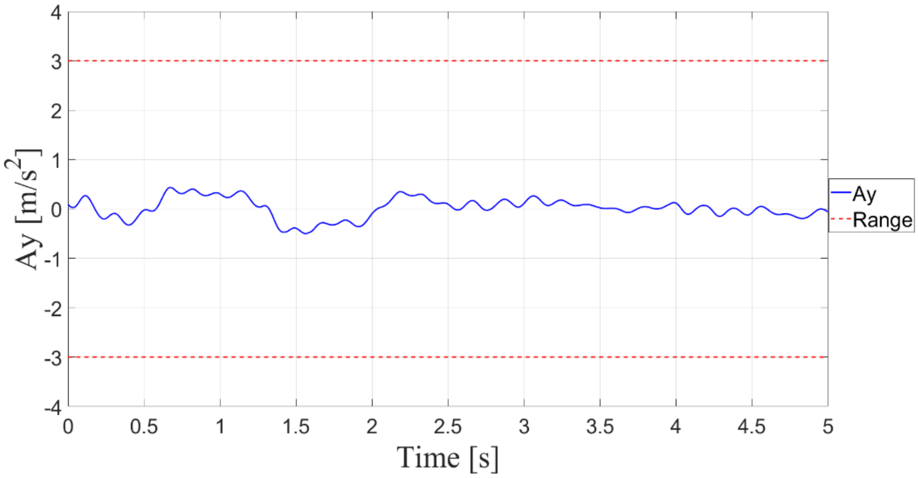


Figure 26. Lateral Acceleration (GS-U-DO)

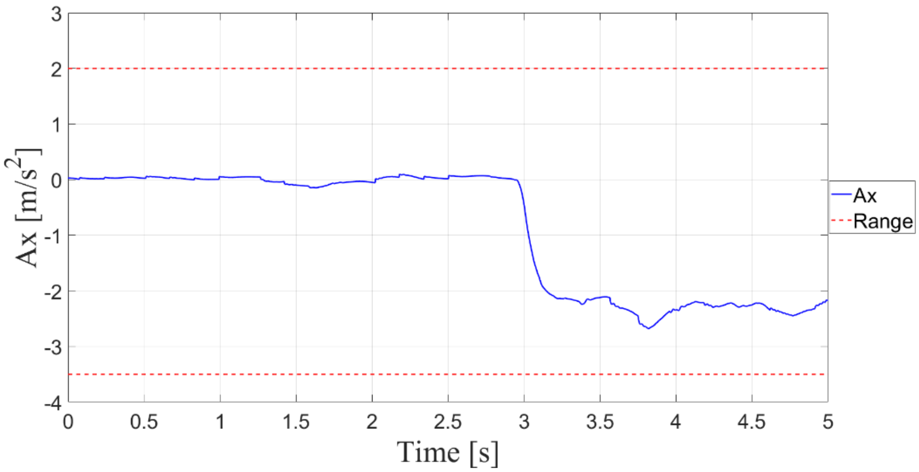


Figure 27. Longitudinal Acceleration (GS-U-DO)

Similar to the other scenarios, all wheels kept contact with the ground as shown by Figure 28 where no wheel experience 0N of vertical force at any point in time. Therefore, safety for this scenario is guaranteed as well.

The steering angle shown in Figure 29 also shows similar values to that of GS-U-N. However, it is to be noted that, upon encountering the dynamic obstacle 3

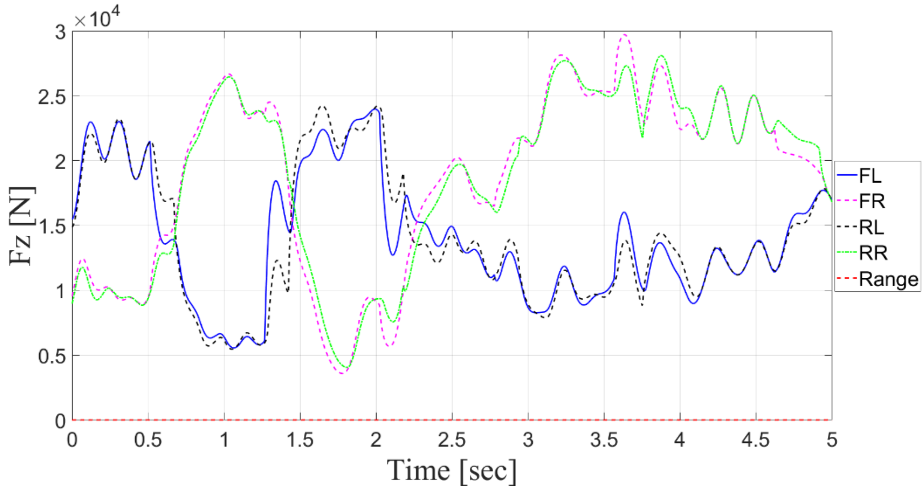


Figure 28. Vertical Force of Each Wheel (GS-U-DO)

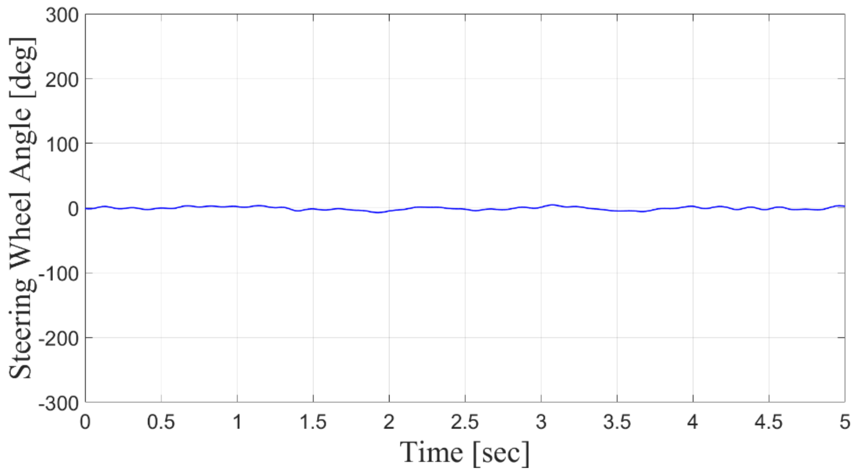


Figure 29. Steering Wheel Angle (GS-U-DO)

seconds into the simulation, a full brake maneuver was triggered (3MPa Full Braking Pressure). Figure 29 shows proportional steering inputs relative to the lateral error, thereby showing that the autonomous driving algorithm worked as intended.

Vertical acceleration also peaked at 1.497m/s^2 as shown by Figure 29. Hence, no significant effect is expected on the on-board sensors and hardware.

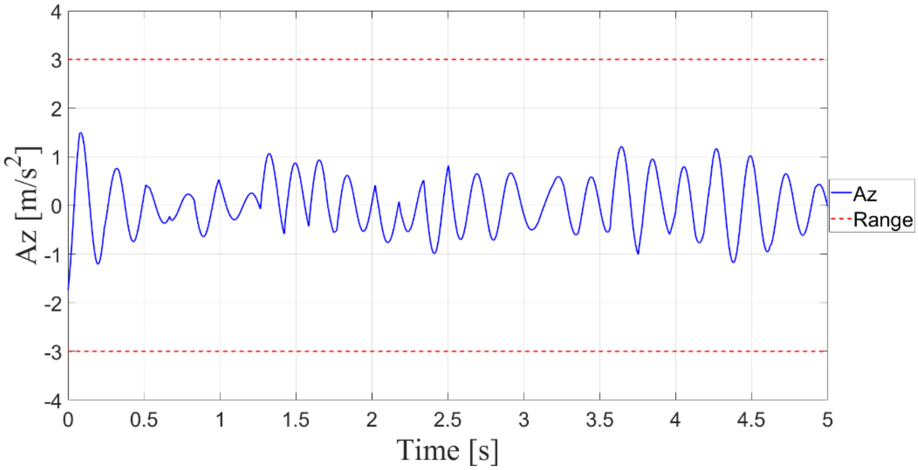


Figure 30. Vertical Acceleration (GS-U-DO)

Chapter 6. Conclusion

This paper presents a total of 10 scenarios as a method for evaluating the autonomous driving performance of UGVs. 4 scenarios were designated for unpaved roads where the overall performance of the vehicle was validated through simulations. Furthermore, transport accident cases for the Korean Army were analyzed to develop a total of 10 Functional Scenarios through the Pegasus 6-layer format. The designed Functional scenarios were further developed into Logical Scenarios by setting acceptable ranges for various scenario parameters based on the Army Field Transport Regulations and the Road Design Regulations set by the Ministry of Land, Transport, and Maritime Affairs, Finally, specific values were chosen within the specified ranges for the scenarios to develop Concrete Scenarios, which were then tested via simulations.

To design an appropriate environment for the scenarios, roads were categorized through 3 main characteristics: Roughness, Frictional Coefficient, and Road Frequency. These factors were applied to more accurately design not only paved roads but also unpaved roads. The simulation vehicle was chosen from one of the available vehicle models in TruckSim. However, exact values for vehicle mass and size can be altered to fit a wider variety of scenarios.

The developed scenarios and environments were replicated in TruckSim to observe values for lateral error, lateral acceleration, longitudinal acceleration, and vertical force on each wheel, which were then compared with values set by ISO regulations to observe the applicability of the UGVs. Overall applicability was determined by 3 indexes: Safety, Autonomous Driving Performance, and Ride comfort. Safety was evaluated by assessing lane keeping capabilities, ACC performance, and the ground contact state of each wheel. Among the 10 scenarios, 6 were for paved roads, which were omitted for simulation studies due to the widely available literature on paved road scenarios. Focus was primarily placed on the remaining 4 scenarios for unpaved roads, where simulation studies were conducted. First, lane keeping performance was evaluated through lateral error and lateral acceleration values. ACC performance was evaluated through longitudinal acceleration values. Then, wheel contact was evaluated through values for vertical force applied on each wheel. Through these 3 metrics, vehicle safety was assessed. Next the steering angle was observed to check if the autonomous driving algorithm as working as intended. Finally, vertical acceleration values were observed to determine the ride comfort.

An advantage provided by this study is that vehicle speed for these scenarios could be altered accordingly. For example, if vehicle speed was increased beyond 40km/h, which is the recommended maximum speed for vehicles travelling on unpaved roads, as per the Army Field Transport Regulations, scenarios TR-U-N and GS-U-SO could not guarantee safe lane keeping performances. These scenarios are expected to contribute in defining safe regulations such as maximum vehicle speed depending on road roughness for the Army Field Transport Regulations in the future. Furthermore, the scenarios can be used to evaluate vehicle performances before actual tests to minimize accidents. Additionally, a wide variety of Concrete scenarios can be further designed by simply changing parameters within the Logical Scenarios. The same applies to the vehicle and road characteristics, where vehicle size, weight, road roughness, frictional coefficient, and road frequency can be altered as desired to generate more specific scenarios, such as muddy or pebble roads, for testing.

Nevertheless, the study does come with some limitations. Firstly, actual vehicle tests could not be conducted due to the lack of military vehicles. Actual test results would have allowed the verification of the simulation results. Furthermore, there still exists a lack in description for road characteristics as factors such as road damping coefficients and soil compactness is expected to affect the movement of the vehicle. Since the UGVs are expected to weigh over 10t, characteristics such as roughness, frictional coefficient, and road frequency may become negligible for conditions such as excessively soft soil. Hence there still exists a need for a more comprehensive set of road parameters.

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초　　록

UGV의 운용적합성 평가를 위한 운용 시험 시나리오 연구

최근 육군은 자율주행 기술을 육군의 무기체계 및 수송체계에 도입하기 위한 연구를 진행하고 있다. 육군의 훈련 및 전시 상황은 대부분 비포장 도로로 이루어져 있어 자율주행 기술을 도입하기 위해서는 일반 도심환경과 다른 상황에서의 성능 변화를 검토해야 한다. 비포장 도로 주행에 따라 차량의 진동으로 인해 차량에 장착된 센서의 인지 능력이 저하되는 예시가 존재한다. 따라서 자율주행 기술의 도입을 위해 육군 특성에 맞는 시나리오를 정의하고, 자율주행 차량의 운용 적합성을 평가할 수 있어야 한다.

본 논문은 육군의 차량의 운용 환경에서 자율주행 차량의 운용 적합성을 평가하기 위한 시험 시나리오와 평가 지표를 개발하였다. 시험 시나리오는 페가수스 프로젝트의 6-레이어 포맷을 참조하여 제안하였다. 페가수스 프로젝트의 정의와 육군 사고사례를 소개하고 이를 바탕으로 시나리오를 개발하였다. 시나리오는 추상 수준에 따라 Functional Scenario, Logical Scenario, Concrete Scenario로 구분하여 작성하였다. 제안한 시나리오에 주행도로의 노면 특성을 포함하여, 육군 운용 환경을 반영하도록 하였다. 운용적합성 평가를 위해서 자율주행 차량의 주행

안전성, 승차감 및 자율주행 성능을 평가하고자 하였다. 안전성 평가 항목은 횡 방향 오차, 횡 방향 가속도, 종 방향 가속도, 각 바퀴 별 연직 방향 힘으로 제시하였다. 승차감은 연직 방향 가속도로 확인하였고, 자율주행 성능은 조향각으로 확인하였다.

개발한 시나리오에 대해 구성한 시뮬레이션 환경에서 자율주행 차량을 테스트하여 제시한 평가 항목에 대한 성능을 검토하였다. 시뮬레이션 환경은 TruckSim 소프트웨어와 MATLAB을 이용하여 구축하였다. 구축한 시뮬레이션 환경에서 시나리오 별 테스트를 통해 자율주행 차량의 주행 안전성, 승차감 및 자율주행 성능을 확인하였다. 특히, 제안한 시나리오 중 비포장도로 곡선 경로를 고속으로 주행하는 경우 차선 유지 성능이 악화됨을 확인하였으며, 제안한 시나리오의 필요성을 알 수 있었다. 제안한 시험 시나리오와 평가 지표는 대한민국 육군의 자율주행 차량의 무기 체계 및 수송 체계에 도입할 때 운용 적합성을 증대하는 데에 기여하고, 수송 안전 예규 작성 시에도 참고할 수 있을 것으로 예상된다.

주요어: 무인지상차량, 자율 주행, 페가수스 프로젝트, 6-레이어 포맷, 운용 적합성 평가 시나리오, 육군

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