Risk scenario designs for driving simulator experiments

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***Abstract*— Driving simulators have become widely used tools for examining the impact of driver behaviour with respect to individual driver differences or road layout by offering a safe, realistic, and controlled environment. In this research, a driving simulator experimental design is provided for testing the main risk factors defined within the i-DREAMS project. The overall objective is a detailed description of the risk scenarios for car drivers which were designed for three risk factors [i.e., tailgating, illegal overtaking, collisions with vulnerable road users (VRUs)] and two additional conditions [i.e., driver distraction and adverse weather conditions]. Accordingly, three different scenarios were designed: 1) drive-1: monitoring scenario with no intervention, 2) drive-2: scenario with driver-state independent intervention, 3) drive-3: scenario with driver-state dependent intervention. Proposed real-time interventions aim to investigate dynamic thresholds (variable-timing thresholds) that can be adapted based on scenario conditions (distraction, weather). Developed scenarios will be tested to assess the performance of the i-DREAMS system in developing a safety tolerance zone for monitoring and intervention.**

Keywords*— *Driving simulator, scenario design, tailgating, illegal overtaking, VRU collision, distraction, adverse weather conditions

I. INTRODUCTION

The progress of computer science, artificial intelligence and traffic engineering has recently contributed to rapidly enhancing simulation technologies. In particular, driving simulators have been broadly used for vehicle design, learning, training, practicing driving skills, and safety research [1] and an array of studies has been conducted to validate, investigate, and analyse driving behaviour [2, 3]. Driving simulators along with the corresponding equipment and technologies (e.g. dash cameras, wearables, Global Positioning System (GPS), steering wheel and heart rate monitoring systems, On-Board Diagnostic (OBD-II) devices or mobile phone applications) have the potential to identify not only physiological driver state indicators, such as distraction, fatigue, drowsiness, or alcohol impairment [4, 5], but also driving performance characteristics, such as speeding, harsh braking, harsh acceleration, or reaction time [6, 7].

Within this context, the i-DREAMS project aims to optimally exploit these opportunities in order to define, develop, test and validate a context-aware safety envelope for driving in a 'Safety Tolerance Zone' (STZ). The STZ has three phases: normal driving phase where the crash risk is minimal; danger phase where the crash risk increases due to the occurrence of external or within-vehicle events; and the avoidable crash phase, where a crash will occur if no mitigating action is taken by the driver or another road user. Taking into account driver background factors and real-time risk indicators, as well as driving task complexity indicators, a continuous real-time assessment will be created to monitor and determine if a driver is within acceptable boundaries of safe operation. Moreover, safety-oriented interventions will be developed to inform or warn the driver in real-time and post-trip, through an app- and web-based gamified coaching platform. The key output of the i-DREAMS project is an integrated set of monitoring and communication tools for intervention and support, including in-vehicle assistance, feedback, and notification tools, as well as a gamified platform for self-determined goal setting.

While the i-DREAMS project includes both simulation experiments and real road experiments or naturalistic driving studies, across various modes (cars, buses, trucks, and rail) in five countries, this work documents a detailed description of the risk scenario design for car driving simulator experiments. Particularly, this paper presents the simulator design scenarios for experiments that will be conducted in both Germany, and Greece. The general parameters and environment of testing, as well as the high-risk scenarios under which the i-DREAMS platform will be tested, are defined and presented. The goal of the driving simulator experiment would be to validate the correct estimation of the STZ, as well as the reliability of the STZ concept (e.g.,

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accuracy of input from monitoring devices). Furthermore, the impact of appropriate feedback in real-time (i.e., message, display, timing) will be explored.

II. Related Work

The appropriate design of simulator experiments as well as the risk scenarios within them are the cornerstone to successfully address the research questions and are discussed in this section.

A. *Design of Simulator Experiments*

The principles governing the experimental design arise from various sources, such as technical factors (e.g., characteristics of simulator devices), organisational factors (e.g., recruiting strategies), human factors (e.g., simulator sickness and carryover effects), statistical and analytical factors (e.g., confounders, sample size and statistical power). The principles of driving simulator experimental design in several stages can be summarised into four general categories [8], followed throughout the i-DREAMS experiment: 1) identifying research questions, 2) transforming research questions to quantifiable outcomes and predictors, 3) formulating hypotheses linking the outcomes and predictors, and 4) designing experiments to test the hypotheses.

B. *Risk Scenarios Examination*

The content of the simulator scenarios will focus on specific target risks. While target risks for different transport modes (i.e., car, bus, truck) may vary, on-road vehicles share similarities. To reach the scope of the i-DREAMS project, several risk factors will be measured for cars, including tailgating, illegal overtaking, VRU collision, and driver distraction and adverse weather as additional conditions. A summary of previous works and study designs of the target risk factors and conditions within driving simulator experiments is provided below.

a) Tailgating

Tailgating, a leading cause of rear-end collisions, occurs when a driver drives behind another vehicle without leaving sufficient time and space to avoid a crash. Such aggressive behaviours are provoked by traffic conditions, the behaviours of other drivers, time pressure, driver impatience or anger, and are demonstrated by unsafe driving manoeuvres. Driver aggressiveness was investigated in a driving simulator study through developing a series of frustrating events within three traffic scenarios [9]. Physiological indicators of drivers' state were not taken into consideration, and due to time limitations, the sample size used in the analysis was rather small. Another study addressed the role of forward collision warning familiarization on a driving simulator involving situations with absent or useless warnings [10]. Participants drove on a simulated two-lane rural road environment and drivers' longitudinal behaviour (i.e., speed, time headway and deceleration) was recorded. Remarkably, the method of familiarisation implemented in this study ended up lowering drivers' confidence in their driving skills and this unexpected effect may come from their insufficient mastery of the driving simulator. Moreover, warnings reduced the time required for drivers to release the accelerator in the experiment described in [11].

b) Illegal Overtaking

With regards to studies examining illegal overtaking, control strategies and decision-making of drivers executing overtaking manoeuvres in a fixed-base driving simulator, were investigated [12]. During overtaking manoeuvres, drivers were instructed to overtake other cars in a highway environment; however, one of the limitations was that the leading cars were not able to change their speed and/or position (e.g., make a left turn) with the result that the frequency of perceptual and decision-making errors may have been underestimated. Another study aimed to examine the effect of traffic density on drivers' left and right lane change and overtaking manoeuvres under three traffic density conditions (high, medium and free traffic density) [13]. The sequence of traffic density conditions was arranged randomly to eliminate the effect of time order, whereas other factors, such as road characteristics and weather conditions, were not considered. Nevertheless, drivers' perceptions of other vehicles and the surroundings had a potential bias in the simulated driving environment. In another study, 100 drivers participated in an interactive driving simulator experiment, in which several scenarios of two-lane highway segments with different geometric and traffic conditions were developed [14]. The scenarios were designed only during sunny day time with good visibility, so adverse weather conditions were not examined.

c) Vulnerable Road Users Collision

VRUs, such as pedestrians, motor/pedal cyclists, and e-scooter riders, are more endangered in traffic, as they have no protection to safeguard them in case of collision. VRU crash scenarios have been frequently designed in a driving simulator environment. Chrysler et al. [15] developed 18 different crash imminent scenarios by using the analyses of pedestrian-vehicle crash frequency and severity. The crash scenarios were triggered at intersection and mid-block crossing areas, and the visual distraction was employed to direct the driver's visual attention away or towards the crossing pedestrian. The scenarios were simulated for day and night-time, and within a variety of roadside environments and speed. Another experiment created the crossing scenarios at 1) mid-block setting using two-level risk factors of time of day, crosswalk marking, roadway type, and pedestrian dressing colour, and 2) a within-subjects repeated measures full factorial design that related to pedestrian safety at intersections, including time of day, vehicle movement, pedestrian movement, and pedestrian visibility factors [16]. Oza et al. [17], aiming at improving pedestrian safety, examined four pedestrian scenarios in simulation: 1) crosswalk scenario: a pedestrian traversing a marked crosswalk with yield-to-pedestrian sign, 2) intersection scenario: the driver confronts a pedestrian crossing the street, after entering the intersection on green phase, 3) turning scenario: the driver confronts a pedestrian, when making a left turn at a signalised intersection, 4) bus-stop scenario: a jaywalker, initially obstructed from the driver's view by a stopped bus, commences crossing the road in front of the driver.

d) Driver Distraction

Distraction refers to the driver temporary diversion of attention from the task of safe driving to the secondary task(s) not related to driving. The secondary task(s) can result from in-vehicle or external sources and engage drivers; 1) visually: tasks that take the driver's eyes off the road, 2) auditory: noises and sounds that can divert driver's attention away from the driving task, 3) physically: tasks that involves removing driver's hand/hands from the steering wheel, and 4) cognitively: tasks that take the driver's focus and attention off while driving.

Amongst various distractions posed to drivers, the use of a mobile phone is associated with highest risk. Texting and driving, as a form of mobile phone distraction, refers to the act of writing/reading a text message, email, or browsing a website on a mobile phone while driving, and can engage drivers visually, auditory, physically, and cognitively. According to relevant literature, drivers who are texting and driving are more prone to be involved in a safety-critical event [18]. However, assessing the relationship between mobile phone use and crash risk is complicated. Some previous studies estimated from between two to nine times higher crash risk for drivers engaged in mobile phone related distraction than non-distracted [19, 20, 18].

Dumitru et al. [21] applied distraction by engaging drivers in Facebook tasks; pressing the like button, performing a check-in, and commenting with the phrase "I'm driving". For a visual-manual distraction, drivers were asked to read out the four randomly generated characters that they received in the form of a text message [22]. The texting and driving distraction was simulated in another experiment by classifying tasks as complex (reading/writing a message more than 10 characters) and simple (less than 10 characters) [23].

e) Adverse Weather Conditions

Due to the considerable impacts of weather on driving behaviour, the occurrence of adverse weather conditions increases the risk of traffic accidents. In particular, a significant 35% and 23% increased risk for road crashes was found due to rain and snow, respectively, while no increase was identified due to frost [24]. A study on the characteristics of driver workload was conducted in a simulated driving experiment on a freeway, under different weather situations (i.e., clear day, moderate rain, moderate rain-fog) and it was revealed that the worse the weather conditions, the higher the driver workload [25]. However, the limited sample should be noted as limitation. Furthermore, a significant impact of rain on driving behaviour and traffic operations, which increased with the intensity of rainfall, was identified [26]. Lastly, an expressway road scenario was built in a driving simulator [27] under adverse weather conditions (i.e., rain, snow, heavy dense fog) and the results demonstrated that bad weather conditions tended to deteriorate car-following performance.

To sum up, it should be mentioned that there has been a limited number of studies, without satisfactory participant samples, focused on adverse weather conditions and driver distraction. Thus, an investigation on tailgating, overtaking and VRU collisions in combination with distraction and adverse weather conditions is needed.

III. Methodology

A. Driving Simulator Experiment

Taking the experimental design considerations into account, the selected risk factors were used for designing the scenarios for the simulator trials. The number of risk factors is considered adequate for a 45-minute session, and was split into three scenarios, one for each drive (each 15-minute) as well as a baseline trial beforehand. In particular, the first scenario (drive-1) includes monitoring drive without interventions, the second scenario (drive-2) includes an intervention drive with fixed timing warnings, and the third scenario (drive-3) includes an intervention drive with interventions based on task completion capability. For the latter one, the modified conditions can cause the intervention thresholds to be variable. Moreover, each risk factor is captured by several separate events to ensure adequate validity of the observations per risk factor.

This paper will present the scenario design for the experiments conducted both in Greece and Germany, as they investigate similar risk factors. In Greece, the driving simulator experiment will take place at the Department of Transportation Planning and Engineering of the National Technical University of Athens (NTUA), where the FOERST Driving Simulator FPF is located. The driving simulator provides a 170° field of view through three 40'' LCD screens. It features adjustable driver seat, steering wheel, dashboard, and two external and one central mirror that appear on the side and on the main screen and display in real time objects and events. Driver controls include pedals (throttle, brake, clutch), gears shifter, and authentic controls for turn indicator, low/high beam, and horn. The FOERST simulator records data at intervals of 33-50 milliseconds, meaning that each second collects values for each variable up to 30 times. The experiment in Germany will be held at the chair of Transportation Systems Engineering of the Technical University of Munich (TUM) using a custom simulator developed by DriveSimSolutions (DSS). The driving simulator is based on a Peugeot 206 and benefits same authentic parts, such as the complete dashboard, adjustable driver seat, steering wheel, and instrument cluster with functional speed and tacho gauges. Visuals are provided through three 49'' 4K monitors that provide a 135° field of view. The simulator uses fully customizable STISIM Drive 3 software, allowing for creation of custom scenarios and data collection at every simulation update frame.

The sample of participants will include 60 healthy participants aged 18-75 years old: 30 Greek drivers and 30 German drivers.

It is worth noting that as there are differences in speed limits and road layout between Greece and Germany, each simulator experiment will be conducted with different speed limits per roadway type, as mentioned in TABLE I.

TABLE I. Greek and German Speed limit regulations

Roadway type	**Greece**	**Germany**
	Speed limits (km/h)	
Two-lane and four-lane two-way urban area with one parking lane at each direction	30	50
Six-lane two-way highway area	130	no speed limit
Two-lane and four-lane two-way rural area without parking lane at each direction	70	70

B. Application of Safety Interventions

During the intervention scenarios, based on the personalized identification of episodes of successful and degraded vehicle operation with respect to the STZ, customized interventions will be proposed. These include real-time and in-vehicle warnings (e.g., audio, visual, haptic) in safety-critical situations (i.e., close to the boundary of the STZ). The two intervention scenarios are described in detail below:

- First intervention scenario: a scenario influencing driving behaviour (i.e., with the use of interventions).

During the intervention scenario, there will be a focus on fixed timing thresholds (and/or message and/or display)

- Second intervention scenario: a scenario to assess the impact of certain conditions on driving behaviour (i.e., distraction, adverse weather conditions). Thus, a comparison can be made to evaluate the changes of driver behaviour caused by optimizing the intervention thresholds (by using dynamic or time-variable thresholds).

Regarding the timing, multistage warnings in alignment with the different stages of the STZ will be tested (e.g., early/late warnings). Research has indicated that early warnings could be beneficial, for instance during a first stage to inform the driver, and during a second stage to pre-warn the driver [28].

C. *Development of Risky Scenarios*

The experimental scenarios will focus on tailgating, illegal overtaking and VRU collision. It should be noted that the variables of interest for the different risk factors are:

- For tailgating: time headway, distance headway, forward collision avoidance.
- For illegal overtaking: average speed, standard deviation of lateral acceleration, standard deviation of lateral position, steering variability, signal use.
- For VRU collision: detection time, reaction time, steering variability, and brake reaction.

For the additional conditions investigated in drive-3 scenario, following variables are of interest:

- For distraction: mobile phone use, attention.
- For adverse weather condition: time headway, distance headway, time-to-collision, reaction time.

Risk factors will be investigated through a series of risky events during the drive-1, drive-2, and drive-3 scenarios.

a) Tailgating

To investigate tailgating, there will be a lead vehicle in front of the driver, to measure following behaviour (under safe driving conditions). Three critical events (CEs) will be investigated within the driving simulator processing. (car)$_1$ refers to the driver and (car)$_2$ refers to the car driving in front of the driver within all risky events (Fig. 1):

- **CE 1**: A (bus/car)$_2$ is driving with low speed in front of (car)$_1$, while the available gap in the opposite traffic is not long enough for an overtaking manoeuvre. The (car)$_1$ has to follow (bus/car)$_2$ for a distance of 300-350m.
- **CE 2:** A (car)$_2$ overtaking (car)$_1$ and suddenly merges into the lane in front of it with the result that (car)$_1$ needs to adjust the driving speed.
- **CE 3:** A car enters the highway in front of (car)$_2$, with the result that the leading (car)$_2$ needs to make a harsh brake.

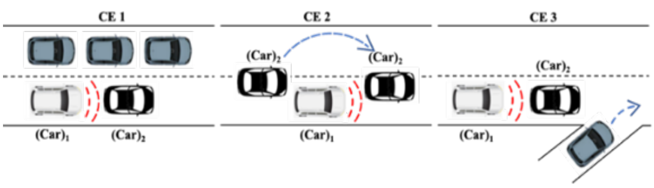

Fig. 1. A schematic overview of risky events of tailgating

b) Illegal Overtaking

To investigate illegal overtaking, risky events will be included whereby an illegal overtaking manoeuvre is provoked as follows (Fig. 2):

- **CE 4:** A (car)$_2$ suddenly getting out of a parking position, with the result that (car)$_1$ needs to make an illegal overtaking or a harsh brake to avoid a potential crash risk.
- **CE 5:** The door of a parked (car)$_2$ suddenly opens in front of (car)$_1$, while (car)$_1$ is approaching.
- **CE 6:** An unexpected incident happens in (car)$_2$, with the result that (car)$_1$ needs to adjust the driving speed and do any manoeuvring.

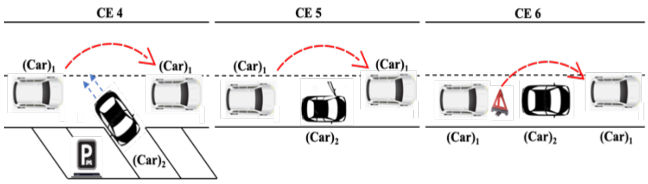

Fig. 2. A schematic overview of risky events of illegal overtaking

c) VRU Collision

The VRU collision is investigated by triggering three crash prone events between pedestrian and vehicle. In all events, the pedestrian starts crossing at a speed of 1.2 m/sec (Fig. 3):

- **CE 7:** A pedestrian crosses the road illegally - the traffic light does not permit crossing- when driver is approaching the intersection on green phase.
- **CE 8:** At a mid-block crossing, when a pedestrian - initially obstructed from the driver's view by a bus- attempts to cross the road while the car is approaching.
- **CE 9:** A pedestrian -initially obstructed from the driver's view by bushes- crosses the road at crossing, while the car is approaching.

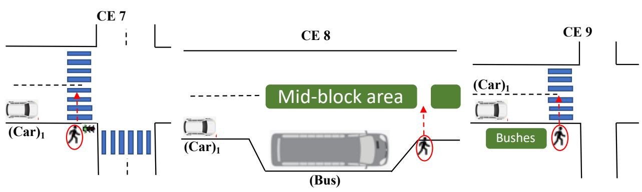

Fig.3. A schematic overview of risky events of VRU collision

Driver distraction and adverse weather conditions will be tested during the drive-3 scenario:

a) Driver Distraction

In total, eight text messages at two levels of simple and complex will be sent by the operator to the participants during the drive-3 trial, in which: six text messages will be triggered before the critical events, and two text messages will be triggered, when there is no event. Before the trial, participants will be trained to only reply to the text messages, which are in the form of a question. The text messages can be sent or received both in German and English.

b) Adverse weather conditions

Some high-risk scenarios for passenger cars will contain driving tests under adverse (i.e., rain, cloud, fog, snow) weather conditions to increase task demand. Specifically, during the third test scenario in which bad weather will be taken into account as a condition for which warning timings might be changed (given sooner, under the assumption that the driver needs more time to react to adjust to the situation).

TABLE II. DRIVER-1 SCENARIO DESIGN - GREECE

	Road type	Distance (m)	Description
Run in		**0**	
Section-1 (tailgating)	Urban - 2x2	500	
		1650	CE 1
		2000	🚘
		2350	↓
Section-2 (illegal overtaking)	Urban - 2x2	3350	☰
		3750	CE 4
		4100	right turn
section 3 (tailgating)	Rural -2x2	5150	left turn
		5650	CE 2
		6150	🚘
		6750	↓
Section-4 (illegal overtaking)	Urban -2x2	7150	┼,
		7850	CE 5
		8300	left turn
Section-5 (tailgating)	Highway - 3x3	8800	right turn
		9800	CE 3
		10750	🚘
		11300	▼
Section-6 (illegal overtaking)	Urban - 2x2	12000	┼,
		12400	🚘
		12750	CE 6
		13100	↓
		13500	right turn
End scenario		**15000**	

TABLE III. DRIVER-1 SCENARIO DESIGN - GERMANY

	Road type	Distance (m)	Description
Run in		**0**	
Section-1 (VRU collision)	Rural -1x1	500	
		750	┼,
		1500	┼,
		1850	CE 9
Section-2 (tailgating)	Rural -2x2	2250-2350	🚘
		4100	🚘🚘
		4400	CE 2
Section-3 (tailgating)	Highway - 3x3	4700	Enter highway
		5200-5700	🚘
		7500-8500	🚘
		8500	↰
		8500	CE 3
		9000	Exit highway
Section-4 (VRU collision)	Urban -2x2	9300	┼!
		9700	☰
		11000	┼!
Section-5 (VRU collision)	Urban -2x2	11450	┼, STOP
		11850-11890	bus at bus-stop
		11890	CE 8
		12350	┼!
		12750	☰
		13150	CE 7
Section-6 (tailgating)	Urban -1x1	13500	┼,
		14350	┼, STOP
		14700-15000	🚘
		15000	CE 1
End scenario		**15500**	

┼,: Unsignalised intersection, ┼, STOP: Intersection stop sign, ┼!: Intersection traffic light,
☰: Pedestrian crossing, ↓ :Reduce driving speed, ▼ Harsh brake,
🚘🚘 : Overtaking (car)2, 🚘 : car in front of (car)1, ↰: car merging into the lane of (car)2,
CE: Critical Event

The distribution of the events across two monitoring scenarios, including the specific locations are presented in TAB.II-III for programming the driving simulator scenarios in i-DREAMS project. Sections are used to counterbalance between scenarios and several 'neutral' events (filler pieces) are embedded creating a realistic driving scenario and minimising confounding effects (e.g., order / learning effects). The intervention scenarios in the drive-2 trials are designed using similar components, but with other order of events. The effect of adverse weather condition and distraction (see TAB.IV) will be investigated through the monitoring scenarios in the drive-3 trial. An example of the designed CE is shown in Figure 4 for the drive-1 scenario in Germany.

TABLE IV. DISTRACTION DESIGN IN DRIVE-3 SCENARIO - TUM

Distance (m)	CE	Distraction	Text Message (TM)
1850	CE 9	Reading TM	"Thank you for participating in the experiment"
4100-4400	CE 2	Reading and replying TM	"Can you name two cities you want to visit?"
5000	No event	Reading TM	"Your dentist appointment is scheduled for 30/11/2020 at 14:15"
7500-8500	CE 3	Reading and replying TM	"Where is your hometown?"
11850-11890	CE 8	Reading TM	"Nice to see you at the café yesterday"
13150	CE 7	Reading TM	"50% discount on online orders! Today only!"
14100	No event	Reading and replying TM	"What are two things you enjoy doing the most?"
14700-15000	CE 1	Reading and replying TM	"27+32=?"

Fig.4. A screenshot of CE7 in the drive-1 scenario – Germany

IV. DISCUSSION

The aim of the current research is to provide a tentative simulator experiment design that will act as the basis for testing the main risk factors of the i-DREAMS project. The overall objective is a detailed description of the risk scenarios which will be designed for different risk factors (i.e., tailgating, illegal overtaking, VRU collisions), driving conditions (i.e., distraction, and adverse weather conditions), and three different scenarios (i.e., monitoring, intervention with fixed timing, and intervention with a changed condition). For the experiments, 60 participants from different age groups (18-75 years old) will be asked to drive in urban, rural and highway road environment with low and high traffic volume. Special scenarios will be developed within a simulated environment to test a variety of situations to assess the performance of the i-DREAMS system.

To test the confounding effects and effect modification, the latter intervention scenario will be included in the experimental design in which environmental conditions will serve as a condition for driving behaviour. Moreover, the experiment will include multiple risk events to increase the within participant variability and consequently increase the statistical power of the study. It should be mentioned that the order of scenarios and events will be randomized among the participants and during the trials. Additionally, each risk factor will be captured by several separate events, to ensure adequate validity of the observations per risk factor. Moreover, the simulator experiments will be supplemented by questionnaires on the participants with regards to the STZ, to validate the corresponding safety capabilities of the system. The acquisition of additional equipment for investigating risk factors is also examined. For example, eye trackers (e.g., Tobii-Pro 2) may become useful for the identification of distraction during the trials.

Nevertheless, several aspects of the experiments need to be carefully taken care. Initially, simulation sickness of participants and dropout rates need to be limited during the span of the experimental procedures, to obtain consistent results for all risk factors. Furthermore, the fact that different simulators are going to be used in Germany and Greece may result in data with different resolution and quality and, consequently, in contradicting results. Therefore, analyses methods that can accommodate different data resolutions, as well as cultural and population characteristics, such as Bayesian Networks and Structural Equation Models are going to be investigated. Finally, the effect of the COVID-19 pandemic on the successful completion of the experiments is also a crucial factor that should be proactively contemplated.

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