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The Effect of Multifactor Interaction on the Quality of Human–Machine Co-Driving Vehicle Take-Over

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Abstract: This paper investigates the effects of non-driving related tasks, take-over request time, and take-over mode interactions on take-over performance in human–machine cooperative driving in a highway environment. Based on the driving simulation platform, a human–machine collaborative driving simulation experiment was designed with various take-over quality influencing factors. The non-driving related tasks included no task, listening to the radio, watching videos, playing games, and listening to the radio and playing games; the take-over request time was set to 6, 5, 4, and 3 s, and the take-over methods include passive and active take-over. Take-over test data were collected from 65 drivers. The results showed that different take-over request times had significant effects on driver take-over performance and vehicle take-over steady state ($p < 0.05$). Driver reaction time and minimum TTC decreased with decreasing take-over request time, maximum synthetic acceleration increased with decreasing take-over request time, accident rate increased significantly at 3 s take-over request time, and take-over safety was basically ensured at 4 s request time. Different non-driving related tasks have a significant effect on driver take-over performance ($p < 0.05$). Compared with no task, non-driving related tasks significantly increase driver reaction time, but they only have a small effect on vehicle take-over steady state. Vehicle take-over mode has a significant effect on human–machine cooperative driving take-over quality; compared with passive take-over mode, the take-over quality under active take-over mode is significantly lower.

Keywords: human–machine cooperative driving; multi-factor interaction; driver take-over performance; vehicle take-over steady state

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1. Introduction

Along with the development of artificial intelligence technology, sensor technology, big data, and other science and technology, the degree of automobile automation has been steadily increasing. However, it still takes a long time for the development of intelligent driving technology to transition fully autonomous driving, so we will be in the human–machine cooperative driving stage for a long time [1,2]. The system shares the control of the vehicle with the human, and when the system encounters an emergency and cannot handle it effectively, the system will send a take-over request to the driver, who needs to quickly enter the driving state and take over the control of the vehicle in time, otherwise, it will most likely lead to a traffic accident [3,4]. Therefore, how to complete the take-over smoothly and safely between automatic driving and manual driving needs to be studied in depth, and the process of this switch involves various aspects, such as scenario factors, driver reaction time, vehicle performance, and human–computer interaction [5].

In recent years, many scholars have conducted studies on take-over behavior and its influencing factors in human–machine cooperative driving. These studies have shown that factors such as non-driving related tasks [6–8], the take-over request method [9,10], and time [11,12] have significant effects on take-over quality. Choi et al. [13] designed driving simulation experiments for two non-driving related tasks, N-back and SuRT (surrogate reference task), and they concluded that both the cognitive load and visual load affect the quality of autonomous driving take-over, but this effect occurs in different time courses. Niu et al. [14] designed driving simulation experiments for three take-over request times, two non-driving related tasks, and two highway take-over scenarios. The analysis results showed that the driver reaction time for the two non-driving related tasks had a significant effect. Lin et al. [15] found that lower crash risk drivers had shorter brake reaction time compared to high crash risk drivers. For all drivers, the engagement in a task led to longer response times, and the time budget affected the longitudinal vehicle control. Shi and Bengler [16] found that characteristics of a non-driving related task influence take-over behavior; manual driving following behavior depends on the compatibility of the demand profiles of the respective non-driving related task and the following driving task. Shi et al. [17] studied the take-over characteristics of college students under the influence of various factors, and found no significant effect of different secondary tasks on take-over time and maximum synthetic acceleration under four request time conditions ($p > 0.05$). Wu et al. [18] tested the effects of manual driving, 5 s take-over request lead time, and 7 s take-over request lead time on take-over performance through driving simulations, and showed that take-over request lead time significantly affected acquisition performance and safety.

In addition, many scholars have explored the impact of drivers' personal characteristics on the quality of take-over. In terms of gender, Hardman et al. [19], Robertson et al. [20], and Nielsen and Haustein [21] found that men have more positive attitudes towards automated driving compared to women. In terms of age, Wang et al. [22] and Scott Parker et al. [23] found that driver perception levels decreased with increasing age, which in turn negatively affected take-over performance. However, some studies have reached the opposite conclusion. Li et al. [24] conducted a driving simulation test and found that there was no significant difference in most of the measurements adopted to quantify take-over performance between female and male drivers. Zhang et al. [25] found no significant effect of driver age on take-over time. Zhou et al. [26] showed that smart vehicle take-over quality was not statistically significantly affected by age, but driver knowledge of human–machine co-driving had a significant effect on take-over quality and safety.

Other scholars have analyzed driver performance at the moment of take-over from driver physiological states, such as eye movements and EEG. Using driver eye-movement data and the NASA-TLX workload questionnaire, Lu et al. [27] determined the effect of different take-over request modes on visual reaction time under visual load from both objective and subjective aspects, so as to evaluate the take-over quality. Wörle et al. [28] collected the EEG data of drivers by setting up a long-term driving simulation test, and found that the quality of the take-over within 15 s after waking up was damaged, resulting in more driving errors. Alrefaie et al. [29] used heart rate and pupil diameter data to study the quality of human–machine co-driving vehicle take-over under the influence of non-driving related tasks.

Several scholars have also explored other factors that affect take-over quality. For example, Kaye et al. [30] found that the use of handheld cell phones under human–machine co-driving conditions did not negatively affect vehicle take-over quality. In addition, the driver's level of trust in the autonomous vehicle affects their cognitive load during autonomous driving [31]. Zhang et al. [32] divided 32 drivers into a high neuroticism group and a low neuroticism group, and investigated the effects of different personality traits and different take-over request times on take-over quality. The results showed that high neuroticism drivers were more likely to take over immediately after a take-over request, while low neuroticism drivers always observed the driving environment first. Doubek et al. [33] designed experiments with different time budgets and traffic density levels, and the results showed that drivers exhibited a considerably higher longitudinal and lateral acceleration than the optimized behavior, especially in the short time budget scenarios.

Although the effects of take-over request time and non-driving related tasks on take-over quality have been studied, no systematic research has been conducted on the take-over quality of human-driven vehicles for the entire human population under the interaction of multiple factors. No studies have been conducted on the interaction effects between individual factors under each variable. Nor have take-over scenarios that require driver-initiated take-over been considered. Instead, according to the results of the Google statistics report, autonomous driving systems are still inseparable from human intervention, and, therefore, active take-over approaches are an integral part of such studies.

In summary, the main objective of this paper is to investigate the factors influencing driver take-over quality and the vehicle take-over steady state, and their significance. In this paper, interactive driving simulation tests with different take-over times, different non-driving related tasks, and different request methods were designed to investigate the take-over response time and steering reaction time used by the driver in response to different influencing factors, as well as the minimum TTC, the maximum synthetic acceleration, and the accident rate when the vehicle takes over. The research flow is shown in Figure 1. The results of this paper can provide a theoretical basis for the study of autonomous driving take-over behavior in highway environments, and can also provide a basis for further design and development of human–machine cooperative driving strategies.

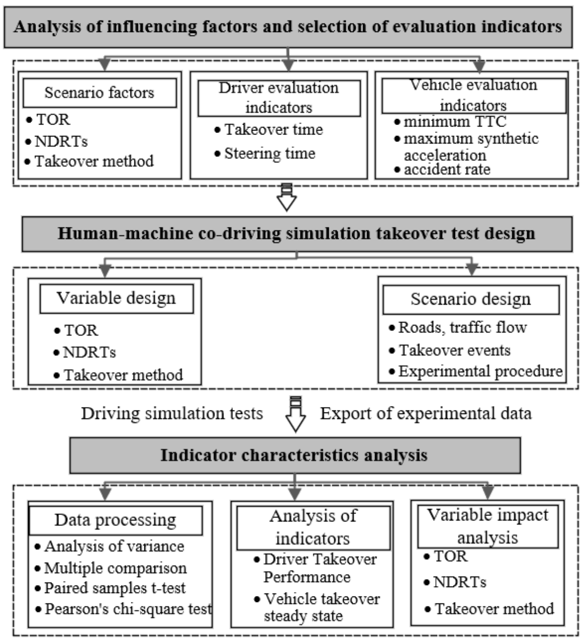

Figure 1. Research flow chart.

2. Materials and Methods

2.1. Experimental Design

2.1.1. Road Scene

The test road is a 6-lane two-way highway located in a plain area, with an overall layout of a 45 km long unsealed loop with a speed limit of 120 km/h. The traffic flow was 300 vehicles/hour in one direction. In addition, the intervals of the scenes and the length of the roads are different in order to avoid too fixed intervals between scenes, while at the same time allowing sufficient intervals for the driver's attention to be focused on non-driving related tasks. Therefore, the road in the scenario is divided into 6 sections: the first section is 8 km long (scenario 1), the second section is 8 km long (scenario 2), the third section is 8.7 km long (scenario 3), the fourth section is 6.8 km long (scenario 4), the fifth section is 7.47 km long (scenario 5), and the sixth section is 5.76 km long (extended road), for a total of 45 km. The general layout of the road scenes is shown in Figure 2.

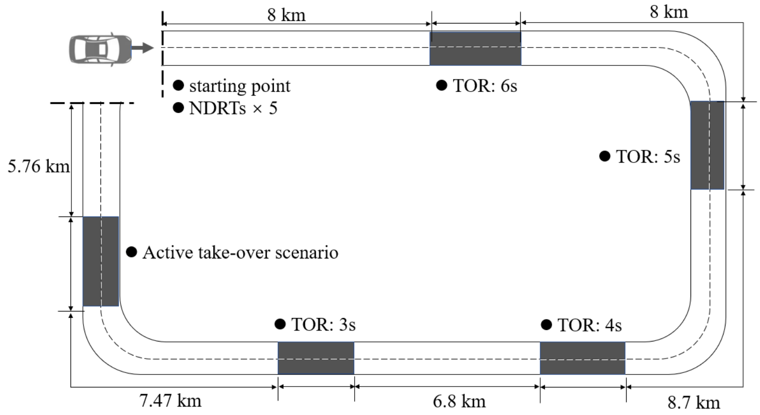

Figure 2. Scenario distribution.

2.1.2. The Non-Driving Related Tasks (NDRTs)

As vehicle automation increases, driver distraction becomes an inevitable problem. The distracted driving behavior of the driver essentially increases the driver's driving load, leading to a decrease in the driver's perceived level of attention and alertness [34], which has a negative impact on driving safety. To investigate the differences in the effects of single and multiple tasks on driving performance under visual and auditory loads and their combined loads, the experiment was conducted by selecting four typical types of tasks: listening to the radio, playing games, watching videos, and listening to the radio and playing games. The specific task designs were as follows.

1. Listening to the radio: the staff will play music and news radio broadcasts for the subject drivers throughout the test, and adjust the sound of the radio according to the driver's request. The subject drivers in this group will also be able to observe the driving environment and freely check the road or mirrors during the automatic driving phase.
2. Playing the game task: the subject plays the mobile phone WeChat app "Animal Restaurant", which is easy to operate and requires essentially no cognitive ability. The driver in this group is not allowed to monitor the driving environment during the automatic driving phase until the take-over request appears.
3. Watching videos: a laptop computer will be placed in front of the driver's right hand side to play the Chinese documentary "China on the tip of the tongue" and the sound of the video will be adjusted according to the driver's request. The driver in this group is not allowed to monitor the driving environment during the automatic driving phase until the take-over request appears.
4. Listen to the radio and play game task: this is a combination of a listen to the radio task and a play game task, where the driver plays a mobile phone app while the staff plays a radio broadcast. The driver in this group is not allowed to monitor the driving environment during the autopilot phase until a take-over request is made.
5. The no task group: drivers were asked to monitor the driving environment at all times, regardless of whether the driving phase was automatic or manual.

The load types corresponding to the five non-driving related tasks are shown in Table 1.

Table 1. The NDRTs.

#	NDRTs	Load Type
1	no task	No load
2	listening to the radio	Auditory load
3	playing games	Visual load
4	watching videos	Audiovisual load
5	listening to the radio and playing games	Audiovisual load

2.1.3. Take-Over Request Time (TOR)

The TOR has been shown to be a determinant of driver take-over performance [35]. It has been shown that too long of a TOR causes the driver to try to first confirm a dangerous situation before taking over, thus prolonging the driving reaction time, while too short of a TOR is not enough to ensure the safety of the take-over. The most common TORs currently used by scholars are 3, 4, and 6 s [36]. Therefore, to explore and investigate the safety threshold of the TOR, the TOR in this experiment is designed as 6 s, 5 s, 4 s, and 3 s.

2.1.4. Take-Over Mode

Current SAE Level 3 automated vehicles are still subject to monitoring false alarms and system failures, and such deficiencies require actions by the driver to compensate. Therefore, the active take-over approach is an issue that must be studied in the development of automated driving technology. As the number of vehicles increases, the number of vehicle–animal accidents on the highway also increases [37]. Due to the constraints of existing technology, it is difficult for fast moving vehicles on motorways to accurately identify animals and alert drivers [38]. The experiment, therefore, designed the unprompted active take-over scenario as a wild animal walking into the driving road ahead. The test design consists of four passive take-over scenarios and one active take-over scenario. To facilitate comparative analysis with the passive take-over test, the active take-over scenario test sets the time between the appearance of wild animals in the field of view of the driver and the occurrence of a collision to 6 s, , the specific descriptions are shown in Table 2.

Table 2. Two types of take-over scenarios and descriptions.

Take-Over Mode	Scene Description	Scene Pictures
Passive take-over	Description: a broken-down car stopped in the middle of the lane in front of this vehicle. Take-over request message: Auditory—continuous "ding-ding" sound. Visual—the words "Please take over the vehicle".	
Active take-over	Description: a wild animal crosses the lane from the right to the left in front of the lane at a speed of 5 km/h. Take-over request information: none.	

This experiment used a mixed design of 5 (5 NDRTs) × 4 (4 TORs) × 2 (2 take-over modes), with a total of 25 types of trials, shown in Figure 3. The NDRTs were the between-group variables, and the TOR and take-over mode were the within-group variables. In the experiments, each test group completed 4 TOR scenarios in the passive take-over mode, and 1 take-over scenario test in the active take-over mode when performing one non-driving related task each.

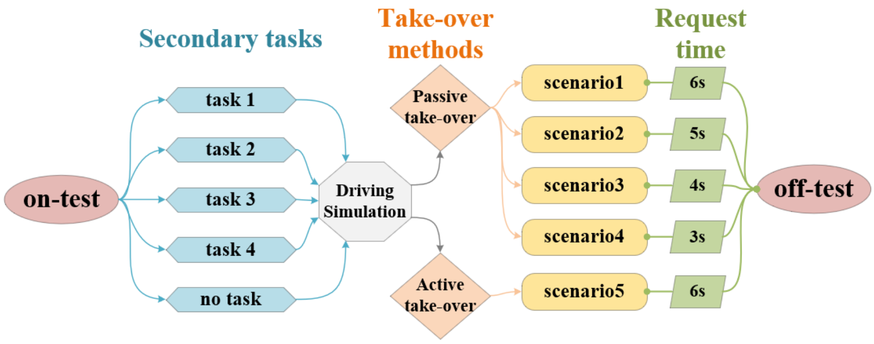

Figure 3. General arrangement of the test scene.

2.2. Apparatus

A simple driving simulator was used for this test, and the hardware consisted of a Fanatec steering wheel-pedal set, and a driving simulation display device, as shown in Figure 4. The simulator is in automatic mode, and the driver only needs to operate the accelerator, brake pedals, and steering wheel when driving manually. Participants could push the red button beside the steering wheel to freely switch the AV between automation mode and manual-driven mode. The scenario design software of the simulator is UC-win/Road, which can realize functions such as creating roads, generating traffic flow, and building driving scenarios. We recorded all relevant driving data, including the vehicle's position, accelerations, driving distance, steering wheel angle, pedal positions, etc.

Figure 4. Driving simulation equipment.

2.3. Participants

A total of 65 subjects were voluntarily recruited for the experiment, and all drivers were divided into five groups according to different NDRTs. There were no significant differences between groups in any of the four personal characteristics of the drivers by the chi-square test ($p > 0.05$). Three drivers showed extreme discomfort with the driving simulator during the test, resulting in 62 valid datasets. All subjects were required to have a valid driver's license for at least two years, and no experience driving a vehicle with a human–machine driving simulator. The subjects were in good physical and mental health and were not taking any drugs that would affect their driving behavior. The basic information of the drivers is shown in Table 3.

Table 3. Basic information of drivers.

Gender		Age/Year		Driving Age/Year		Total Driving Mileage/10^4 KM	
Female	**Male**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
18	44	35.29	6.88	9.85	5.21	6.01	1.55

2.4. Procedure

Five non-driving related task groups are required to take turns conducting the experiment. The experimental procedures are described below:

The participants sign an informed consent form and fill in a basic information questionnaire, which includes information on the subject's demographic information, driving experience, mental status, and whether or not they are taking medication.

Staff explain the subject's research, inform the participants about the take-over operation of the automated driving system, the non-driving related tasks, the take-over requirements, the take-over scenarios, and other test contents.

The participants are given sufficient time to familiarize themselves with the operation of the driving simulator and to carry out driving simulation training for other scenarios, with a short break for the driver at the end of the pre-test.

The formal test starts with the vehicle driving automatically, during which the driver is required to take both hands off the steering wheel and both feet off the pedals, while the task group driver begins to perform the non-driving related tasks. The passive take-over scenario requires the driver to take over the vehicle and perform hazard avoidance maneuvers when prompted by the system. In an active take-over scenario, however, the driver can take over the vehicle when a hazardous event is in his or her field of vision.

The driver can take over the vehicle by turning the steering wheel, pressing the brake pedal, or pressing the accelerator pedal, and the vehicle changes to manual driving mode when the steering wheel is turned by 1% or the pedal is pressed by 10%. When the driver has successfully avoided a hazard and the vehicle is moving forward smoothly, control of the vehicle can be handed over to the automatic driving system by pressing the designated button on the steering wheel.

2.5. Evaluation Metrics

The evaluation metrics of this study are divided into two parts, which are used to evaluate driver take-over performance and the vehicle take-over steady state. The descriptions of each metric are shown in Table 4. The accident rate is a reflection of the success of the take-over and can be a qualitative judgment of the quality of the take-over. In automatic driving take-over studies, the take-over reaction time, the steering reaction time, the minimum TTC, and the maximum synthetic acceleration are the most commonly used take-over performance evaluation indexes [39–42], and are widely used by scholars.

Table 4. Evaluation metrics and descriptions.

Metrics	Definition
Driver Take-Over Performance	
take-over reaction time	The length of time from when the automated driving system sends a take-over request message to when the driver steers or brakes.
steering reaction time	The time from the start of the take-over request message from the autopilot system to the time the driver changes the steering wheel corner.
vehicle take-over steady state	
minimum TTC	Test vehicle longitudinal acceleration speed to 0 or successfully change lanes to avoid obstacles, the minimum collision time from the front of the obstacle.
maximum synthetic acceleration	The maximum arithmetic square root of the sum of the squared lateral and longitudinal accelerations over the course of the scenario, starting with the take-over request message from the autopilot system and ending with the scenario.
accident rate	The ratio of the number of tests in which collisions and vehicle loss of control occurred to the number of all tests.

Note: TTC $= \frac{d_{n+1}-d_n}{V_n-V_{n+1}}$. where d_{n+1} is the distance travelled by the previous vehicle, d_n is the distance travelled by the test vehicle, V_n is the current speed of the vehicle n and V_{n+1} is the current speed of the vehicle in front of the vehicle n.

3. Results

3.1. Driver Take-Over Performance Analysis

3.1.1. Significance Analysis of Driver Take-Over Performance

The driver take-over performance was tested for significant differences under the influence of a single control variable, controlling for each TOR and each NDRT separately, and the effect of different NDRTs and different TORs on each driver take-over performance indicator was investigated. The statistical results are shown in Table 5.

Table 5. Driver take-over performance checklist.

Test Variables	Take-Over Reaction Time			Steering Reaction Time		
	Mean	**Med**	***p***	**Mean**	**Med**	***p***
no task	1.3 s	1.22 s	0.002	1.69 s	1.68 s	0.001
listening to the radio	1.49 s	1.35 s	0.000	1.99 s	1.84 s	0.004
playing games	1.89 s	1.83 s	0.000	2.60 s	2.35 s	0.000
watching videos	2.05 s	2.01 s	0.000	2.87 s	2.40 s	0.036
listening to the radio and playing games	1.89 s	1.84 s	0.015	2.47 s	2.32 s	0.002
6 s	2.17 s	2.04 s	0.003	2.17 s	2.04 s	0.002
5 s	1.86 s	1.84 s	0.001	1.86 s	1.84 s	0.021
4 s	1.53 s	1.57 s	0.000	1.53 s	1.57 s	0.000
3 s	1.33 s	1.26 s	0.001	1.33 s	1.26 s	0.002
passive take-over	2.17 s	2.04 s	0.000	3.03 s	2.91 s	0.000
active take-over	4.69 s	4.81 s		5.32 s	5.52 s	

1. Effect of a single variable on take-over response time.

(1) Impact of the TOR on take-over response time.

Analysis of variance for take-over response time data under different conditions was conducted, and the results showed that the TOR had a significant effect on response time, $p < 0.05$. The effect of different TORs on response time metrics was most significant when the NDRTs were watching videos ($p < 0.001$), playing games ($p < 0.01$), and listening to the radio ($p < 0.01$). For different tasks with the same driving load, the results of the descriptive statistics were used to assist in the analysis. When the audiovisual load was increased simultaneously, the multi-task listening to the radio and playing games (mean = 1.89 s; med = 1.84 s) had a shorter take-over time than the single task watching videos (mean = 2.05 s; med = 2.01 s).

(2) Impact of non-driving related tasks on take-over response time.

When the TOR was 6 s ($p = 0.003 < 0.01$), 5 s ($p = 0.001 < 0.01$), 4 s ($p = 0.000 < 0.001$), and 3 s ($p = 0.001 < 0.01$), there were significant differences in the response time of drivers with different NDRTs, $p < 0.05$. Among them, the NDRT had the most significant effect on the response time when the TOR was 4 s, indicating that drivers were more vulnerable to the driving load at the TOR of 4 s.

(3) Impact of take-over mode on take-over response time.

A paired-sample *t*-test was used to analyze them comparatively. Overall, the response time in the passive take-over mode (mean = 2.17 s; med = 2.04 s) was significantly lower than in the active take-over mode (mean = 4.69 s; med = 4.81 s) ($t = -14.737$, $p = 0.000$).

2. Effect of a single variable on steering response time.

(1) Impact of TOR on steering response time.

Different TORs had a significant effect on the steering reaction time, $p < 0.05$. The change in the TOR had the most significant effect on the steering reaction time when the NDRT was playing the game ($p = 0.000 < 0.001$). When simultaneously increasing the audiovisual load, multi-tasking listening to the radio and playing games (mean = 1.69 s;

med = 1.68 s) resulted in shorter steering response times than single task watching videos (mean = 2.47 s; med = 2.32 s).

(2) Impact of non-driving related tasks on steering reaction time.

The different NDRTs also had a significant effect on the driver steering response time, $p < 0.05$. The same effect as the NDRTs on the response time was found, with the most significant effect when the TOR was 4 s ($p = 0.000 < 0.001$), followed by 6 s ($p = 0.002 < 0.01$), 3 s ($p = 0.002 < 0.01$), and 5 s ($p = 0.021 < 0.05$). This indicates that drivers involved in the NDRTs were occupied with more visual and auditory resources compared to no task, reducing the driver performance in completing steering responses.

(3) Impact of take-over mode on steering response time.

A paired-sample *t*-test of the driver steering reaction times under both take-over modes showed that the steering reaction times were significantly lower under the passive take-over mode (mean = 3.03 s; med = 2.91 s) than under the active take-over mode (mean = 5.32 s; med = 5.52 s) ($t = -12.876$, $p = 0.000$).

3.1.2. Driver Take-Over Performance Interaction Impact Analysis

Bonferroni post hoc tests were performed on the driver take-over response time and the driver steering reaction time for multiple comparisons. Tables 6 and 7 show the results of multiple analysis tests on the effects of the NDRTs and the TOR on the driver reaction time.

Table 6. Multiple Comparison Test of the Effect of TOR on Driver Response Time.

Driver Response Time Indicators	**NDRTs**	**Significant Difference Values for Different Take-over TORs under Non-Driving Related Tasks**					
		3–4 s	**3–5 s**	**3–6 s**	**4–5 s**	**4–6 s**	**5–6 s**
Driver take-over time	no task			0.001			
	listening to the radio			0		0	
	playing games		0.002	0		0.015	
	watching videos		0.033	0		0.001	
	listening to the radio and playing games			0.016			
Driver steering time	no task		0.009	0.002			
	listening to the radio			0.015		0.006	
	playing games			0		0.001	
	watching videos					0.04	
	listening to the radio and playing games			0.001			

Table 7. Multiple comparison analysis test of the effect of the NDRTs on driver reaction time.

Driver Response Time Indicators	**NDRTs**	**Significant Difference Values of Different TORs under Each Non-Driving Related Task**								
		A–B	**A–C**	**A–D**	**A–E**	**B–C**	**B–D**	**B–E**	**C–D**	**C–E**
Driver take-over time	6 s				0.002					
	5 s		0.011		0.006					
	4 s		0.008	0.009	0.001	0.008	0.01	0.001		
	3 s			0.005	0.002					
Driver steering time	6 s		0.006		0.007					
	5 s									
	4 s		0.025	0.007	0.003		0.031	0.012		
	3 s				0.001					

Note: no task—A; listening to the radio—B; playing games—C; watching videos—D; listening to the radio and watching videos—E.

1. Effect of interaction variables on take-over response time

Multiple comparisons of response times for different NDRTs showed a significant difference between the 3 s and 6 s TORs ($p < 0.05$); when the NDRTs were listening to the radio, playing games, and watching videos, there was a significant difference between 4 s and 6 s TORs ($p < 0.05$); there was a significant difference between the 3 s and 5 s TORs when drivers were involved in visual load single tasks (playing games and watching videos).

Multiple comparisons of response times for different NDRTs showed that there was a significant difference ($p < 0.01$) between the no task group and the listening to the radio and playing games group for any TOR condition; when the TOR was 5 s, there was a significant difference between the no task group and the playing games group; at the 4 s TOR, there was a significant difference between both the no task group and the listening to the radio group and the visual load task group (playing games, watching videos, and listening to the radio and playing games); there was a significant difference between the no task group and the simultaneous increase in visual and auditory load task group (watching videos, listening to the radio and playing games) at the 3 s TOR.

2. Effect of interaction variables on steering reaction time

The analysis of the driver steering reaction time in different TOR conditions showed that there was a significant difference between the 3 s and 6 s TOR for all tasks or no task, except for the watching video task ($p < 0.05$). In the 6 s TOR condition, there was a significant difference ($p < 0.01$) between the no task group and the playing games group, and between the no task group and the listening to the radio and playing games group.

The analysis of the driver response time and the steering response time shows that the TOR affects the driver response time significantly, and the analysis results show that the response time and the steering response time decrease with the TOR, while the data position parameter decreases. This indicates that drivers tend to respond immediately in emergency take-over situations; non-driving related tasks have a significant effect on the driver response time, with the position parameters always ranked as watching video > listening to the radio and playing games > playing games > listening to the radio > no task. However, the response time for a single task is longer when the driving load is the same.

3.2. Vehicle Take-Over Steady State Analysis

3.2.1. Vehicle Take-Over Steady-State Significance Analysis

The vehicle take-over steady state was tested for significant differences under the influence of a single control variable. Each TOR and each NDRT were controlled separately to investigate the effects of different NDRTs and different TORs on each take-over steady state metric. The statistical results are shown in Table 8.

Table 8. Vehicle take-over steady-state inspection table.

Test Variables	**Take-Over Reaction Time**			**Steering Reaction Time**			**Accident Rate**
	Mean	**Med**	***p***	**Mean**	**Med**	***p***	**%**
no task	2.02 s	1.83 s	0.000	7.05	7.11	0.008	9.86%
listening to the radio	1.66 s	1.46 s	0.000	6.42	6.09	0.002	14.09%
playing games	1.57 s	1.27 s	0.003	7.89	8.26	0.001	23.94%
watching videos	1.55 s	1.45 s	0.000	8.59	8.65	0.013	25.35%
listening to the radio and playing games	1.70 s	1.54 s	0.008	7.69	7.64	0.000	26.76%
6 s	2.48 s	2.61 s	0.071	6.23	6.35	0.238	0%
5 s	1.89 s	1.92 s	0.066	6.61	7.20	0.004	1.41%
4 s	1.23 s	1.17 s	0.033	7.73	8.14	0.026	7.04%
3 s	0.77 s	0.73 s	0.166	9.49	9.16	0.319	42.25%
passive take-over	2.48 s	2.61 s	0.000	6.23 s	6.35 s	0.000	50.70%
active take-over	0.76 s	0.53 s		8.21 s	8.40 s		49.30%

1. Effect of a single variable on the minimum TTC.

(1) Impact of TOR on vehicle minimum TTC

ANOVA was performed for each vehicle take-over steady state indicator. The ANOVA results for the minimum TTC showed that the variables in the TOR had a significant effect on the response time, $p < 0.05$. The effect was most significant when the NDRT was listening to the radio ($p = 0.000 < 0.001$), watching a video ($p = 0.000 < 0.001$), or no task ($p = 0.000 < 0.001$). When the NDRT was listening to the radio and playing games, it had a slightly smaller effect than the other groups, suggesting that the drivers were more immersed in a single task.

(2) Impact of non-driving related tasks on vehicle minimum TTC

Under different NDRT conditions, there was a significant effect on the vehicle minimum TTC only when the TOR was 4 s ($p = 0.033 < 0.05$), while the effect was not significant when the TOR was 6 s, 5 s, and 3 s. This shows that 4 s may be the vehicle take-over steady-state threshold for driver take-over.

(3) Impact of take-over mode on vehicle minimum TTC

A paired *t*-test was performed for the minimum TTC under different take-over modes, and the results showed that the minimum TTC under the passive take-over mode (mean = 2.48 s; med = 2.61 s) was significantly greater than that under the active mode (mean = 6.23 s; med = 6.35 s) (t = 6.817, $p = 0.000$), indicating that the passive take-over mode is safer.

2. Effect of a single variable on the maximum synthetic acceleration of a vehicle

(1) Impact of the TOR on the maximum synthetic acceleration

ANOVA results show that each variable in the TOR has a significant effect on the maximum synthetic acceleration of the vehicle, $p < 0.05$; the most significant effect was found when the NDRT was listening to the radio and playing games ($p = 0.000 < 0.001$), while the least significant effect was found in the video watching group ($p = 0.013 < 0.05$), and the significance of the remaining task groups was less than 0.01. The variability of the values was greater in the multi-task group than in the single task group for the same driving load, indicating that increased workload affects the stability of avoidance operations.

(2) Impact of non-driving related tasks on the maximum synthetic acceleration

The effect of different NDRTs on the maximum synthetic acceleration was not fully significant. The different NDRTs had a significant effect on the maximum synthetic acceleration when the TOR was 5 s ($p = 0.004 < 0.01$) and 4 s ($p = 0.026 < 0.05$), while the effect was not significant at 6 s ($p = 0.238$) and 3 s ($p = 0.319$).

(3) Impact of take-over mode on the maximum synthetic acceleration

The maximum synthetic acceleration under different take-over modes was analyzed using a paired-samples *t*-test, and the results showed that the active mode significantly reduced the longitudinal stability of the take-over (mean = 8.21 m/s^2; med = 8.40 m/s^2) compared to the passive mode (mean = 6.23 m/s^2; med = 6.35 m/s^2) (t = −4.677, $p = 0.000$).

3. Effect of a single variable on accident rate

A Pearson's chi-square test was used to analyze the differences in accident rates among the groups, and the results in Figure 5 show that, in terms of the effect of request time on accident occurrence, the accident rate at 3 s (42.25%) was significantly higher than at 4 s (7.04%) ($\chi^2 = 21.06$, $p = 0.000 < 0.001$) and 5 s (1.41%) ($\chi^2 = 34.47$ $p = 0.000 < 0.001$), implying that overly tight time budgets make it difficult to ensure take-over safety.

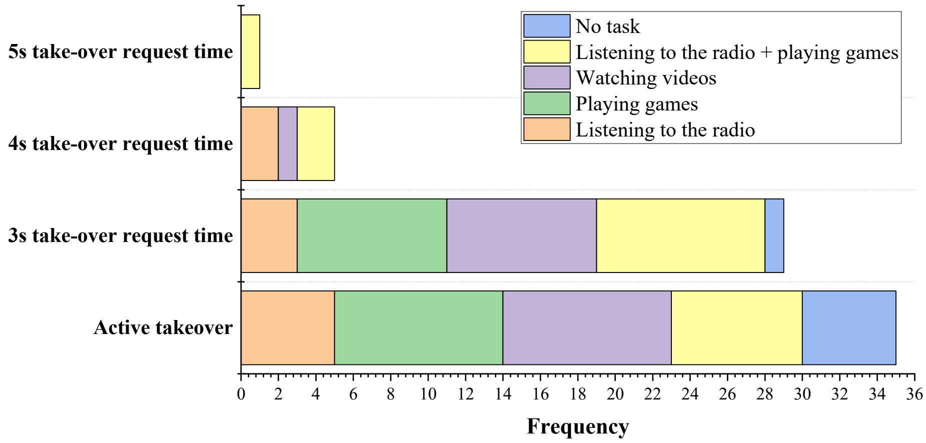

Figure 5. Distribution of accidents under the interaction of factors.

Regarding the effect of NDRTs on accident occurrence, overall, there was no significant effect of the driver involvement in different tasks on the accident occurrence ($p > 0.05$). In the passive take-over condition, a Pearson's chi-square test was performed for the tasked group versus the non-tasked group, and the results showed that the partial driving load had a significant effect on the accident rate of take-over. When the NDRTs were playing games ($\chi^2 = 5.39$, $p = 0.02 < 0.05$), watching videos ($\chi^2 = 7.14$, $p = 0.008 < 0.05$), and listening to the radio and playing games ($\chi^2 = 9.52$, $p = 0.002 < 0.05$), there was a significant effect on the accident rate compared to the no task group, but only the listening to the radio task that increased the auditory load ($\chi^2 = 2.51$, $p = 0.113 > 0.05$) was not statistically significant compared to the no task group, showing that performing a visual load task significantly increases the accident rate during take-over.

3.2.2. Vehicle Take-Over of Steady State Interaction Effects

The Bonferroni post-hoc tests for the minimum TTC and the maximum synthetic acceleration were performed for multiple comparisons, and Tables 9 and 10 show the results of the multiple analysis tests for the effect of the TOR and the NDRTs on the vehicle take-over steady state, respectively.

Table 9. Multiple Comparison Test of the Effect of the TOR on Driver Response Time.

Vehicle Take-Over Steady State Indicators	**NDRTs**	**Significant Difference Values of Different TORs under Each Non-Driving Related Task**					
		3–4 s	**3–5 s**	**3–6 s**	**4–5 s**	**4–6 s**	**5–6 s**
Vehicle minimum TTC	no task	0.019	0	0	0.018	0	0.003
	listening to the radio		0	0	0.046	0	
	playing games			0.017		0.01	
	watching videos		0.009	0		0	0.011
	listening to the radio and playing games					0.012	
Vehicle maximum synthetic acceleration	no task		0.016	0.018			
	listening to the radio		0.002	0.017			
	playing games			0			
	watching videos						
	listening to the radio and playing games		0.003	0			

Table 10. Multiple comparison analysis test of the effect of the NDRTs on driver reaction time.

Vehicle Take-Over Steady State Indicators	NDRTs	Significant Difference Values of Different TORs under Each Non-Driving Related Task									
		A–B	A–C	A–D	A–E	B–C	B–D	B–E	C–D	C–E	D–E
Vehicle maximum synthetic acceleration	6 s										
	5 s					0.007		0.019			
	4 s							0.027			
	3 s										

Note: no task—A; listening to the radio—B; playing games—C; watching videos—D; listening to the radio and watching videos—E.

1. Effect of interaction variables on vehicle minimum TTC

Multiple comparisons of the minimum TTC at different TORs yielded Table 9, where there was a significant difference between the 4 s and 6 s TORs under any non-driving related task ($p < 0.05$); when the driver did not have any driving load, the effect of the different TORs on the minimum TTC was significant, and the difference between any two TOR groups was statistically significant ($p < 0.05$).

Multiple comparisons of the minimum TTC under different NDRTs yielded Table 10, and there was no statistically significant difference between the groups for NDRTs at any TOR ($p > 0.05$).

2. Effect of interaction variables on the maximum synthetic acceleration

Multiple comparisons of the maximum synthetic acceleration under different TOR conditions reveal in Table 9 that the differences between the 3 s and 5 s ($p < 0.05$) and the 3 s and 6 s ($p < 0.05$) TORs were statistically significant when the NDRT was listening to the radio, listening to the radio and playing games, and no task; when the NDRT was playing games, there was a significant difference between the 3 s and 6 s TORs, within the video watching group; the differences between any TORs were not significant.

Multiple comparisons of the maximum synthetic acceleration under different NDRTs yielded Table 10. There was no significant difference between the different NDRTs at the 3 s and 6 s TORs; the difference between the listening to the radio group and the listening to the radio and playing games group was statistically significant at the 5 s and 6 s TORs, and there was a significant difference between the listening to the radio group and the playing games group when the TOR was 5 s.

4. Discussion and Conclusions

In this paper, the level and degree of influence of driving simulation test data were analyzed using a single factor combined with multiple comparison analysis. We investigate both the driver take-over performance and the vehicle take-over stability state. Our findings can be summarized as follows:

Different TORs have significant effects on the driver take-over response time, the steering reaction time, the vehicle minimum TTC, and the maximum synthetic acceleration. The response time, the steering reaction time, and the minimum TTC decreased with decreasing TOR, and the maximum synthetic acceleration increased with decreasing TOR.

The indicators of the driver take-over performance are significantly affected by different NDRTs, and the driver take-over performance decreases with the increasing driving load. In contrast, the vehicle take-over steady state was significantly affected by different NDRTs only at specific TORs, but again there was a tendency for the vehicle take-over steady state to decrease with the increasing driving load. In addition, the take-over performance under multi-tasking was significantly better than single tasking when the driving loads were the same, indicating that drivers would be more engaged with a single task.

The vehicle take-over method has a significant effect on the vehicle take-over quality. Compared to the passive take-over mode, the take-over quality in the active mode is significantly lower. Therefore, for people who have not been exposed to autonomous vehicles, hazard moment messages are necessary.

Finally, the accident rate was analyzed under the three influencing factors, and it was found that the highest accident rate was found under the 3 s TOR and active take-over mode conditions. The accident rate spiked when the 3 s TOR increased to the 4 s TOR, indicating that the safety threshold of the human–machine collaborative driving vehicle TOR is between 4 s and 3 s. There are still some limitations in this study; for example, this test scenario was chosen for highway driving, and other road conditions were not considered. In addition to freeways, urban roads and rural roads with higher traffic volumes should also be studied. The scenario does not take into account the situation that other vehicles do not yield when changing lanes, etc. The complexity of the scenario should be further enriched in the future to explore the quality of the take-over of human–machine cooperative driving vehicles under complex traffic conditions.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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References

1. Mohammed, K.; Abdelhafid, M.; Kamal, K.; Ismail, N.; Ilias, A. Intelligent Driver Monitoring System: An Internet of Things-Based System for Tracking and Identifying the Driving Behavior. *Comput. Stand. Interface* **2023**, *84*, 103704. [CrossRef]
2. Lo Cigno, R.; Segata, M. Cooperative Driving: A Comprehensive Perspective, the Role of Communications, and Its Potential Development. *Computer. Commun.* **2022**, *193*, 82–93. [CrossRef]
3. Chen, J.; Sun, D.; Li, Y.; Zhao, M.; Liu, W.; Jin, S. Human–Machine Cooperative Scheme for Car-Following Control of the Connected and Automated Vehicles. *Physics A* **2021**, *573*, 125949. [CrossRef]
4. Li, X.; Wang, Y. Shared Steering Control for Human–Machine Co-Driving System with Multiple Factors. *Appl. Math. Model.* **2021**, *100*, 471–490. [CrossRef]
5. Morales-Alvarez, W.; Sipele, O.; Léberon, R.; Tadjine, H.H.; Olaverri-Monreal, C. Automated Driving: A Literature Review of the Take over Request in Conditional Automation. *Electronics* **2020**, *9*, 2087. [CrossRef]
6. Lu, G.; Zhao, P.; Wang, Z.; Lin, Q. Impact of Visual Secondary Task on Young Drivers' Take-over Time in Automated Driving. *China J. Highw. Transp.* **2018**, *31*, 165–171.
7. Ma, S.; Zhang, W.; Shi, J.; Yang, Z. The human factors of the take-over process in conditional automated driving based on cognitive mechanism. *Adv. Psychol. Sci.* **2020**, *28*, 150–160. [CrossRef]
8. Yoon, S.H.; Ji, Y.G. Non-Driving-Related Tasks, Workload, and Takeover Performance in Highly Automated Driving Contexts. 2019. Available online: https://www.sciencedirect.com/science/article/abs/pii/S1369847818302262 (accessed on 3 March 2023).

9. Chen, W.; Sawaragi, T.; Hiraoka, T. Adaptive Multi-Modal Interface Model Concerning Mental Workload in Take-over Request during Semi-Autonomous Driving. *SICE J. Control Meas. Syst. Integr.* **2021**, *14*, 10–21. [CrossRef]
10. Bazilinskyy, P.; Petermeijer, S.M.; Petrovych, V.; Dodou, D.; de Winter, J.C.F. Take-over Requests in Highly Automated Driving: A Crowdsourcing Survey on Auditory, Vibrotactile, and Visual Displays. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *56*, 82–98. [CrossRef]
11. Xu, C.; Li, P.; Li, Y.; Merat, N.; Lu, Z.; Guo, X. Takeover Performance and Workload under Varying Automation Levels, Time Budget and Road Curvature. In Proceedings of the 2022 IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers (IPEC), Dalian, China, 14 April 2022; IEEE: Piscataway, NJ, USA; pp. 1379–1385.
12. Tan, X.; Zhang, Y. The Effects of Takeover Request Lead Time on Drivers' Situation Awareness for Manually Exiting from Freeways: A Web-Based Study on Level 3 Automated Vehicles. *Accid. Anal. Prev.* **2022**, *168*, 106593. [CrossRef]
13. Choi, D.; Sato, T.; Ando, T.; Abe, T.; Akamatsu, M.; Kitazaki, S. Effects of Cognitive and Visual Loads on Driving Performance after Take-over Request (TOR) in Automated Driving. *Appl. Ergon.* **2020**, *85*, 103074. [CrossRef]
14. Niu, J.W.; Zhang, X.M.; Sun, Y.P.; Qin, H. Analysis of the Driving Behavior During the Takeover of Automatic Driving Vehicles in Dangerous Traffic Situations. *China J. Highw. Transp.* **2018**, *31*, 272–280.
15. Lin, Q.; Li, S.; Ma, X.; Lu, G. Understanding Take-over Performance of High Crash Risk Drivers during Conditionally Automated Driving. *Accid. Anal. Prev.* **2020**, *143*, 105543. [CrossRef]
16. Shi, E.; Bengler, K. Non-Driving Related Tasks' Effects on Takeover and Manual Driving Behavior in a Real Driving Setting: A Differentiation Approach Based on Task Switching and Modality Shifting. *Accid. Anal. Prev.* **2022**, *178*, 106844. [CrossRef]
17. Shi, D.; Wang, T.; Chen, Y.; Liu, C. Exploring the Effects of Request Time, Secondary Task, and Take-Over Mode on Take-Over Performance. In Proceedings of the 2021 6th International Conference on Intelligent Transportation Engineering (ICITE 2021), Beijing, China, 29–31 October 2021; Zhang, Z., Ed.; Lecture Notes in Electrical Engineering; Springer Nature Singapore: Singapore, 2022; Volume 901, pp. 993–1006, ISBN 978-981-19225-8-9.
18. Wu, H.; Wu, C.; Lyu, N.; Li, J. Does a Faster Takeover Necessarily Mean It Is Better? A Study on the Influence of Urgency and Takeover-Request Lead Time on Takeover Performance and Safety. *Accid. Anal. Prev.* **2022**, *171*, 106647. [CrossRef]
19. Hardman, S.; Berliner, R.; Tal, G. Who Will Be the Early Adopters of Automated Vehicles? Insights from a Survey of Electric Vehicle Owners in the United States. *Transp. Res. Part D Transp. Environ.* **2019**, *71*, 248–264. [CrossRef]
20. Robertson, R.D.; Meister, S.R.; Vanlaar, W.G.M.; Mainegra Hing, M. Automated Vehicles and Behavioural Adaptation in Canada. *Transp. Res. Part A Policy Pract.* **2017**, *104*, 50–57. [CrossRef]
21. Nielsen, T.A.S.; Haustein, S. On Sceptics and Enthusiasts: What Are the Expectations towards Self-Driving Cars? *Transp. Policy* **2018**, *66*, 49–55. [CrossRef]
22. Wang, Q.; Chen, H.; Gong, J.; Zhao, X.; Li, Z. Studying Driver's Perception Arousal and Takeover Performance in Autonomous Driving. *Sustainability* **2022**, *15*, 445. [CrossRef]
23. Scott-Parker, B.; De Regt, T.; Jones, C.; Caldwell, J. The Situation Awareness of Young Drivers, Middle-Aged Drivers, and Older Drivers: Same but Different? *Case Stud. Transp. Policy* **2020**, *8*, 206–214. [CrossRef]
24. Li, S.; Blythe, P.; Zhang, Y.; Edwards, S.; Guo, W.; Ji, Y.; Goodman, P.; Hill, G.; Namdeo, A. Analysing the Effect of Gender on the Human–Machine Interaction in Level 3 Automated Vehicles. *Sci. Rep.* **2022**, *12*, 11645. [CrossRef] [PubMed]
25. Zhang, B.; de Winter, J.; Varotto, S.; Happee, R.; Martens, M. Determinants of Take-over Time from Automated Driving: A Meta-Analysis of 129 Studies. *Transp. Res. Part F Traffic Psychol. Behav.* **2019**, *64*, 285–307. [CrossRef]
26. Zhou, H.; Kamijo, K.; Itoh, M.; Kitazaki, S. Effects of Explanation-Based Knowledge Regarding System Functions and Driver's Roles on Driver Takeover during Conditionally Automated Driving: A Test Track Study. *Transp. Res. Part F Traffic Psychol. Behav.* **2021**, *77*, 1–9. [CrossRef]
27. Lu, Z.; Zhang, B.; Feldhütter, A.; Happee, R.; Martens, M.; De Winter, J.C.F. Beyond Mere Take-over Requests: The Effects of Monitoring Requests on Driver Attention, Take-over Performance, and Acceptance. *Transp. Res. Part F Traffic Psychol. Behav.* **2019**, *63*, 22–37. [CrossRef]
28. Wörle, J.; Metz, B.; Baumann, M. Sleep Inertia in Automated Driving: Post-Sleep Take-over and Driving Performance. *Accid. Anal. Prev.* **2021**, *150*, 105918. [CrossRef]
29. Alrefaie, M.T.; Summerskill, S.; Jackon, T.W. In a Heart Beat: Using Driver's Physiological Changes to Determine the Quality of a Takeover in Highly Automated Vehicles. *Accid. Anal. Prev.* **2019**, *131*, 180–190. [CrossRef]
30. Kaye, S.-A.; Demmel, S.; Oviedo-Trespalacios, O.; Griffin, W.; Lewis, I. Young Drivers' Takeover Time in a Conditional Automated Vehicle: The Effects of Hand-Held Mobile Phone Use and Future Intentions to Use Automated Vehicles. *Transp. Res. Part F Traffic Psychol. Behav.* **2021**, *78*, 16–29. [CrossRef]
31. Zhang, Y.; Ma, J.; Pan, C.; Chang, R. Effects of Automation Trust in Drivers' Visual Distraction during Automation. *PLoS ONE* **2021**, *16*, e0257201. [CrossRef]
32. Zhang, W.; Zeng, Y.; Yang, Z.; Kang, C.; Wu, C.; Shi, J.; Ma, S.; Li, H. Optimal Time Intervals in Two-Stage Takeover Warning Systems with Insight Into the Drivers' Neuroticism Personality. *Front. Psychol.* **2021**, *12*, 601536. [CrossRef]
33. Doubek, F.; Loosveld, E.; Happee, R.; de Winter, J. Takeover Quality: Assessing the Effects of Time Budget and Traffic Density with the Help of a Trajectory-Planning Method. *J. Adv. Transp.* **2020**, *2020*, 6173150. [CrossRef]
34. Eisma, Y.B.; Eijssen, D.J.; de Winter, J.C.F. What Attracts the Driver's Eye? Attention as a Function of Task and Events. *Information* **2022**, *13*, 333. [CrossRef]

35. Tanshi, F.; Soffker, D. Determination of Takeover Time Budget Based on Analysis of Driver Behavior. *IEEE Open J. Intell. Transp. Syst.* **2022**, *3*, 813–824. [CrossRef]
36. Eriksson, A.; Banks, V.A.; Stanton, N.A. Transition to Manual: Comparing Simulator with on-Road Control Transitions. *Accid. Anal. Prev.* **2017**, *102*, 227–234. [CrossRef]
37. Saad, W.; Alsayyari, A. Loose Animal-Vehicle Accidents Mitigation: Vision and Challenges. In Proceedings of the 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), Aswan, Egypt, 2–4 February 2019; IEEE: Piscataway, NJ, USA; pp. 359–364.
38. Sharma, S.U.; Shah, D.J. A Practical Animal Detection and Collision Avoidance System Using Computer Vision Technique. *IEEE Access* **2017**, *5*, 347–358. [CrossRef]
39. Altendorf, E.; Schreck, C.; Wessel, G.; Canpolat, Y.; Flemisch, F. Utility Assessment in Automated Driving for Cooperative Human-Machine Systems. *Cogn. Technol. Work* **2019**, *21*, 607–619. [CrossRef]
40. Gao, F.; He, B.; He, Y. Detection of Driving Capability Degradation for Human-Machine Cooperative Driving. *Sensors* **2020**, *20*, 1968. [CrossRef]
41. McDonald, A.D.; Alambeigi, H.; Engström, J.; Markkula, G.; Vogelpohl, T.; Dunne, J.; Yuma, N. Toward Computational Simulations of Behavior During Automated Driving Takeovers: A Review of the Empirical and Modeling Literatures. *Hum. Factors* **2019**, *61*, 642–688. [CrossRef]
42. Fu, C.; Sayed, T. A Multivariate Method for Evaluating Safety from Conflict Extremes in Real Time. *Anal. Methods Accid. Res.* **2022**, *36*, 100244. [CrossRef]