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研究課題名（和文） Driver behavior modeling and its application to a guidance-as-needed steering system for individualized lane change assistance

研究課題名（英文） Driver behavior modeling and its application to a guidance-as-needed steering system for individualized lane change assistance

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研究成果の概要（和文）：パーソナルドライバーの車線変更行動のモデル化と、触覚インターフェースを介して適切なガイダンスを提供するシステムの設計の研究を行っている。実験から収集されたドライバーの行動データを分析することにより、運転スタイルを考慮した新しい車線変更モデルが提案された。その後、車両センサデータとドライバーの視線行動を測定することにより、意図に基づく触覚インターフェースが設計され、車線維持と車線変更タスクによって有効性が示された。さらに、腕の筋肉活動を測定する適応型触覚インターフェースが設計され、ドライビングシミュレーターと実車の実験結果は、ドライバーの受容性だけでなく、安全性と快適性を向上させることを示す。

研究成果の学術的意義や社会的意義
My research provides insights on understanding how driver interacts with haptic shared control system. Moreover, by designing a guidance-as-needed system, my research helps to raise people’s motivation and ability to move that would expand their life space by improving driving safety and comfort.

研究成果の概要（英文）：This research focuses on modeling lane change behavior of individual drivers and designing a guidance-as-needed steering system through haptic interface. At the beginning of this project, a novel lane change model that takes account of driving styles was developed by analyzing driver behavior data collected from driving simulator experiments. After that, an intention-based haptic guidance steering system was designed by real-time measuring vehicle sensory data and driver gaze behavior, which shows its effectiveness for both lane keeping and lane changing tasks. Furthermore, an adaptive haptic guidance system by real-time monitoring driver arm muscle activity was designed and evaluated in lane change tasks. The driving simulator and real-vehicle experiment results show that, compared to a one-size-fits-all interface, the developed guidance-as-needed interface by taking account of individualized behavior is capable to improve driving safety and comfort as well as driver acceptance.

研究分野： Human-Machine Interaction

キーワード： Shared control　Haptic interface　Driver behavior modeling　Driver monitoring system　Mobility system　Steering assist system　Human factors　Machine learning

１．研究開始当初の背景

Although the development of automation has been going fast, it does not mean that human will be replaced. From the viewpoint of human factors, understanding and developing driver automation interaction is essential for accelerating the introduction of vehicle automation in realistic driving situations. Normally, there are two ways of driver-automation control shifting: trading of control which means that either the human or the automation system is responsible for a function, and an active agent changes alternately from time to time; and sharing of control which means that the human and the automation system work together simultaneously to achieve a single function. Shared steering control enables a human driver and an automation system simultaneously and cooperatively control the vehicle through a haptic interface. However, the current problem is that the existed haptic shared control system frequently induces confusion and conflict to drivers, since driver steering behavior is various due to individual differences. Therefore, in order to solve the problem of driver-automation conflict and to improve driver acceptance, the haptic shared control system will be designed on an as-needed basis by monitoring driver status and predicting driver intention.

２．研究の目的

The purpose of proposed research is to improve driving safety and comfort (e.g. reduced workload and lower collision risk) through design and evaluation of a guidance-as-needed steering system for individualized lane change assistance. The main objectives are as follows:

(1) To build a model to understand and predict lane change behavior of individual drivers.

(2) To design a haptic shared control system to provide reliable haptic guidance on an as-needed basis by monitoring driver status and predicting driver intention.

(3) To evaluate the effectiveness of the haptic shared control system on improving individual lane change performance and driver acceptance by driving simulator and real-vehicle experiments.

３．研究の方法

A framework of driver-automation shared control through haptic interface on the steering wheel is shown in Figure 1. For a driving task, the driver mainly uses visual perception, brain decision, and arm operation to control the steering wheel. At the meantime, the automation system (i.e. haptic guidance steering system shown in the figure) provides assistant torque on the steering wheel. In this research, in addition to vehicular sensory data, driver physiological behavioral data were measured in real time to make the haptic guidance system adaptable to individual drivers.

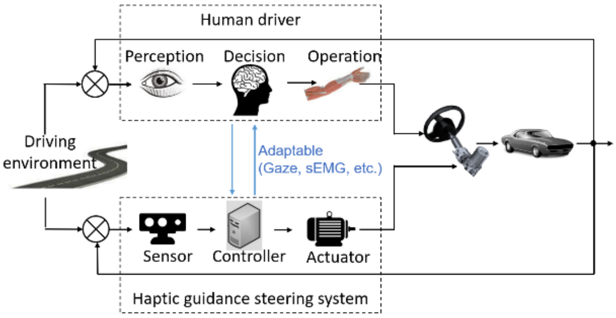

Figure 1. Schematic diagram of haptic shared control.

As shown in Figure 2, a gaze-tracking system (Smart Eye AB, Sweden) was employed to measure the driver's head and eye movements in a driving simulator experiment. The system comprised two infrared flashes and three cameras, and it did not cause any physical burden to the participants during the measurements. The driving simulator consisted of brake and accelerator pedals, an electric steering system, an instrument dashboard, and two rear-view mirrors. In addition, a 140° field-of-view of driving scene was visualized by three projectors. In the driving simulator, the electric steering system was connected to the host computer through a controller area network bus. The electric steering system consisted of a steering wheel, a motor, and an electronic control unit (ECU). The ECU calculated the active assistance torque, namely haptic guidance torque, and then actuated the motor.

Figure 2. Driving simulator and COMS EV

A Myo armband system (Thalmic Labs, Inc.) was employed to measure the sEMG signal of driver's dominant forearm in the driving simulator and real-vehicle experiments as show in Figure 2. The muscle activity was measured by calculating the root mean square (RMS) value of the activation from eight sEMG sensors within the armband. Normalization of driver grip strength was performed by measuring the maximum sEMG value for each participant before the formal experiment. In the Super Compact Electric Vehicle COMS (Toyota Auto Body Co., Ltd.), a servomotor and an angular sensor are attached to steering column to generate haptic guidance torque and measure the steering wheel angle. The maximum torque of servomotor is 70 N·m and the resolution of angular sensor is 0.01°.

４．研究成果

(1) Driver model for lane change intention prediction

To build a driver lane change model, the entire lane-change process was considered as a regression problem to give a prediction of time to lane change and time to lane change completion. A GRU-based neural network was built and compared with LSTM and SVM methods. A dataset from nine participants included 432 times (236 to right, 196 to left) lane change was collected in the experiment. These lane-changing and lane-keeping data were processed and formed about 25000 samples. Three participants were randomly selected and their last 30 mins data, respectively (about 2200 samples) were set to be test data. The rest about 19000 were randomly chosen for training and 3800 for validation. We fix our labeling window as three seconds and the sampling rate of 60 Hz.

To comparing our method, we also prepared two Support Vector Machine (SVM), one for predicting TLC and one for TLCC, and a LSTM network, as shown in Table 1. Two SVM showed much larger error than two network models. While the GRU showed less error than LSTM. The result indicates that at any moment, GRU network can predict the t_{TLC} with an error about 0.58 s and t_{TLCC} about 0.51 s. It proves that our model is capable of predicting the exact time to lane change and time to completion.

Table 1. RMSE comparison of different regression models

Prediction Model	Regression RMSE	
	t_{TLC} (s)	t_{TLCC} (s)
SVM (TLC)	1.6650	
SVM (TLCC)		0.9200
LSTM	0.7488	0.5639
GRU	**0.5780**	**0.5115**

Furthermore, the regression method can be converted to classification result. To be more specific, considering any labels greater than 3 s as one, which represents lane-keeping state and labels less than 3 s as zero for lane change state. We evaluate classification results with *Accuracy*, *Precision* and *F1* as shown in Table 2. Where the True Positive (TP) predictions are the correct prediction of actual lane changes. The True Negative (TN) predictions are the correct prediction of lane-keeping states. While the False Positive (FP) and the False Negative (FN) are the misclassifications of actual lane changes and lane-keeping. Two network models showed a high score in three metrics. SVM had a very high *Precision* but low *F1* and *Accuracy* which leading to a low ability to distinguish negative samples. While GRU shows better than LSTM in all scores. These high scores illustrate that anticipating TLC and TLCC at the same time is possible and adding TLCC as output would not be an interference in TLC classification problem.

Table 2. Classification comparison after converting

Prediction Model	Classification Evaluation		
	Accuracy	*Precision*	*F1*
SVM (TLC)	0.7335	**0.9205**	0.7823
LSTM	0.9347	0.8923	0.8896
GRU	**0.9476**	0.8980	**0.9131**

(2) Intention-based haptic guidance for lane changing tasks

In a driving simulator experiment, 12 participants drove seven trials to investigate two factors, as shown in Table 3. In manual driving condition, the participants drove without assistance. In conditions 2 to 7, the participants drove with the intention-based haptic steering (IBHS) system and different assistance methods. The effect of haptic torque strength and lane change assistance methods on driving performance was investigated.

The result of mean time duration of a LC is plotted in Figure 3. It can be observed that the duration showed a significant reduction after supporting steering torque (F (6,652) = 9.03, p < 0.001). The t-tests between the Manual and different IBHS systems indicated that except for the Weak-Gentle method (p = 0.208), all methods showed significance in shortening the LC duration. The two-way ANOVA test for IBHS methods revealed the significance in changing the LC duration among torque strengths (F (1,559) = 21.63, p < 0.001), and ΔTLC revelated the speed of LC (F (2,559) = 6.4,

Table 3. Experimental conditions

Condition	Factor one Haptic torque strength (When in consistent)	Factor two lane changing (LC) assistance
1 Manual	No	No
2 Strong-Rapid	Strong, $\tau_{hapa} = K_h \tau_{hapi}$	Rapid, $\Delta T_{LC} = 4$ s
3 Strong-Normal	Strong, $\tau_{hapa} = K_h \tau_{hapi}$	Normal, $\Delta T_{LC} = 6$ s
4 Strong-Gentle	Strong, $\tau_{hapa} = K_h \tau_{hapi}$	Gentle, $\Delta T_{LC} = 8$ s
5 Weak-Rapid	Weak, $\tau_{hapa} = 0.4 \bullet K_h \tau_{hapi}$	Rapid, $\Delta T_{LC} = 4$ s
6 Weak-Normal	Weak, $\tau_{hapa} = 0.4 \bullet K_h \tau_{hapi}$	Normal, $\Delta T_{LC} = 6$ s
7 Weak-Gentle	Weak, $\tau_{hapa} = 0.4 \bullet K_h \tau_{hapi}$	Gentle, $\Delta T_{LC} = 8$ s

$p = 0.002$). However, no significance was found in the interaction (F (2,560) = 0.81, $p = 0.447$). It can be seen there was a tendency for the duration to be reduced when ΔTLC became shorter. Thus, a strong assisting torque is more effective than a weak one in shortening the time duration.

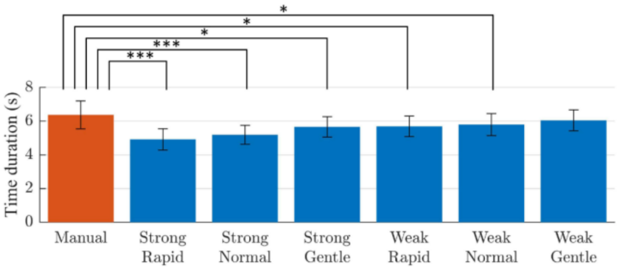

Figure 3. Lane changing duration time.

The mean steering wheel angular velocity during LC is presented in Figure 4. The RMS of the steering angular velocity was significantly different under conditions of manual and haptic guidance assisting driving (F (6,652) = 24.39, $p < 0.001$). However, only the Strong group showed significance in increasing the RMSs of the steering angular velocity (Rapid: $p < 0.001$, Normal: $p = 0.014$, Gentle: $p = 0.049$). For the different IBHS methods, the two-way ANOVA revealed significance in changing the steering velocity among assisting torque (F (1,559) = 75.86, $p < 0.001$) and ΔTLC (F (2,559) = 26.84, $p < 0.001$). Significance also was found for the interaction (F (2,559) = 0.81, $p = 0.002$). This conclusion agrees with the duration changing tendency, as fast steering behaviors generally shorten the LC duration.

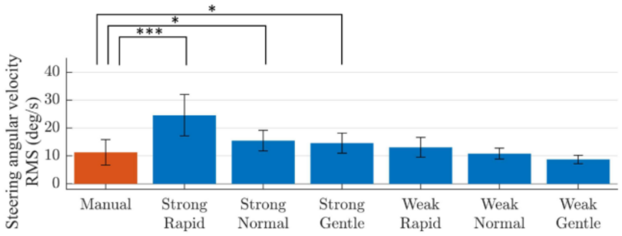

Figure 4. Steering wheel angular velocity when shifting.

(3) Adaptive haptic shared control via forearm sEMG measurement

(a) Effect of adaptive haptic shared control on driver behavior and lane change performance

In the experiment, 10 participants drove under five conditions, as shown in Table 4, each with a different type of haptic guidance: (1) No haptic guidance (Manual), (2) haptic guidance with a strong feedback gain (HG-Strong), (3) haptic guidance with a normal feedback gain (HG-Normal), (4) haptic guidance decreases when grip strength increases (HG-Decrease), and (5) haptic guidance increases when grip strength increases (HG-Increase). Data were statistically analyzed using one-way repeated measures ANOVA with the Fisher-Hayter Post Hoc test to determine whether there was any significant difference between the driving conditions.

Table 4. Experimental conditions with different types of haptic guidance

Condition	Description	Feedback gain (K)
Manual	No haptic guidance	0
HG-Strong	Fix authority with strong feedback	1.0
HG-Normal	Fix authority with normal feedback	0.5
HG-Decrease	Adaptive authority with decreased feedback as grip strength increases	$1.0 - \frac{sEMG}{sEMG_{REF}}$
HG-Increase	Adaptive authority with increased feedback as grip strength increases	$\frac{sEMG}{sEMG_{REF}}$

The results shown in Table 5 indicate that the driver behavior, in terms of steering behavior, lane departure risk, and driver workload, was different between driving with adaptive authority haptic guidance and with fixed authority haptic guidance. A reduction in both lane departure risk and driver workload was found in the condition of HG-Decrease compared to manual driving and fixed authority haptic guidance. This outcome suggests the potential of the adaptive authority of HG-Decrease to improve driver-automation cooperation for a steering task.

Table 5. Means and standard deviations of the dependent measures of driver behavior

Variable	Manual (1) M(SD)	HG-Strong (2) M(SD)	HG-Normal (3) M(SD)	HG-Dec (4) M(SD)	HG-Inc (5) M(SD)	p	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
RMS of driver input torque (N·m)	1.096 (0.072)	0.596 (0.140)	0.786 (0.092)	0.657 (0.149)	0.884 (0.142)	< 0.001	***	***	***	***	***	0.49	***	*	0.12	*
RMS of SWA (deg)	24.1 (6.8)	26.5 (8.1)	25.2 (6.8)	23.2 (5.8)	24.1 (6.2)	0.009	+	0.29	0.64	1.00	0.71	+	0.16	**	0.48	0.46
Maximum positive value of SWA (deg)	39.6 (16.2)	47.2 (20.0)	41.8 (17.8)	38.3 (15.9)	40.3 (15.7)	0.002	***	0.66	0.76	0.98	0.27	**	0.11	0.19	0.89	0.20
Minimum negative value of SWA (deg)	-44.5 (14.4)	-47.2 (16.9)	-44.1 (12.8)	-41.0 (12.7)	-44.4 (12.3)	0.032	0.47	0.99	***	1.00	0.64	*	0.70	0.11	1.00	*
Lateral error at the end of 1st LC (m)	0.439 (0.125)	0.335 (0.203)	0.397 (0.156)	0.280 (0.165)	0.406 (0.133)	0.014	+	0.62	*	0.85	0.51	0.86	0.53	+	0.97	*
Lateral error at the end of 2nd LC (m)	0.211 (0.098)	0.194 (0.122)	0.229 (0.094)	0.167 (0.073)	0.241 (0.119)	0.243	0.95	0.89	0.60	0.91	0.80	0.82	0.64	0.23	0.99	*
RMS of normalized sEMG (%)	8.10 (3.62)	8.66 (4.18)	7.86 (3.52)	7.58 (3.72)	7.86 (3.39)	0.265	0.82	0.95	0.58	0.69	0.62	0.27	0.45	0.78	0.80	0.91

$^{+}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

SWA: Steering wheel angle; LC: Lane change.

To further test the adaptive steering system, a haptic interface with adaptive stiffness based on forearm muscle activity measurement was designed in a real-vehicle experiment. By referring to the conditions in the driving simulator experiment, there are two types of adaptive stiffness: steering stiffness decreases when grip strength increases, and steering stiffness increases when grip strength increases. The condition of fixed stiffness was conducted as a comparison. Steering wheel angle and vehicle position were measured to evaluate the driving performance. Significant difference was not found between the adaptive steering stiffness and fixed steering stiffness (data now shown), as the currently designed lane change task did not induce greater risk. Future study with a more demanding driving task should be conducted.

(b) Effect of adaptive haptic shared control on distracted driver behavior

In the experiment, 18 participants drove under six conditions for a double lane change task as shown in Table 6. Two driver states were considered: attentive and distracted. For each state, there were three types of haptic guidance: manual steering or HG-Non, HG-Fixed (haptic guidance with fixed authority), and HG-Adaptive (haptic guidance with adaptive authority). The steering wheel torque provided by the adaptive haptic guidance was real-time computed based on the normalized sEMG value.

Table 6. Experimental conditions

Condition	Driver State	Haptic Guidance
1	Attentive	Manual (HG-Non)
2	Attentive	HG-Fixed
3	Attentive	HG-Adaptive
4	Distracted	Manual (HG-Non)
5	Distracted	HG-Fixed
6	Distracted	HG-Adaptive

Figure 5 and Table 7 show the results of the lateral error at the end of the first lane change. Pairwise comparisons indicated that for the attentive condition, the lateral error was significantly higher for manual steering than for HG-Fixed with $p < 0.05$ and tended to be higher for HG-Adaptive with $p < 0.1$. The lateral error for distracted was significantly lower in the case of HG-Fixed than in manual, where $p < 0.05$; HG-Adaptive was significantly lower than HG-Fixed ($p < 0.01$). Furthermore, HG-Adaptive tended to be significantly lower than HG-Fixed with $p < 0.1$. This indicated that, for distracted drivers, HG-Adaptive yielded a greater reduction in the lane departure risk than that of HG-Fixed and manual steering.

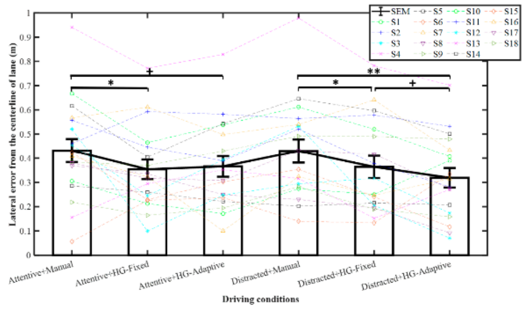

Figure 5. Lateral error with respected to lane centerline at end of first lane change

The results of the driver workload assessed by the NASA-TLX are shown in Figure 6 and Table 7. With the pairwise comparisons, the overall driver workload for distracted was significantly higher than for attentive ($p < 0.001$). Moreover, for distracted, HG-Fixed yielded a lower overall workload ($p < 0.1$), lower physical demand ($p < 0.1$), and lower effort ($p < 0.1$), and HG-Adaptive yielded a lower temporal demand ($p < 0.1$). This indicates that the driver workload increased during the secondary task, and the haptic guidance system effectively reduced the workload of distracted drivers.

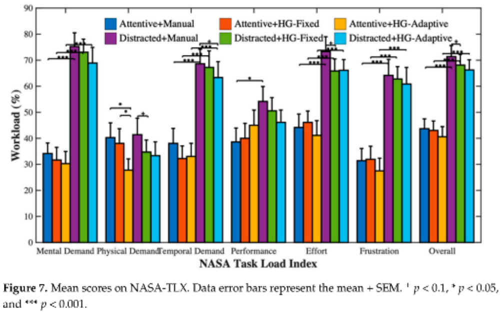

Figure 6. Mean scores on NASA-TLX.

Table 7. Means and standard deviations of the dependent measures of driver behavior

Variable	Attentive and Manual (1) M (SD)	Attentive and HG-Fixed (2) M (SD)	Attentive and HG-Adaptive (3) M (SD)	Distracted and Manual (4) M (SD)	Distracted and HG-Fixed (5) M (SD)	Distracted and HG-Adaptive (6) M (SD)	Driver State *p*-Value	HG *p*-Value	Interaction *p*-Value
RMS of driver input torque (N·m)	1.029 (0.064)	0.734 (0.072)	0.633 (0.106)	1.029 (0.058)	0.722 (0.081)	0.643 (0.149)	0.941	0.000 ***	0.454
RMS of SWA (degree)	18.897 (3.182)	19.122 (2.551)	19.403 (2.674)	17.976 (2.015)	18.592 (2.058)	18.555 (2.049)	0.059 +	0.198	0.732
Peak value of SWA at the 1st LC (degree)	28.497 (7.116)	28.040 (6.986)	29.468 (7.394)	25.274 (4.366)	26.323 (3.826)	28.274 (5.265)	0.046 *	0.024 *	0.203
Peak value of SWA at the 2nd LC (degree)	−33.815 (6.301)	−33.135 (5.184)	−32.867 (5.763)	−33.035 (4.758)	−31.296 (3.052)	−31.203 (3.811)	0.056 +	0.092 +	0.595
Peak value of lateral acceleration at the 1st LC (m/s^2)	1.702 (0.437)	1.670 (0.418)	1.761 (0.445)	1.501 (0.264)	1.571 (0.229)	1.684 (0.313)	0.046 *	0.026 *	0.180
Peak value of lateral acceleration at the 2nd LC (m/s^2)	−1.983 (0.381)	−1.944 (0.312)	−1.936 (0.356)	−1.929 (0.280)	−1.828 (0.189)	−1.833 (0.228)	0.047 *	0.147	0.619
Duration of double LC (s)	8.613 (1.044)	8.437 (0.689)	8.123 (0.595)	8.731 (0.788)	8.088 (0.626)	8.290 (0.811)	0.867	0.002 **	0.083 +
RMS of normalized sEMG (%)	7.116 (3.501)	6.746 (3.686)	6.696 (3.547)	6.947 (3.966)	6.309 (3.908)	7.120 (4.053)	0.822	0.099 +	0.208
Lateral error at the end of 1st LC (m)	0.432 (0.203)	0.354 (0.172)	0.366 (0.181)	0.430 (0.204)	0.364 (0.195)	0.319 (0.171)	0.391	0.000 ***	0.296
Lateral error at the end of 2nd LC (m)	0.193 (0.111)	0.214 (0.123)	0.169 (0.100)	0.241 (0.099)	0.215 (0.101)	0.224 (0.133)	0.033 *	0.650	0.114
NASA-TLX overall workload	43.685 (16.020)	43.019 (15.408)	40.593 (16.489)	71.407 (17.924)	68.130 (17.330)	66.241 (16.541)	0.000 ***	0.166	0.826
Relative score of pairwise preference	0.647 (0.786)	0.882 (0.781)	1.471 (0.624)	0.353 (0.702)	1.059 (0.748)	1.588 (0.507)	1	0.001 **	0.314

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. SWA: steering wheel angle; LC: lane change; HG: haptic guidance.

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　4件／うちオープンアクセス　3件）

１．著者名 Wang Zheng、Suga Satoshi、Nacpil Edric John Cruz、Yan Zhanhong、Nakano Kimihiko	４．巻 21
２．論文標題 Adaptive Driver-Automation Shared Steering Control via Forearm Surface Electromyography Measurement	５．発行年 2021年
３．雑誌名 IEEE Sensors Journal	６．最初と最後の頁 5444～5453
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JSEN.2020.3035169	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Nacpil Edric John Cruz、Wang Zheng、Yan Zhanhong、Kaizuka Tsutomu、Nakano Kimihiko	４．巻 -
２．論文標題 Surface Electromyography-controlled Pedestrian Collision Avoidance: A Driving Simulator Study	５．発行年 2021年
３．雑誌名 IEEE Sensors Journal	６．最初と最後の頁 1～1
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JSEN.2021.3070597	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Yan Zhanhong、Yang Kaiming、Wang Zheng、Yang Bo、Kaizuka Tsutomu、Nakano Kimihiko	４．巻 -
２．論文標題 Intention-Based Lane Changing and Lane Keeping Haptic Guidance Steering System	５．発行年 2020年
３．雑誌名 IEEE Transactions on Intelligent Vehicles	６．最初と最後の頁 1～1
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TIV.2020.3044180	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Wang Zheng、Zheng Rencheng、Nacpil Edric John Cruz、Nakano Kimihiko	４．巻 16
２．論文標題 Modeling and analysis of driver behaviour under shared control through weighted visual and haptic guidance	５．発行年 2022年
３．雑誌名 IET Intelligent Transport Systems	６．最初と最後の頁 648～660
掲載論文のDOI（デジタルオブジェクト識別子） 10.1049/itr2.12163	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Wang Zheng、Suga Satoshi、Nacpil Edric John Cruz、Yang Bo、Nakano Kimihiko	４．巻 21
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s21227691	査読の有無 有
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１．発表者名 Gia Quoc Bao Tran
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関