Evaluating the Applicability of GUI-based Steering Laws to Virtual Reality Car Driving: A Case of Width-Changing Paths

Masahiro Fukui*

Meiji University, Tokyo, Japan, ev200587@meiji.ac.jp

Takumi Takaku

Meiji University, Tokyo, Japan, takumi.meiji.fms@gmail.com

Satoshi Nakamura

Meiji University, Tokyo, Japan, nkmr@meiji.ac.jp

Shota Yamanaka

Yahoo Japan Corporation, Tokyo, Japan,

For a proper car navigation system, it is necessary to model the level of driving difficulty according to the road geometry. As for curved paths with constant width, Yamanaka et al. verified that steering-law-based models for predicting the speed and time needed to perform GUI tasks, can be applied to models of driving difficulty. Incidentally, changes in road width, such as chicane and lane narrowing, make it more challenging to travel along the road. Therefore, we designed narrowing and widening roads of different widths and conducted experiments on a driving simulator to investigate how road width changes affect driving difficulty. As a result, the most appropriate model for the movement time had adjusted r^2 value of 0.9736. Our results also indicated that reflecting the difference between widening and narrowing is not important to make the model more accurate when the task is easy to some extent.

CCS CONCEPTS • **Human-centered computing → HCI theory, concepts and models; Virtual reality.**

Additional Keywords and Phrases: Driving, Driving Simulator, Road width, Steering Law, Modeling

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1 INTRODUCTION

As car navigation systems become more sophisticated, more and more forms of assistance to car drivers, such as route recommendations and arrival time prediction, are becoming available. However, despite significant individual differences, drivers' preferences for particular road geometries, such as aversion to curves or confidence in traveling along narrow straights, are not reflected. As a practical example, according to a questionnaire survey of 2,000 driver's license holders conducted by Nakagawa et al. [1], many novice drivers needed help with specific road conditions, such as narrow roads and merging.

To assist such drivers in driving safely and comfortably, it is more desirable to recommend accessible routes than routes that minimize driving time. To realize a route recommendation system that reflects individual driver preferences, it is necessary to clarify the effects of road conditions on driving and quantify the degree of difficulty. Although repeated driving is required to quantify the difficulty caused by road conditions, it is unrealistic to cover countless conditions.

Here, using vast knowledge of operating difficulty in the graphical user interface (GUI) to quantify driving difficulty is conceivable [2]. The steering law is a model for predicting speed and the time needed to pass through a given path based on its geometry. Previous studies have shown that this model can be used to estimate safe speeds for driving on straight [3,4] and circular roads [5]. Furthermore, Zhai et al. [6] experimented and implied that the steering law for real cars was also valid for a VR simulator.

In addition to straight and circular paths, models of more general geometries, such as turning angle [7], curvature [8,9], sequential linear path segments [10], and narrowing or widening tunnels [11], have been developed for GUIs. However, whether they can be applied to driving has not yet been verified. Thus, we developed a driving simulator reproducing multiple geographical conditions in a 3D space [12]. As a first step in modeling driving difficulty by using this simulator, we experimented with models for a curved path that apply to driving on curves and found that the models were applicable with some modifications [13].

Incidentally, changes in road width, such as chicane and road narrowing [20, 21], also affect driving difficulty. In this study, we investigate the effect of changes in road width on driving difficulty by improving the driving simulator [13]. Specifically, as shown in Figure 1, we experimented to verify whether the results of the steering law experiment could be applied to car driving on roads narrowing or widening monotonically and linearly in the driving simulator.

2 RELATED WORK

2.1 Use of the driving simulator

Driving simulators are used for many purposes. There are two main advantages to using them. The first advantage is that the cost of experiments with the simulator is very low compared to those on real roads. For example, DriverLab realistically renders rain and darkness to study their influence on drivers' performance [14]. Other studies have used simulators to investigate the effect of road sign placement [15] and bumpy pavement surfaces [16]. Using simulators is warranted because changing these conditions on actual roads costs too much.

The second advantage is that researchers can test dangerous situations without any risks. For instance, simulators allow us to test safety when drivers are drunk, sleepy, or distracted by roadside vegetation or cell phones. Since our experiment is based on the assumption that narrowing roads are more dangerous, using a simulator is appropriate for safety reasons in this case.

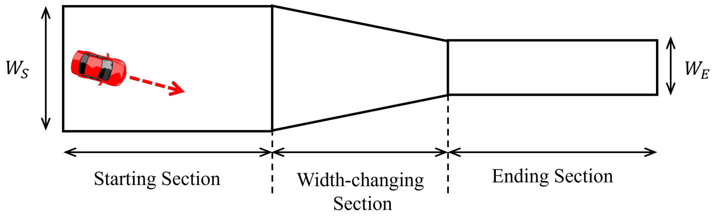


Figure 1: An Entire Course

As far as we know, Zhai et al.'s study is the only one that has used a simulator to verify whether the steering law holds for driving on straight and circular roads [6]. However, before their research, models that were equivalent to the steering law had already been validated by several research groups for straight paths [3,4] and circular courses [5] with real cars. Thus, Zhai et al. researched to verify whether models for driving in actual vehicles can be applied to ones for driving on a VR simulator. In other words, the GUI-based models proposed originally in HCI were not used enough for car driving (actual or VR), even though HCI researchers have developed various models.

To bridge the gap between real car driving and existing HCI findings, We researched to verify whether the models for a curved path proposed in the HCI field [9] can be applied to car driving in a VR simulator [13]. As a result, it turned out that the models needed some modifications to maximize the prediction accuracy. However, the models covered in this study are only partial; many other models are yet to be tested for their accuracy in driving.

2.2 Steering law

Accot et al. [17] found a steering law to model the movement time (MT) for GUI tasks. This model quantitively expresses the relationship between MT and the task parameters, as shown in Fig. 2, as follows:

$$MT = a + b \times ID, ID = \frac{A}{W} \quad (1)$$

where A and W are the length and width of a constant-width tunnel, ID is the task's difficulty index and a and b are empirically determined constants. Equation 1 means that navigating a narrower or longer tunnel is more complicated. It is also known that the steering law applies to tasks involving traversing simple straight or circular paths and using computer mice or pen tablets [18,19].

2.3 Steering law in path narrowing or widening

Accot et al. also derived a model for a narrowing straight tunnel. The index ID for a narrowing tunnel (ID_{NT}) is expressed as:

$$ID_{NT} = \frac{A}{W_E - W_S} ln \frac{W_E}{W_S} \quad (2)$$

where A is the length of the width-changing section, W_S is the width of the starting section, and W_E is the width of the ending section.

Furthermore, Yamanaka et al. [11] found that passing through a widening tunnel is easier than doing so through a narrowing one. However, the ID_{NT} is calculated to have the same value as ID for a widening tunnel (ID_{WT}) based on the model of Accot et al. Focusing on this problem, they modeled the ID difference between narrowing and widening tunnels (known as ID_{Gap}) as follows:

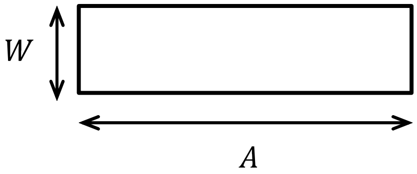


Figure 2: A constant-width tunnel

$$ID_{Gap(k)} = \frac{A(W_S - W_E)}{kW_S W_E} \quad (3)$$

where k is a regression constant. In other words, this model redefines ID_{NT} by modifying it with ID_{Gap} as follows:

$$ID_{NT} = \frac{A}{W_E - W_S} ln \frac{W_E}{W_S} + ID_{Gap(k)} \qquad (4)$$

As a result, it turned out that the model of Yamanaka et al. is far more accurate than the model of Accot et al. Moreover, they showed that the model can predict the MT of narrowing tunnels (MT_{NT}) from the MT of widening ones (MT_{WT}), too.

2.4 Effects of road narrowing in the real world

On real roads, a narrow lane width for a specific section, known as a narrowing measure, is used to slow down vehicles for traffic safety. Several studies have investigated the effect of road narrowing on driving speed.

Sołowczuk et al. [20] measured traffic volume and speed counts before and after the installation of the road narrowing treatment, covering 100 passing vehicles in a dangerous zone. As a result, the speed of cars at that point turned out to be reduced by 15 km/h. Distefano et al. [21] conducted an experimental investigation measuring speed on a narrow road in an urban area in Catania, Italy. They found that the average speed of passing vehicles could be reduced by 36% in the vicinity of the narrowed area, compared to the average speed in the previous section of the road.

However, the road conditions in these studies were few, and the experimental design needed to consider detailed parameters of road geometries, making it inadequate to model driving difficulty for each road condition.

3 DRIVING EXPERIMENT

3.1 Experiment overview

We recruited 20 undergraduate and graduate students (12 males and 8 females) with driving licenses as participants in the experiment. This study conducted experiments using a driving simulator, focusing on the speed and time to pass through width-changing sections on a course with multiple road widths and path lengths. Our main purpose in this study is to verify whether the models of Accot et al. [17] and Yamanaka et al. [11] for pen-based width-changing-path steering can be applied to car driving. Plus, we analyzed the difference between the models. We hypothesized that the model of Yamanaka et al. was far more accurate than that of Accot et al., as shown by Yamanaka et al.'s experiments for GUI tasks referred to in Section 2.3.

The driving simulator (Figure 3) was improved from Yamanaka et al.'s system [13] to be able to generate courses with arbitrary values for parameters such as the start width, the length of the width-changing section, and the end width, as shown in Figures 1 and 4.

The driving simulator was equipped with Oculus Quest2 as the head-mounted display (HMD), Fanatec's ClubSport Wheel Base V2.5 as the steering controller, Fanatec's Podium Hub Lenkrad Classic 2 as the steering wheel, and Fanatec's ClubSport Lenkrad Classic 2 as the pedals. The steering wheel was Fanatec's ClubSport Pedals V3 inverted, and the seat was Next Level Racing's NLR-S010.

Figure 3: Data from the pedals and steering wheel and the participant’s head motions in the real world are linked to the car’s velocity and the view in the HMD.

被験者プロファイルが未選択です!

計測(単位＝初速角度:[°]，初速大きさ:[km/h]，他:[m])

#	経路長	始端幅	終端幅	前半長	後半長	初速角度	初速大きさ
0	100	3	5	100	100	1	60
1	100	3	7	100	100	1	60
2	20	5	3	100	100	1	60

☑ 順番をランダム化

エラー時の動作
☐ 何もしない
☐ 最後にもう一度（シャッフルなし）
☑ 最後にもう一度（シャッフルあり）

ステータス
コース: 不明
座標：
速度：
レイテンシ: 0 ms
送信: 12:00:00 AM
受信: 12:00:00 AM

Figure 4: Configuring and monitoring system for HMD.

3.2 Experimental design

In this experiment, we focus on the effect of road parameters, including A, W_S and W_E. Other possible factors that may affect driving difficulty, such as whether it is day or night, weather, number of lanes, and traffic, will be included in our future work, because it is too hard to cover all of them in a single paper.

As shown by Yamanaka et al. [13], width has little effect on driving difficulty when the road is too broad. For this reason, six types of pairs, made from two different widths out of 2.5 m, 5.0 m, and 7.0 m, were adopted as the W_S and W_E. Also, As were 20 m, 50 m, and 100 m.

It is inappropriate to set the initial position of the car in the center of the road and parallel to the road because participants can drive with a firm foot on the accelerator pedal without operating the steering wheel. Thus, cars were set to start with a one-degree rightward deviation from the frontal plane, and all participants were required to handle the steering wheel in the first straight section.

Furthermore, the starting section was set at 100 m because the steering wheel and accelerator pedals were unstable immediately after the start. In addition, the ending section was set at 100 m after the width-changing section, and the goal line was placed at the end. Without this, participants might aim to touch the end line of the width-changing section, leading to unrealistic driving, such as finishing at an extremely steep angle, ignoring what would happen after the goal. In addition, as previous studies have shown [12,13], the running speed varies significantly from participant to participant, even if they are verbally instructed to maintain a specific speed. Thus, the initial velocity was set at 60 km/h so that all participants had similar speeds.

3.3 Experimental procedure

To minimize the effect of experimental habituation, a total of 18 courses, consisting of six combinations of widths and three varieties of path lengths, were presented randomly in one set, and the experiment participants were asked to perform a total of five sets (90 trials). Figure 5 shows the shape of each course.

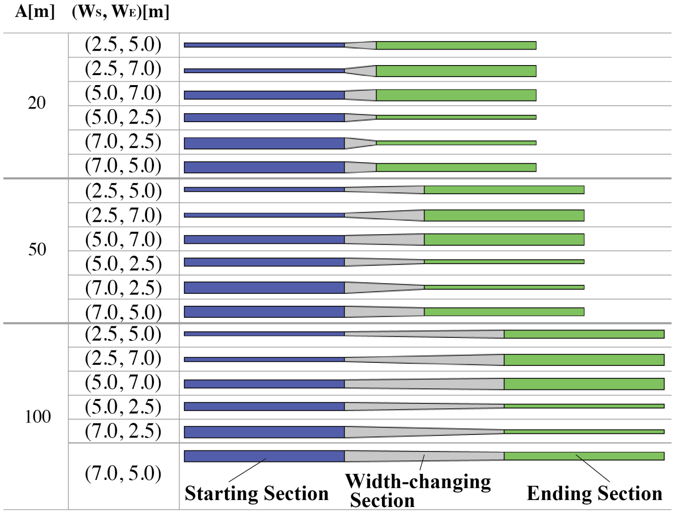
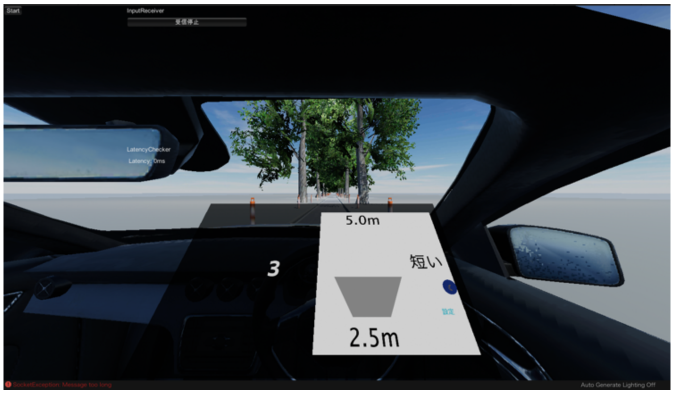


Figure 5: The 18 path conditions used in the experiment.



SocketException: Message too long

Figure 6: A path condition as viewed in the HMD.

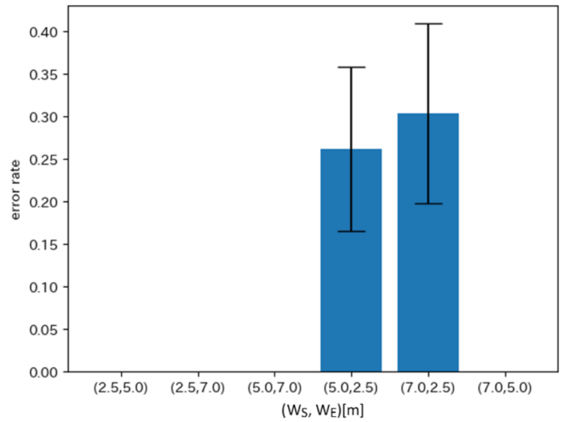


Figure 7: Error rate for each W_S and W_E condition.

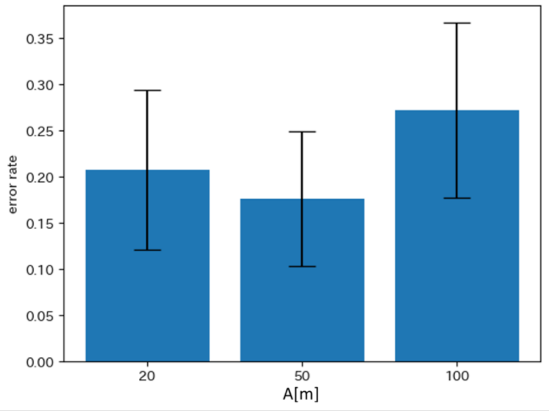


Figure 8: Error rate for each path-length condition.

A countdown was held at the beginning of each trial (see Figure 6). At that time, information on the course was presented as illustrations with text so that the experimenter could prepare for driving in advance. Data measurement began when the countdown reached zero and ended when the front of the car reached the goal. The measure was repeated until participants reached the goal under every single condition.

The participants were instructed to avoid riding up on the curb, driving extremely slowly, and driving as fast as possible without causing errors. Considering individual differences in how people see VR using HMDs, we checked the participants' physical condition and whether they could concentrate at the end of each set. We allowed them to take a break at any time they wished. The experiment took one hour per person from the practice run to the end of the measurement.

4 RESULTS

This section describes the results of error rates and average MT within the width-changing section for each of W_S, W_E, and A.

4.1 Error rates for each road width and length of the width-changing section

The total number of errors in this experiment was 573 out of 2,373 trials by the 20 participants. Of these, 82 occurred during the width-change section. Figure 7 shows the average error rate for each pair of starting and ending widths, and Figure 8 shows the average error rate during the width change interval for each width change interval length. hen W_S was 7.0 m and W_E was the same, the error rate was lower. The error rate was zero for other cases, including all widening paths. Figure 8 shows that the error rate was highest when A was 100 m and lowest when it was 50 m.

4.2 Movement time for each road width and length of the width-changing section

Table 1 shows the average time to pass through the width-changing section for each road condition. Comparing the two states, in which A was equal, and W_S and W_E were swapped, the passage time for the narrowing condition was longer than that for the widening condition in all cases. The difference in MT was minor when W_S and W_E were 5.0 m or more significant. For example, in the situation where A was 100 m, there was a 0.50-second difference in MT when W_S and W_E were in pairs of 2.5 m and 7.0 m. However, when W_S and W_E were in pairs of 2.5 m and 7.0 m, there was only a 0.02-

Table 1: Average MT for 18 path conditions.

(W_S, W_E)[m]	Average MT[s]		
	A 20m	A 50m	A 100m
(2.5, 5.0)	1.09	2.71	5.12
(5.0, 2.5)	1.15	2.98	5.64
(2.5, 7.0)	1.08	2.66	4.95
(7.0, 2.5)	1.20	2.83	5.45
(5.0, 7.0)	0.77	2.00	3.93
(7.0, 5.0)	0.80	2.04	3.95

second difference in MT. This means that the difference between narrowing roads and widening ones was too tiny to affect MT when W_S and W_E were 5.0 m or more.

5 DISCUSSION

5.1 Effects of changes in road width on acceleration

Figures 9 (a)-(c) are graphs with the distance from the starting point on the horizontal axis and the average acceleration of all participants when passing through that point on the vertical axis. The legend of the graph indicates the value of W_S and W_E [m], respectively. The gray background part represents the width-changing section. The lengths of the width change intervals are 20 m, 50 m, and 100 m from left to right.

Figures 9 show that the amount of gas pedal operation increased at once at the beginning when the width was always 5.0 m or more and was slightly affected by the road width change. When W_E was 2.5 m, the accelerator pedal was depressed according to W_S in the early phase. The accelerator pedal was released to a minimum value near the width-change section and then depressed gradually. The greater the A, the lower the amount of gas pedal was. When W_S was 2.5 m, the amount of pedal use increased rapidly at the beginning of the section and reached its maximum value when the car reached the width-changing section. When W_E was wider, the maximum value of the amount of pedal use was greater, and the amount of pedal use increased more rapidly in the early phase.

From above, the effect of changes in road width on the accelerator was limited when the road was always broader than 5.0 m. However, when the width increased from 2.5 m, the effect was more substantial as the width increased rapidly. In the condition where the road width narrowed to 2.5 m, the wider the W_S, the more strongly the accelerator was pressed. Then, the longer the width-changing section, the more the accelerator was depressed.

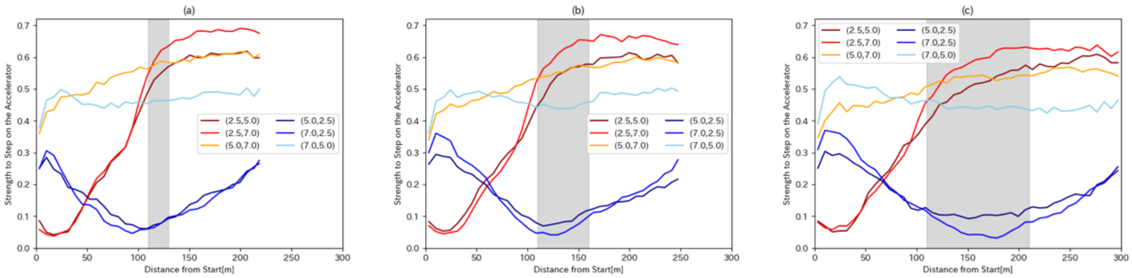


Figure 9: Pressure on the accelerator on the width-changing section when A is (a)20m, (b)50m, (c)100m.

5.2 Effects of changes in road width on driving difficulty

The experimental results showed that the average MT was shorter when W_S and W_E were 5.0 m or more compared to other conditions. Also, MTs for the two conditions where W_S and W_E were swapped were similar. Therefore, driving difficulty was very low in this case, which means the effect of the road width change could be minimal when the road is always wider than 5.0 m.

On the other hand, when the W_S was 2.5 m, the average MT was shorter when the W_E was greater, suggesting that driving difficulty decreases if the road widens more rapidly. When the W_E was 2.5 m and the A was 20 m, the error rate and average MT increased as the W_S became greater. When A was 50 m or longer, as the W_S increased, the average MT decreased even though the error rate increased. Considering the argument in Section 5.1, the reason why such contradictive phenomena happened is that participants tended to step on the accelerator a bit too strongly when the W_S was so large.

From this result, driving difficulty was scarcely affected by changes in road width when the width was always 5.0 m or more. In other cases, the driving difficulty basically decreased as the road widened rapidly and increased as the road narrowed quickly, except for a few situations where MT was excessively small due to the wide starting section.

6 MODELING OF DRIVING DIFFICULTY BY THE STEERING LAW

Based on the experimental results, we verified whether the steering law could be applied to quantify the driving difficulty of a route with varying road widths on a driving simulator.

6.1 Applicability to Model Driving Difficulty

Figure 10 shows the narrowing case, Figure 11 shows the widening case, and Figure 12 shows all cases with ID on the horizontal axis and MT on the vertical axis. The blue and red dots in these figures show the experimental data for the narrowing and widening cases, respectively, and the straight line is a linear regression of the data.

Initially, the Accot et al. model was designed mainly for steering tasks on narrowing paths. However, while the model used in Figure 10 showed the highest goodness of fit ($R^2 = 0.98$) among Figures 10-12, the diagrams in Figures 11 and 12 also showed high values ($R^2 \geq 0.96$), indicating that the model could be used to estimate MT with sufficiently high accuracy even under widening conditions in this experiment.

Next, we verified whether Yamanaka et al.'s model could be applied to predict movement time in driving when all width conditions were covered. Because the models used in figures 12-14 had different numbers of coefficients, to examine the model fit in a more statistical manner, we compared models by using the adjusted coefficient of determination (adjR^2) and Akaike's Information Criterion (AIC) [22]. The free parameter k of $ID_{Gap(k)}$ used in this model was determined in each experiment, and $k = 9.15$ was optimal in this case, so this value was used to correct ID_{NT}. Figure 13 is a plot of the corrected data. The model in this graph had a higher value of adjR^2 and a smaller value of AIC than the model used in Figure 12, indicating that the model of Yamanaka et al. is more accurate than that of Accot et al.

Incidentally, it is possible that the participants always drove the car considering the narrowest width to avoid errors and did not consider width variation. In such a case, it would be more appropriate to use a model that does not depend on the width change, so the width change section was considered as a path with a constant width equal to the narrower width of the starting and ending widths, and the MT was estimated as:

$$ID_{NT} = \frac{A}{\min\,(W_S, W_E)} \quad (5)$$

Figure 14 is obtained by calculating ID in Equation (5). As a result, the model used in this graph had a smaller value of adjR^2 and a higher value of AIC than the models used in Figures 12 and 13. Therefore, it was clear that the width change

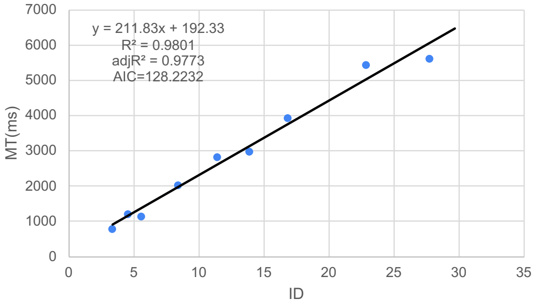


Figure 10: Relation between ID and MT of narrowing path. (from now on, blue plots stand for narrowing conditions)

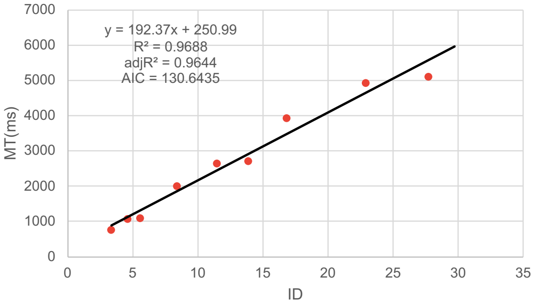


Figure 11: Relation between ID and MT of widening path. (from now on, red plots stand for narrowing conditions)

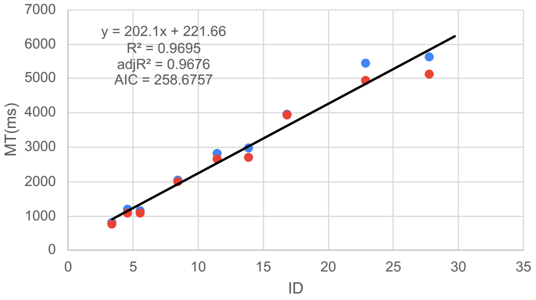


Figure 12: Relation between ID in Equation (2) and MT of all kinds of path.

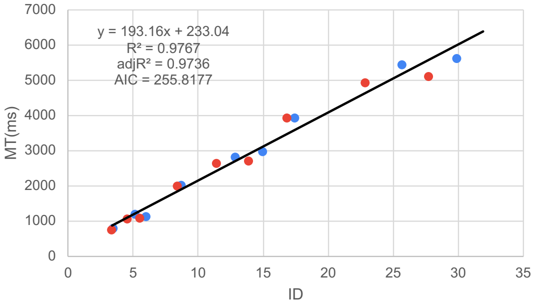


Figure 13: Relation between ID defined in Equation (4) and MT of all kinds of path.

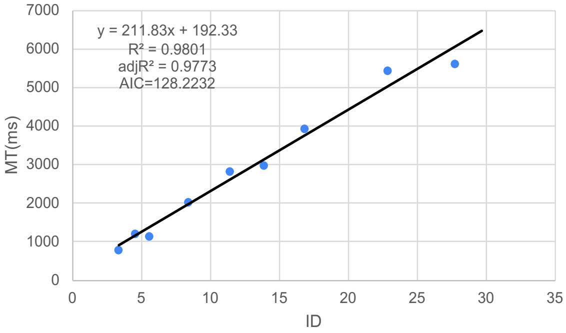


Figure 14: Relation between ID defined in Equation (5) and MT.

influences the driving difficulty.

6.2 Validity of Using the Model to Predict Movement Time

We tested the feasibility of inferring MT from ID using the models of Accot et al. and Yamanaka et al. As a result, it was revealed that the accuracy of both models was sufficiently high, and the model of Yamanaka et al. was a better fit for both widening and narrowing conditions.

However, the hypothesis mentioned in Section 3.1 was not supported: There was no significant difference in the accuracy of the two models. Comparing pairs of two conditions whose A was the same and where W_S and W_E were swapped, this might have been because of the choice of ID in this experiment. For instance, as shown in Figure 12, many pairs of conditions with $ID_{WT} \leq 20$ had almost the same MT values. This indicates that the reason why there was no significant difference in accuracy between the two models was because ID_{Gap} did not have such a great effect. On the other hand, some pairs with $ID_{WT} > 20$ had differences between MT_{WT} and MT_{NT} to some extent, so Yamanaka et al.'s model was considered even more effective for data with $ID_{WT} > 20$. To substantiate this possibility, we will investigate the difference in accuracy between the two models by re-experimenting under challenging conditions such that ID_{WT} is higher than twenty, for example using courses with narrower and longer width-changing sections.

7 CONCLUSION

In this study, we modeled and quantified the effect of road width changes on driving difficulty. Experiments were conducted on six starting and ending width pairs and three width change section lengths. The error rate, average passing time at the width change section, and accelerator operation were analyzed and discussed. The results showed that the effect of road width change on driving difficulty was limited under conditions where the road widths were 5.0 m or more. However, the amount of width change affected the increase or decrease in driving difficulty under other conditions.

In addition, we verified whether the steering-law-based model of Accot et al. and that of Yamanaka et al. could be assessed by the ID calculated from the road conditions. The results showed that both models could be used to estimate with sufficient accuracy, and the Yamanaka et al. model showed a slightly better fit, which means our hypothesis that this model shows a far better fit was not supported.

Further modeling of driving skills will be conducted after redesigning the difficulty level of the course. We also plan to conduct experiments on other factors, such as turning angle [7], curvature [8], and sequential linear path segments [10], to verify the feasibility of model and to realize a route recommendation system that can respond to a wide range of conditions.

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