Analysis of the interaction between driving intention and vehicle behavior based on driving simulation experiments

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ABSTRACT

Analyzing the interaction patterns between vehicles is an effective means of analyzing the causes of congestion and accidents on expressways. To analyze vehicle behavior from a micro perspective, this study was conducted using a driving simulator to investigate the vehicle operational behavior generated by participants on a specific road section. Through separate interviews, the study investigated the intentions and reasons behind the participants' behavior during the replay process. The study decomposed and extracted 24 key words and structured combination the interview responses into four operational intention groups. The study found that the vehicle behavior corresponding to each operational intention group was significantly different. The analysis of the participants' operational behavior in different driving environments based on the relationships between operational intentions can provide policy recommendations for relevant transportation departments and provide theoretical support for driving behavior analysis.

Keywords: driver intention, driving behavior, driving simulator, interview, urban expressway

1. INTRODUCTION

In urban roads, especially at intersections and sections with frequent lane changes and complex traffic flow, traffic congestion and accidents often occur. Most existing traffic flow theories consider these impacts solely from a macro perspective and cannot fully analyze these phenomena. Therefore, analyzing the interaction between microscopic vehicles, the mechanism of driver behavior, and implementing countermeasures are effective means to understand traffic congestion and accident impact. Many vehicle behavior models have been proposed to analyze micro vehicle interactions. However, most existing traffic flow models and analysis methods only consider gap selection and linear differences during the following and lane changing processes. In addition, many studies are focused on specific situations, but the actual behavior of vehicles is the result of complex influences from different stages and scenarios, and various driving environments and stages gradually change with changes in traffic conditions.

Michalik D et al.[1] conducted a study using a vehicle driving simulator to collect and evaluate driver input data for analyzing driver behavior and driving styles. Riener A [2] compared driver reaction times between real-world and simulated environments by summarizing preliminary results on simulating driving behavior, providing a general indicator for describing the differences in reaction time. Taheri M et al.[3] discovered that drivers' individual behaviors and characteristics, such as controlling vehicle speed, driving calmly and relaxed, and appropriately adjusting speed based on road structure variations, all impact their driving performance. Santos J et al.[4] compared standardized visual performance tests for driving in three research environments (laboratory, simulator, and instrumented vehicle) and evaluated the influence of a standardized auxiliary visual search task on driving performance across these facilities. Shechtman O et al.[5] identified driver behavioral responses on the road and in the simulator by analyzing the types and quantity of driving errors. The study results demonstrated that evaluating driving errors during turns in a simulator can be extrapolated or transferred to real-world driving. Kaplan S[6] discusses and comprehensively presents mature technologies for monitoring driver attention using either visual or non-visual features. Pradhan et al. and Sagberg et al.[7][8] conducted studies by constructing hazardous traffic scenarios to investigate the differences in hazard perception levels and response times among non-drivers. Scialfa et al.[9] utilized the same methodology to test the response times and alertness of novice drivers. David Crundall et al.[10] collected driving clips and recruited 30 drivers for the experiment. They watched videos and answered questions to analyze their ability to recognize potential hazards.

During driving, when the distance to the preceding vehicle suddenly shortens, the driver may shift from the idea of "following the preceding vehicle" to "braking to ensure safety." In this situation, the driver will consider hard braking. In

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addition, when changing lanes, drivers sometimes have stage-specific thoughts such as "faster" or "start turning the steering wheel now and cross the lane." The vehicle's actions will also gradually slow down and turn the steering wheel according to the driver's thinking each time. These drivers' thinking about the current driving situation is called "driving intention."

It is assumed that there are multiple stages and forms of vehicle behavior corresponding to multiple driving intentions and modeling of vehicle behavior considering driving intentions has been carried out. The potential variables of this model are the driving intentions that change over time, and the behaviors such as acceleration and speed are output as vehicle behaviors corresponding to driving intentions. The model parameters are obtained by maximum likelihood estimation using vehicle trajectory data, which can probabilistically estimate the driving intentions at each time point. This can also be seen as a framework for inferring driver driving intentions based on externally observed vehicle trajectories. However, even if driving intentions can be inferred through the model, the true values of driving intentions cannot be determined without directly asking the driver. Therefore, it is not possible to verify whether the inferred driving intentions are correct.

The main research content of this article is the study of the correspondence between driving intentions and vehicle behavior. Through investigating the subjects of driving simulator experiments, the relationship between drivers' actual driving intentions, actual driving operations, and vehicle behavior is studied. The method of this study is to investigate the experimental subjects to understand the correspondence between their driving intentions and actual driving behavior. The investigation was conducted through interviews by the author to ensure the accuracy and reliability of the investigation. Finally, by collecting and organizing data, the correspondence between the driving intentions that drivers actually hold and the vehicle behavior as observable driving operation results is analyzed. The study also summarizes whether the changes in driving intentions are related to changes in vehicle behavior and whether these changes have characteristic features.

2. DESIGN OF DRIVING SIMULATION EXPERIMENT

The aim of this study is to conduct multiple drives while ensuring uniformity of surrounding vehicles and road conditions, and record the driver's intentions as data. Compared to existing methods of analyzing driver thinking and decision-making, the driver intention information obtained through this interview has the following two characteristics:

(a) it can obtain driver intention information that is continuous in time;

(b) it can obtain the vehicle and environmental conditions at the time each driving intention occurs.

The experimental procedure is shown in Figure 1.

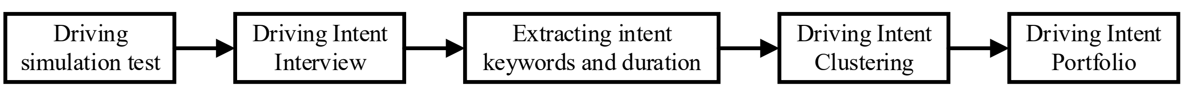


Figure 1. Flowchart of driving intent combination generation

A total of 30 participants' information was collected in the experiment, with each person undergoing 15 trials and one interview. The driving simulation experiment included five sets of 2-4 interval drives, including preparatory driving, and an interview was conducted for the last drive in each set (a total of five times). The experiment simulated driving and merging on the urban expressway in Xi'an city, and except for allowing the test vehicle to change lanes during the final drive at the Zhuque Road roundabout, it followed the leading vehicle throughout the experiment. The experimental design path is shown in Table 1.

Table 1. Simulation of the road profile.

Experimental sequence	**Road Overview**	**Forward vehicles**	**Interference and lane merging from other lanes**	**Total length**
1	Virtual two-lane highway	4 units	None	4 km
2-4	Part of Xi'an South Second Ring Road Expressway	Several	Vehicle lane changing behavior exists	4km
5	Xi'an Zhuque Road Roundabout	Several	Multiple vehicles merge and diverge here	2km

The interview was conducted one-on-one near the driving simulation laboratory, with the interviewer asking the participant about their driving intentions at 20-second intervals while playing and stopping the video of the drive. At each stop, the participant was asked, "What was the principle or intention behind your driving during this period?" and allowed to answer freely. If there was a change in the responses obtained at the 20-second interval, the participant was asked to pinpoint the time point where the change occurred while the video was played again. For example, if the response "stepped on the gas to speed up" was obtained 20 seconds after the previous response, and then the response "slowed down because the car ahead was approaching" was obtained, the video was played before and after the change to help the participant identify the time point when they started to slow down. The basic information of the participants is shown in Table 2.

Table 2. Attributes of subject characteristics.

Age	Man	Women	Total
20~30 years old	12	6	18
31~40 years old	4	3	7
40~50 years old	3	2	5
Total	19	11	30

3. ACQUISITION OF RESULTS FROM SIMULATION EXPERIMENTS

3.1 Extraction of driving intentions

In the interview survey of this study, the initial question asked was the same, which was "What was the principle behind your driving during these 20 seconds?" However, the subsequent semi-structured interview was appropriately guided based on the participant's response to include the content of driving intention. Since the response content itself was not structured, the driving intentions that the model could handle were summarized.

The processing procedure involved summarizing the interview content and the time extension brought about by driving simulation. Figure 2. shows the processing flow, where the vertical axis represents the degree of concentration of time and the horizontal axis represents the degree of concentration of the meaning content of driving intention. The combination of operational intentions refers to the group associated with multiple operational intentions. As the coordinates move towards the upper right, the concentration level increases.

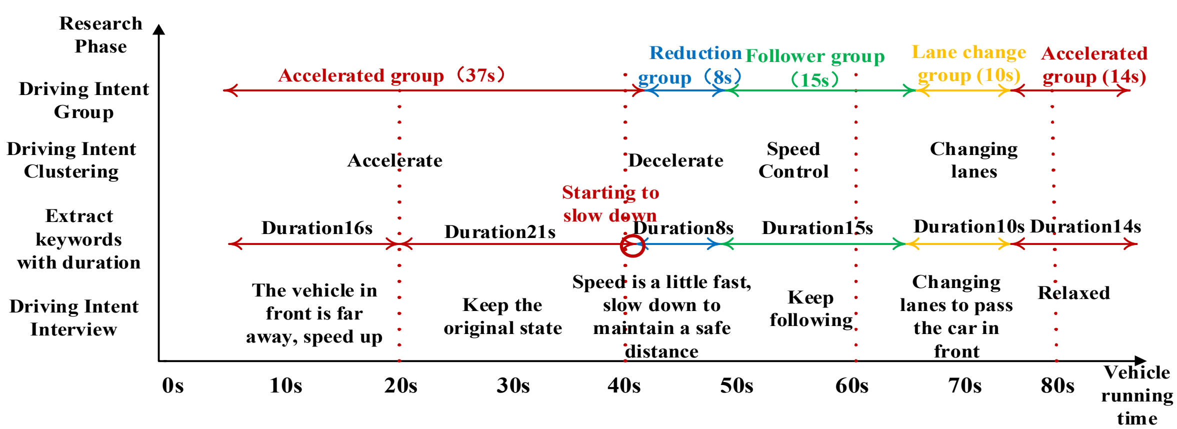


Figure 2. Structured treatment of the interview situation and responses

3.2 Extraction processing of driving intent codes

As the first step in extracting the combination of operational intentions, in order to quantify the interview responses, key words were extracted from the responses and 27 key words were defined as shown in Table 3. These key words could represent the responses of all participants at various time points.

Next, based on the time range shown in Figure 2, the effective time period for each key word was determined (the time period during which the key word response was valid). The interview survey provided information on the timing of changes in driving intentions, which was used to determine the time period during which each key word in Table 3 was valid. For the same key word, a series of valid time periods and information matching the key word at that time were generated. If no clear time point of change was obtained, as shown in Figure 1, the time points where the key words were answered every 20 seconds were weighted and set as valid time periods.

3.3 Driving Intent Portfolio

Using the data from the above valid time periods, the key words were clustered to generate eight operational intention codes. The clustering threshold was set according to the statistical value of the simulated driving operation data to avoid merging key words with significant behavioral differences.

Finally, using the operational intention codes, a combination analysis was conducted using the Ward method on the corresponding effective time periods of the interview responses, resulting in the generation of four combinations of operational intentions. These combinations had the same effective periods for the interview responses. This study assumed that the responses of the participants belonging to each combination roughly represented the same driving intention. This method tends to merge smaller population groups. Denote the populations as A and B, which are combined to form AB. The formula for this combination is as follows:

$$SSE_A = \sum_{i=1}^{n_A} (y_i - \bar{y}_A)'(y_i - \bar{y}_A) \; for \; y_i \in A \tag{1}$$

$$SSE_B = \sum_{i=1}^{n_B} (y_i - \bar{y}_B)'(y_i - \bar{y}_B) \; for \; y_i \in B \tag{2}$$

$$SSE_{AB} = \sum_{i=1}^{n_{AB}} (y_i - \bar{y}_{AB})'(y_i - \bar{y}_{AB}) \; for \; y_i \in AB \tag{3}$$

$$\bar{y}_{AB} = \frac{\sum_{i=1}^{n_A} y_i + \sum_{j=1}^{n_B} y_i}{n_A + n_B} = \frac{n_A \bar{y}_A + n_B \bar{y}_B}{n_A + n_B} \tag{4}$$

Table 3. Clustering and combination of driving intent keywords.

Driving Intent Keywords	**Driving Intent Clustering**	**Intent Group**
Safety, acceleration, relaxation, shorten the distance between vehicles	Accelerate	Acceleration group
Catching up, accelerating to avoid obstacles, overtaking	Chase	
Drive at appropriate speed, maintain distance, drive normally, observe road environment	Hold status	Follow group
Stay between vehicles, accelerate slightly, maintain speed, adjust speed, reduce speed slightly	Speed control	
Slow down, need to be more cautious, reduce speed	Decelerate	Deceleration group
Braking, unexpected situation	Sudden deceleration	
Too slow ahead, steering ahead to change lanes, alerts for side-by-side vehicles	Changing lanes	Lane change group
Avoiding obstacles ahead, left/right lane safer, about to enter merge zone	Cautious lane change	

4. ANALYSIS

4.1 Classification of experimental driving behavior based on driving intention

Based on the driving intentions obtained from the interview responses, the time spent by each participant during the driving experiment was categorized according to the same operational intention unit. For each categorized operational intention, its corresponding periods were analyzed in relation to the observed vehicle behavior in the driving simulation. Table 4. shows the total time periods classified. From the observed time periods for each operational intention category, it can be confirmed that there were no operational intention combinations with very little time assigned to them.

Table 4. Total driving time for each driving intention.

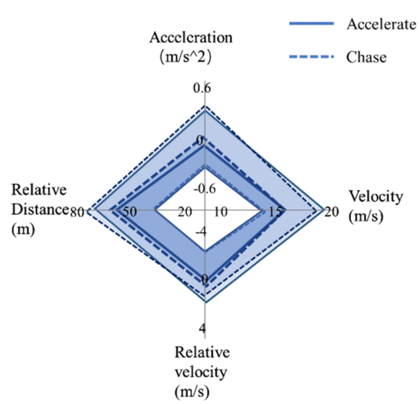
Driving Intent Group	**Total running time（s）**
Acceleration group	2553.4
Follow group	8892.1
Deceleration group	4877.9
Lane change group	2208.1

The indicators representing vehicle behavior observed in the driving experiment included the vehicle's own acceleration, speed, relative distance and speed to the vehicle in front. In this chapter, these indicators were compared between the four operational intention groups classified in the previous chapter, in order to understand the characteristics of each operational intention group from the perspective of vehicle behavior.

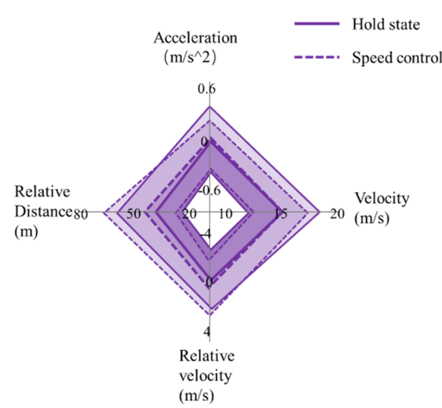
The fastest speed observed in this experiment was around 80 km/h, and the braking distance to stop safely at this speed was around 80m. Participants were expected to respond to the vehicle in front when the relative distance was within 90m. Therefore, this experiment analyzed continuous time periods of 10 seconds or more within 90m of relative distance to the vehicle in front.

4.2 The relationship between driving intentions and vehicle behavior

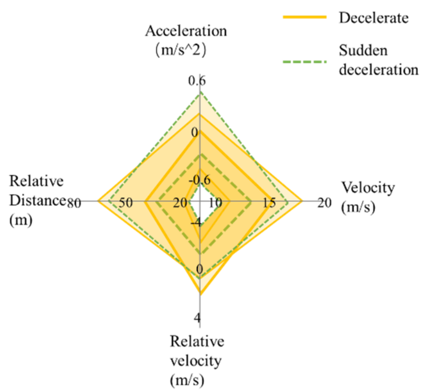
We focus on the differences between each combination of operational intentions in the four operational intention groups. The radar chart in Figure 3 distinguishes between the intentions obtained from different key words within each group by analyzing four indicators: acceleration, speed, relative distance to the vehicle in front, and relative speed. The chart depicts the average values using a thick line, and the 20% and 80% percentiles using thin lines, which are filled in between. The 20% and 80% values are used to represent the range of distribution, where more than half of the data is distributed around the median value. In addition, in order to emphasize subtle differences under large values, the axis scale in Figure 3 is proportional to the square of the values.



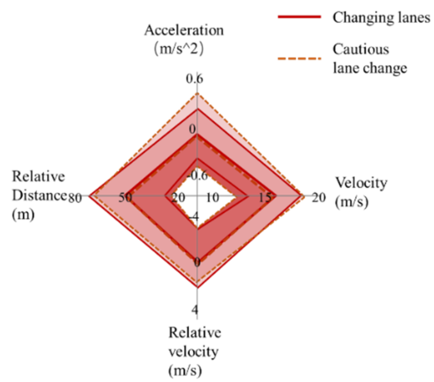
(a) Acceleration group



(b) Relative distance group



(c) Relative velocity group



(d) Speed group

Figure 3. Statistical values for each combination of driving intentions (average: thick line, 20%, 80% values: thin line)

Figure 3.a shows the statistical values of each operational intention combination within the acceleration group. In the two comparative analyses of operational intention combinations, the "chase" operational intention has larger values in all statistical indicators compared to the "accelerate" operational intention. Additionally, the other statistical indicators show a similar trend.

Figure 3.b shows the statistical values of each operational intention combination within the following group. The "Hold state" operational intention combination has a shorter relative distance, and smaller 80% percentile values for speed and acceleration, suggesting that the driver is more alert during this phase. This combination likely includes situations where the driver is being cautious. Moreover, as no difference was found between the other two operational intention combinations, it is likely the same operational intention from a vehicle behavior perspective.

Figure 3.c displays the statistical values of each operational intention combination within the deceleration group. The "sudden decelerate" operational intention combination has a larger deviation in acceleration and a smaller speed, which can avoid unstable driving. This combination is considered to include situations where the driver is cautious of the surroundings. The average relative speed to the vehicle in front in the "decelerate" operational intention combination is greater than the 80% percentile value, likely due to the fact that in some cases, the vehicle in front may accelerate slightly after decelerating, which is not included in the "decelerate/avoid" operational intention combination.

In Figure 3.d, the statistical values of the two operational intention combinations within the lane change group are compared, and it is found that the deviations of both combinations are small. The "changing lanes" operational intention combination includes scenarios where the driver yields to other vehicles in the lane, and has a larger deviation in acceleration, suggesting it includes situations that require multiple adjustments in speed. The 20% and 80% percentile values for this lane change group are far apart in all indicators, indicating a large behavioral deviation. Therefore, in modeling lane change behavior, in addition to using indicators such as the position relationship of the destination vehicle, other information also needs to be considered.

5. SUMMARY

The purpose of this article is to validate the author's underlying hypothesis that vehicle behavior corresponding to various driving intentions will present different characteristics in a series of studies where the author used model performance to represent vehicle behavior. To this end, the author developed a methodology for data acquisition and analyzed the collected data. Through the use of cluster analysis, the driving intentions of the drivers were grouped into eight combinations of driving intentions and further classified into four groups of driving intentions, making statistical analysis possible, and the results supported the underlying hypothesis.

However, some operational intention combinations among the eight groups have almost identical statistical values. This may be because even if the operational intentions were almost the same originally, each interviewee's answers to the interview questions were different, leading to different operational intention combinations being extracted. Additionally, there are many similar driving behaviors in the driving experiments, and there may be more operational intentions on actual roads. Overall, this knowledge is very useful for building vehicle behavior models that consider operational intentions.

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