Analysis of Naturalistic Driving Behavior While Approaching an Intersection and Implications for Route Guidance Presentation

Toshihisa Sato and Motoyuki Akamatsu

Institute for Human Science and Biomedical Engineering,
National Institute of Advanced Industrial Science and Technology (AIST)
Central-6 bidg., 1-1-1 Higashi, Tsukuba, Ibaraki 305-8566, Japan
toshihisa-sato@aist.go.jp,
akamatsu-m@aist.go.jp

Abstract. This study focuses on an analysis of the naturalistic driving behavior before making a right turn at an intersection. We conducted experiments on a public road and measured driver behavior, vehicle state, and headway and rear distances. The results suggest that the positions of the front and rear vehicles and the vehicle velocity have an influence on the onset location of covering the brake pedal. Structural equation modeling (SEM) was applied to estimate these relationships quantitatively. The results imply that the SEM with latent variables can represent the hypotheses obtained from the analysis of the measured data. We propose a detection method of unusual driver behavior by predicting the driver's preparatory behavior using the SEM, and possible new application of in-vehicle navigation systems is discussed.

Keywords: Mobile interactions, Route guidance information, Driver behavior, Naturalistic driving study, Structural equation modeling.

1 Introduction

In-vehicle navigation and communication systems are now popular all over the world. Drivers use route guidance information via the in-vehicle navigation systems while driving from the origin to the destination. The route guidance instruction helps drivers to choose and maintain the routes with lower mental workload. The auditory information on the route guidance is provided for drivers three times while approaching a target intersection. For example, "Please turn to the right at the intersection 700m ahead!", "Please turn to the right at the intersection 300m ahead!", and "Please turn to the right soon". These presentation timing is usually constant in any road traffic conditions or changes in correspondence to the vehicle velocity [1]. However, the presentation timing is too early or too late if driver's usual onset timing of the preparation for making a turn is later or earlier. It is essential to develop a human-centered system design, i.e. to develop a presentation timing adapted to the typical driver's preparatory behavior based on the investigation on natural driving behavior under real road traffic environments.

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In this study, we focused on the presentation timing of the voice instruction just prior to making the turn. This information can trigger a change in driving behavior from straight mode to preparation mode while approaching a target intersection.

1.1 Objectives and Approaches of This Study

The objectives of this study are as follows:

(a) Analyze naturalistic driving behavior before making a right turn at a specific intersection.
(b) Investigate the influence of traffic conditions around the target intersection on the onset location of the driver's preparatory behavior.
(c) Construct a driver model for describing the relationships between the driver behavior and the traffic conditions and for predicting the location where a driver begins preparation for making a right turn.
(d) Propose new application of in-vehicle navigation systems based on the behavior analysis and the driver model construction.

We conducted experiments using an instrumented vehicle on a public road in order to measure the natural driving behavior before making a right turn at an intersection. We focused on leading and following vehicles as the traffic conditions in the vicinity of the target intersection. In this study, the leading vehicle is defined as a forward vehicle that travels straight toward the target intersection. We did not analyze the traffic situations in which the forward vehicle turned to the right, as did the driver's own vehicle. The following vehicle is defined as a vehicle that follows the driver's vehicle in the same traffic lane, regardless of whether or not the following vehicle turns to the right at the turning point.

We used a structural equation modeling technique for investigating the impact of the traffic conditions on the onset location of the driver's preparatory behavior. The structural equation modeling is a modeling methodology depicting relationships among multiple variables hypothesized by theory and empirical research.

2 Experiment

2.1 Participants

Four drivers (three males and one female) participated in the experiments. The average age of the participants was 34.8 years (age range: 22 - 52 years). The average driving experience was 16.3 years (experience range: 3 - 33 years). All participants drove a passenger vehicle almost every day in their daily lives. They are not professional drivers, i.e. truck or taxi drivers.

2.2 Experimental Vehicle

Passenger vehicles with various sensors and a recorder system were developed to detect the vehicle driving state, including driving velocity, acceleration and geographical position, and to measure the driver's behavior, including accelerating, braking, and steering operations [2]. The relative distance and relative velocity to the leading and following vehicles were recorded with laser radar units that were fixed within the front and rear bumpers. The position of the driver's right foot (covering the accelerator or brake pedal without pressing) was measured by laser sensors fitted above the pedal surfaces. The turn signal activation was detected by adding encoders to the lever.

In summary, the following data sets were collected by the instrumented vehicles.

- Vehicle velocity, vehicle acceleration, vehicle angle, vehicle angular velocity
- Geographical position by a GPS sensor
- Relative distance and relative velocity to a leading or following vehicle
- Position of the right foot (covering the accelerator or brake pedal)
- Stroke of the accelerator and brake pedals
- Steering wheel angle, turn signal
- Visual images by CCD cameras (front view, rear view, right and left traffic lines, driver's face, driver's glancing view)

The data was recorded on a laptop computer and mobile hard disks via a driving recorder system. The driving recorder system was fixed inside the trunk of the experimental vehicle to encourage naturalistic driving behavior of the participants.

2.3 Experimental Design

We carried out repeated experiments using the four experimental vehicles on a public road in Tsukuba. The selected driving route was a 30-minute trip (total mileage: about 15 km) that included several left and right turns. The four participants started driving on the identical route per 10 minutes in order to measure each participant's driving behavior under similar traffic situation.

The total trips were 40 trials (over a period of about 8 weeks), and each participant made the recorded drives once a day on weekdays. Practice drives were made before the measurement trials so that the participants could drive from the origin to the destination without using a map. The participants were instructed to drive in their typical manner.

2.4 Target Intersection and Variables

Figure 1 shows an image of the analyzed intersection on the experiment route. The intersection has a designated lane for making a right turn. There is a long straight road about 2 km as far as the target intersection, which has two traffic lanes.

Driver preparatory behavior before making the right turn corresponds to activating the turn signal and deceleration. We focused on the foot movement to cover the brake pedal as the decelerating operations.

The behavioral events were quantified by using the remaining distance to the center of the target intersection (the stop line for turning to the right) at the onset of each preparatory maneuver. We also analyzed the vehicle velocity when the turn signal was activated and the brake pedal was covered by the driver's right foot, as well as the relative distances and speeds toward the leading and following vehicles before the driver entered the designated right-turn lane.

Fig. 1. Overview of target intersection

Within the total of 40 experimental trials for each participant, we did not use the data from the traffic conditions in which a lead vehicle also turned to the right at the target intersection or a vehicle had stopped at the stop line, and the data when there was a red light at the intersection. Valid data sets under appropriate conditions were about 30 trips for each participant.

3 Experimental Results

There were variations in the onset locations of covering the brake pedal and activating the turn signal over all of the experimental trials. Especially, large variations were found in the remaining distance to the center of the intersection when covering the brake pedal. It is considered that the onset location has an increasing or decreasing tendency when drivers are familiar with the experimental route. The results obtained from the long-term observation suggest that the adaptation to a driving route does not influence the onset location of the driver's preparatory behavior.

3.1 Relationship Between Vehicle Velocity and Driver's Preparatory Behavior

Figure 2 presents the results of the remaining distance to the center of the target intersection at the onset of each preparatory maneuver, based on the vehicle velocity when covering the brake pedal. The onset locations of covering the brake pedal are positively correlated with the driving speeds. When the driving velocity while approaching the target intersection is higher, the remaining distance when covering the brake pedal is longer. The slower driving speed leads to the closer onset location to the target intersection.

The onset locations of the turn signal activation while approaching the intersection at slower driving speeds tended to be closer to the center of the intersection than those at faster speeds. However, the decreasing tendencies were not remarkable compared to the results for covering the brake pedal. The drivers tended to activate the turn signal at a remaining distance of between 80m and 100m to the center of the target intersection, independent of the vehicle velocity.

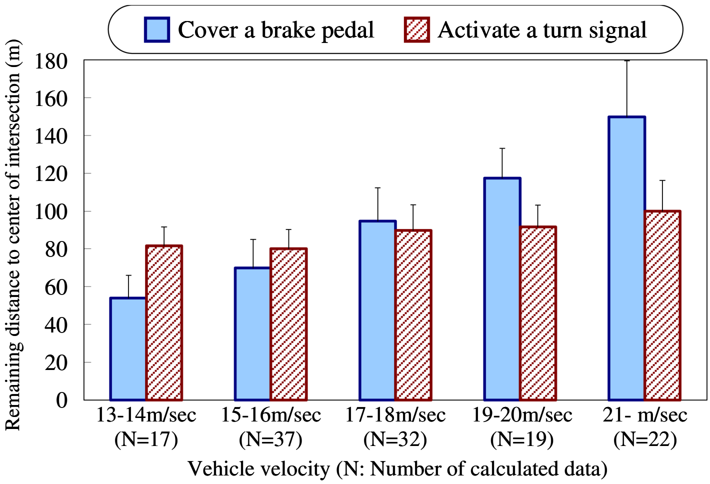

Fig. 2. Results of the onset location of each behavioral event based on the vehicle velocity when covering the brake pedal. The remaining distance has been calculated within all participants based on a classification of the driving speed. We adopted the driving speeds when the driver moved their right foot to cover the brake pedal before making a right turn, because the vehicle velocity at the onset of covering the brake pedal was almost equal to that at the onset of activating the turn signal.

3.2 Relationship Between Relative Distance to the Lead Vehicle and Driver's Preparatory Behavior

Figure 3 presents the results of the onset location of each behavioral event based on the relative distance to the leading vehicle, including the absence of a leading vehicle. The remaining distances to the center of the target intersection when covering the brake pedal were shorter compared to no leading vehicles. The shorter headway distance caused a closer onset location to the center of the intersection, indicating a linear relation between the decelerating point and relative distance to a lead vehicle.

The remaining distances when the turn signal was activated while approaching the target intersection with a leading vehicle were almost equal to those without the lead vehicle. The onset location of the turn signal operation was independent of the existence of and relative distance to a leading vehicle.

These tendencies are similar to the relationship between the vehicle velocity and the driver's preparatory behavior before making the right turn.

There were almost no differences in the relative speed between the driver's vehicle and the lead vehicle. The results imply that the drivers approach the turning point in a car-following condition.

3.3 Relationship Between Relative Distance to the Following Vehicle and Driver's Preparatory Behavior

Figure 4 presents the results of the remaining distance to the center of the intersection when each behavioral event occurs based on the relative distance to the following

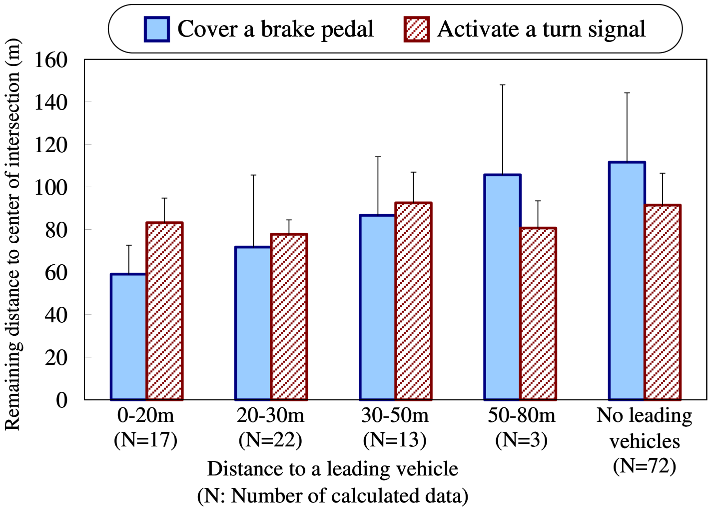

Fig. 3. Results of relationship between the onset location of each behavioral event and the relative distance to a leading vehicle. We have calculated the average remaining distance when each behavioral event occurred among the participants by classifying the relative distance to the leading vehicle and in the absence of a lead vehicle. The headway distance was categorized into four groups.

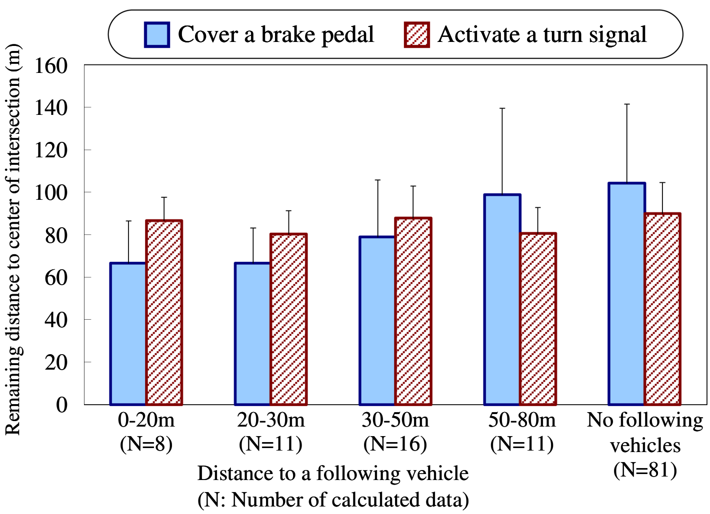

Fig. 4. Results of relationship between the onset location of each behavioral event and the relative distance to a following vehicle. We have calculated the average remaining distance when each behavioral event occurred among the participants, similar to the analyses based on the relative distance to a leading vehicle. The rear distance was categorized into the same four groups as the classification of the headway distance.

vehicle, including the absence of a following vehicle. The onset locations of covering the brake pedal while driving with a following vehicle were closer to the intersection compared to driving without a following vehicle. The closer the relative distance from the following vehicle, the shorter the remaining distance at the onset of covering the brake pedal. The results based on the relative distance to a following vehicle indicated similar tendencies to the relationship between the headway distance and the driver's decelerating operatoin.

The onset locations of activating the turn signal were almost stable in the five categories of the relation between the host and following vehicles. The experimental results in terms of the headway and rear distances suggest that the onset location of turn signal operation is almost constant and independent of the relative position between the host vehicle and a forward or following vehicle.

There were almost no differences in the relative velocity between the driver's vehicle and the following vehicle, which is similar to the relationship between the host and lead vehicles.

4 Modeling of Driver Preparatory Behavior Using Structural Equation Model

The observation results of the driver's preparatory behavior before making the right turn suggest that the vehicle velocity and the headway and rear distances influence the onset location of the foot movement to cover the brake pedal, and they have less influence on the onset location of the turn signal activation. We constructed a structural equation model using the measured data sets (vehicle velocity, relative distances to leading and following vehicles, and onset locations of covering the brake pedal and activating the turn signal) in order to estimate the observed relationships quantitatively.

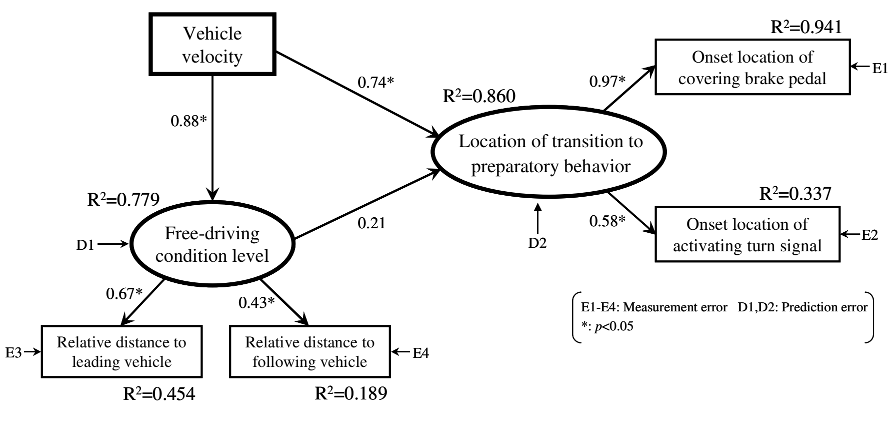

Fig. 5. Path diagram of the structural equation model and results of the estimation of path coefficients and factor loadings (standardized weights). The maximum likelihood method was used for the model estimation.

Figure 5 shows the structured model of driver preparatory behavior with estimated path coefficients and factor loadings. Two latent variables, the free-driving condition level and the location of transition to preparatory behavior, are input to the model specification. The free-driving condition level is defined using two indicator variables: the relative distance to the leading vehicle and the relative distance to the following vehicle, suggesting that shorter headway or rear distances mean close car-following conditions. The latter latent variable has two indicator variable: the onset location of covering the brake pedal and the onset location of activating the turn signal.

Table 1 presents the results of model fit indices. All model fit indices suggest an acceptable level of fit, supporting that the specified model depicts well the relationship among the driving speed, the free-driving condition level, and the location of transition to preparatory behavior.

Table 1. Goodness-of-fit indices for the proposed structured equation model. Non-significant chi-square value indicates little difference between the sample variance-covariance matrix and the reproduced variance-covariance matrix. GFI, AGFI and CFI more than 0.95 and RMSEA less than 0.05 reflect a good model fit [3].

χ^2 (df)	0.62 (3)
p value	0.892
GFI (Goodness-of-Fit Index)	0.998
AGFI (Adjusted Goodness-of-Fit Index)	0.990
CFI (Comparative Fit Index)	1.000
RMSEA (Root-mean-square error of approximation)	0.000

5 Implications for Route Guidance Presentation

5.1 Presentation Criteria of Route Guidance Information

The measurement of driver's preparatory behavior before making a right turn reveals that the remaining distances at the onset of the decelerating operation while driving without leading or following vehicles tend to be longer compared to the turn signal operation. On the other hand, the onset locations of the driver's decelerating behavior tend to be closer to the center of the target intersection compared to the turn signal activation when they drive with leading and following vehicles at close range, because the decelerating behavior is influenced by the relative position between the driver's vehicle and the forward or following vehicles.

It is effective to change the behavioral index based on the relative position to lead and following vehicles for the development of criteria of the presentation timing of route guidance information which helps drivers to begin preparation for making a right turn at a usual location. The information presentation criteria would be determined by measurement and accumulation of the driver's decelerating operation when driving without a leading or following vehicle and when approaching a target intersection under far car-following conditions. And the route guidance instruction would be provided for drivers at timing based on measurement and accumulation of the turn signal operation when driving with leading and/or following vehicles at close range. The voice instruction would be presented a few seconds earlier than the estimated criteria in order to accommodate the driver's response time to the provided information (see Fig. 6).

5.2 Detection of Unusual Driver Behavior Based on Prediction of Onset Location of Driver Preparatory Behavior

The specified structural equation model can predict the onset locations of right foot movement and turn signal activation based on the vehicle velocity and the headway and rear distances, as well as present the relationship among the driving speed, the traffic condition and the location of transition to preparation for making a right turn. The factor score for the free-driving condition level can be calculated by using the factor loadings for the relative distance to the lead vehicle and the relative distance to the following vehicle. The calculated factor score and the recorded vehicle velocity can predict the factor score for the location of transition to preparatory behavior, and the onset location of each preparatory maneuver can be inferred from the predicted factor score and each factor loading. Thus, the onset locations of covering the brake pedal and activating the turn signal can be predicted by using the measured variables and the estimated path coefficients and factor loadings of the structural equation model.

We compared the predicted onset locations and the observed values using the data sets which were not input to the model estimation. The prediction accuracy was the highest compared to predictions in which the vehicle velocity and the headway or rear distances are not taken into account or predictions using a single regression model with one independent variable, namely driving speed. The findings indicate that the specified structural equation model contributes to highly accurate prediction of when drivers move their right foot from the accelerator pedal to the brake pedal and activate the turn signal based on the driving speed and the traffic conditions while approaching the target intersection.

The prediction of the onset location of driver's preparatory maneuver can be applied to advanced functions of in-vehicle navigation systems. When the route guidance instruction is presented, the system linked with the sensors collecting driving speed and relative distances to the leading and following vehicles can predict the onset location of the driver's preparatory behavior using the specified structural equation model. If a driver does not begin to prepare to make a right turn after reaching the predicted onset location, the system can assess the driver's navigational error, i.e. the driver did not accurately identify the turning point, or did not notice the information provision, and then restate the route guidance or issue a warning. The detection method of the unusual behavior while approaching an intersection can be applied to measure a driver's fatigue and wakefulness level while driving and to reduce driver errors caused by temporary deterioration of the driver's internal states. Figure 6 shows the concept of the presentation criteria of route guidance information and the detection method of the driver's unusual behavior.

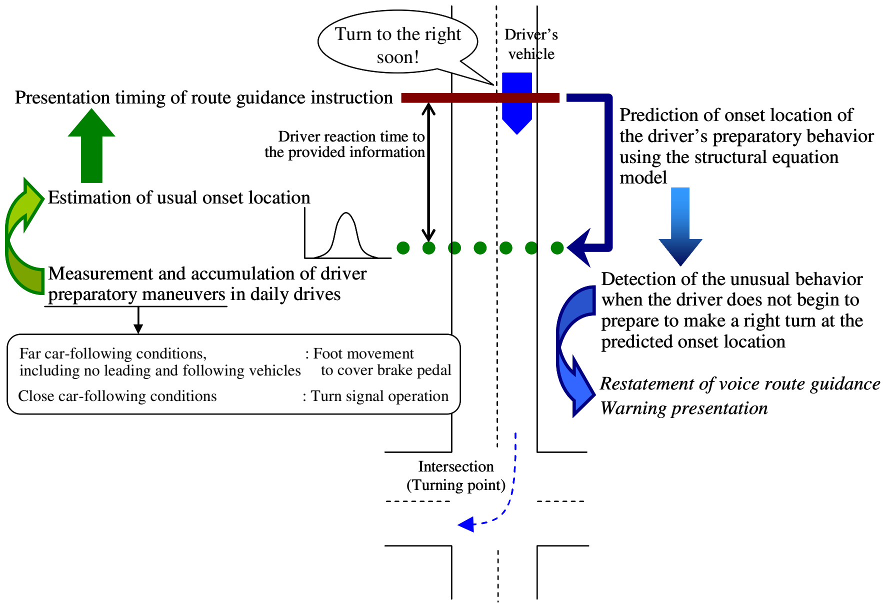

Fig. 6. Concept of the presentation criteria of route guidance instruction adapted to driver's usual preparatory behavior and the restatement method of the guidance based on the behavior prediction

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