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Multi-parameter prediction of drivers' lane-changing behaviour with neural network model

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ABSTRACT

Accurate prediction of driving behaviour is essential for an active safety system to ensure driver safety. A model for predicting lane-changing behaviour is developed from the results of naturalistic on-road experiment for use in a lane-changing assistance system. Lane changing intent time window is determined via visual characteristics extraction of rearview mirrors. A prediction index system for left lane changes was constructed by considering drivers' visual search behaviours, vehicle operation behaviours, vehicle motion states, and driving conditions. A back-propagation neural network model was developed to predict lane-changing behaviour. The lane-change-intent time window is approximately 5 s long, depending on the subjects. The proposed model can accurately predict drivers' lane changing behaviour for at least 1.5 s in advance. The accuracy and time series characteristics of the model are superior to the use of turn signals in predicting lane-changing behaviour.

1. Introduction

Lane-changing behaviour has a significant effect on driving safety and the stability of traffic flow (Sivak et al., 2007). During the lane-changing process, the information processed by the drivers is more complicated than that processed while remaining in a lane. If drivers fail to accurately judge the appropriate lane-change time or the relative movement characteristics of related vehicles, accidents may occur and result in casualties and property damage (Petzoldt et al., 2014; Jin, 2013).

Various of lane-change auxiliary systems have been developed in an attempt to ensure driver safety during the lane-changing process. Such systems operate by monitoring the related conflict vehicles with millimetre-wave radar or high-accuracy cameras. Once turn signals are recognized, the auxiliary system may assume that a lane change will be executed at some time in the near future, and the system enters its working mode. When a conflict object is detected by the auxiliary system within a given distance, warning signals are sent to remind the drivers of the potential danger (Hirose et al., 2004). However, in practice, prediction of lane-changing behaviour on the basis of turn signals is unreliable. According to the experiment conducted under realistic on-road conditions, the operation rate of drivers' turn signals is below 50% by the initiation of the lane changing behaviour, which certainly affects the warning accuracy rate and reliability of a lane-changing auxiliary system that is triggered by turn signals (Salvucci and Liu, 2002).

In recent years, researchers have pursued ways to improve the performance of lane-changing auxiliary systems by identifying drivers' operation intentions. Specifically, researchers have tried to identify lane-changing intent via drivers' visual search behaviours and vehicles' motion characteristics. Based on gaze data of interest zones, Lethaus et al. (2013) predicted drivers' driving intent via compound model, and in their previous research, they have proved that drivers may pay more attention to side mirrors than to inside mirrors when executing leftward lane changes (Lethaus and Rataj, 2007). Salvucci et al. (2007) suggested that before a lane change occurred, a driver always shifted attention from the current lane to the target lane. Doshi and Morris (2011, 2009) proposed that in addition to eye movements, head movements could be used to detect drivers' lane-changing intentions, and developed a real-time on-road prediction system to detect driver's intention. Peng et al. (2013a,b) constructed an intent index system by analysing the differences between lane keeping and lane changing intent stages, and developed a method to detect drivers' lane-changing intentions using evidence theory.

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If drivers' lane-changing intentions could be precisely identified from their driving behaviour, rather than relying on turn signals, the performance of lane-changing assistance systems could be greatly improved. However, challenges arise in the practical application of lane-changing intent identification technologies. Although an assistance system may detect a driver's intent to change lanes, this does not mean that a lane change will definitely occur at some time in the future. Even if a driver intends to execute a lane change, he may change his mind for various reasons, such as a vehicle rapidly approaching from behind in the target lane. We call this the "intent revocation phenomenon", and it cannot be easily predicted using the existing intent identification technologies (Lee et al., 2014; Hofmann et al., 2010).

Lane-changing intent can typically be detected from a driver's eye and head movements before the execution of a lane change (Lethaus and Rataj, 2007). Based on intent identification, if we could consider vehicle motion states and the relative motion between the object vehicle and other (conflict) vehicles in a comprehensive manner, we may be able to predict lane-changing behaviour accurately before the manoeuvre.

This study was conducted to develop a reasonable method for predicting lane-changing behaviour. The remainder of the paper is organized as follows. First, the testing platform and experimental design are presented. Second, the procedure used to select lane changing intent and lane keeping data samples is described, along with the procedure used to determine the lane changing intent time window. Third, lane-changing behaviour predictors are identified based on eye and head movement characteristics, in combination with information on the relative motion of conflict vehicles. Finally, the use of a neural network to develop a model for real-time prediction of lane-changing behaviour is described.

2. Experiment

2.1. Subjects

A total of 16 experienced drivers, nine men and seven women, were recruited to take part in our experiment. The subjects were between the ages of 28 and 50, with an average age of 41.1 years and a standard deviation of 5.85 years. Each of the subjects had got a driver's licence for at least four years and had driven a total distance of at least 80,000 km. The drivers participated in physical fitness examinations that showed that all of the subjects were free from any visual, physical, or psychological impairment and could meet the demands of the experiment. After the experiment, the subjects were reimbursed for a certain amount of their lost income.

2.2. Procedure

Due to the convenience and simplicity of simulation experiment, research on drivers' behaviour characteristics is typically conducted using driving simulators (Lee et al., 2014; Salvucci et al., 2007). However, simulations do not reflect the effect of the surrounding environment as well as naturalistic on-road driving tests. As a result, experimental results obtained from simulation often fail to represent drivers' real behavioural characteristics (Dziuda et al., 2014; Jagannath and Balasubramanian, 2014). To address this problem, we built an integrated data collection platform to acquire information on drivers' behavioural characteristics, vehicle motion status, etc. The experiment was conducted as a naturalistic driving test: each driver was told to drive completely according to his or her own driving expectations, habits, and real-time judgement of the conditions of the surrounding environment.

Before the experiment was run, the drivers first provided personal information by filling out a form developed by the research team. The team calibrated the instruments based on the coordination of the subjects. The subjects each had 15 min to familiarize themselves with the testing vehicle and were told about the testing route. Then, after a 10-min break, the naturalistic on-road experiment began.

2.3. Test platform

To achieve our research objective of developing a model for prediction of lane-changing behaviour, we needed to collect data on the vehicle motion states, driving environment, and the drivers' behaviours. The integrated data collection platform developed for this purpose included the following sensors and instruments: a faceLAB 5 eye tracking system (for tracking eye and head movements), a VBOX (for recording vehicle velocities, lateral accelerations, longitudinal accelerations, yaw rates, etc), millimetre-wave radars (for measuring the relative motion between the object vehicle and conflict vehicles), a lane identification system (for recording the lateral position of the vehicle in the lane), a torque sensor (for measuring the steering wheel angle and steering angular velocity), and a data acquisition meter. The system components are shown in Fig. 1.

2.4. Test route

The objective of this study is to develop a prediction model for lane-changing behaviour for use in a lane-changing assistance system. In general, such a system is activated when the speed of the vehicle reaches approximately 50 km/h (Wang et al., 2014). To enhance the practical applicability of the research results, we chose to locate our test route on the G25 expressway (from Huzhou to Changxing, Zhejiang, China), which was a two-way four-lane road with a speed limit of 110 km/h. The length of the portion of the expressway used as the test route was approximately 25 km.

3. Lane-changing intent time window

3.1. Initiation of a lane change

The selection of the lane change sample is a key step in the development of the behaviour prediction model. The complete lane-changing process can be divided into several stages, as shown in Fig. 2. The most urgent problem to be solved is determination of the initiation of a lane change. To avoid the subjectivity of the existing methods (Huo, 2010), we develop a new method for determining the initiation of a lane change as a function of the lateral position of the vehicle in the lane and the steering wheel angle.

The sampling frequency of the data collection system is 10 Hz. The distances from the left front wheel and right front wheel to the left lane and the right lane, respectively, are denoted by L_1 and L_2, as shown in Fig. 3. Table 1 shows a portion of the data for a lane change, illustrating the changes in the lateral position of the vehicle and the steering wheel angle over time. According to Table 1, the lateral position of the vehicle change slightly between the adjacent sampling times in the lane keeping stages. However, when the effects of the vehicle's lateral position and steering wheel angle are considered, the rate of change obviously increase during the sampling time highlighted in grey, so this is considered to be the moment of initiation of the lane change (as shown in Fig. 4).

3.2. Determination of lane changing intent time window

As other researchers have shown, in comparison to lane keeping behaviours, drivers tend to exhibit distinct eye and head movement characteristics before changing lanes (Hsu and Liu, 2008; Olsen