Transportation Research Part C 67 (2016) 47–61

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

A binary decision model for discretionary lane changing move based on fuzzy inference system

Esmaeil Balal [a], Ruey Long Cheu [a,*], Thompson Sarkodie-Gyan [b]

[a] Department of Civil Engineering, The University of Texas at El Paso, 500 W. University Ave, El Paso, TX 79968, USA
[b] Department of Electrical & Computer Engineering, The University of Texas at El Paso, 500 W. University Ave, El Paso, TX 79968, USA

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 12 February 2016
Accepted 16 February 2016

Keywords:
Lane change
Fuzzy logic
Fuzzy inference system
Gap
Distance
Time-to-collision

ABSTRACT

This paper presents a Fuzzy Inference System (FIS) which models a driver's binary decision to or not to execute a discretionary lane changing move on freeways. It answers the following question "Is it time to begin to move into the target lane?" after the driver has decided to change lane and have selected the target lane. The system uses four input variables: the gap between the subject vehicle and the preceding vehicle in the original lane, the gap between the subject vehicle and the preceding vehicle in the target lane, the gap between the subject vehicle and the following vehicle in the target lane, and the distance between the preceding and following vehicles in the target lanes. The input variables were selected based on the outcomes of a drivers survey, and can be measured by sensors instrumented in the subject vehicle. The FIS was trained with Next Generation SIMulation (NGSIM) vehicle trajectory data collected at the I-80 Freeway in Emeryville, California, and then tested with data collected at the U.S. Highway 101 in Los Angeles, California. The results of the test have shown that the system made lane change recommendations of "yes, change lane" with 82.2% accuracy, and "no, do not change lane" with 99.5% accuracy. These accuracies are better than the same performance measures given by the TRANSMODELER's gap acceptance model for discretionary lane change on freeways, which is also calibrated with NGSIM data. The developed FIS has a potential to be implemented in lane change advisory systems, in autonomous vehicles, as well as microscopic traffic simulation tools.

1. Introduction

Lane changing model is as important as car-following model that govern the second-to-second motion of vehicles in microscopic traffic simulation tools (FHWA, 1995; PTV, 2007; Quadstone, 2009; TSS, 2002; Caliper, 2011). The microscopic driving behavior is also related to macroscopic property of traffic flow (Laval and Daganzo, 2006; Zhao et al., 2013; Zheng et al., 2013). Therefore, it can be said that both lane changing and car-following models are the fundamental building blocks of traffic flow theory. In the advent of semi-autonomous and autonomous vehicles, the understanding and accurate modeling car-following and lane changing behavior, including the replication of driver's decisions, is critical to the safe operations of these vehicles and the surrounding traffic. Although car-following has been studied by researchers for more than 50 years, relatively fewer examinations on lane changing behavior have been made. This could be due to the facts that (i) a lane change involves two-dimensional motions; and (ii) there are relatively more (up to five) vehicles involved in a lane changing

* Corresponding author.
E-mail addresses: ebalalvarnosfaderani@miners.utep.edu (E. Balal), rcheu@utep.edu (R.L. Cheu), tsarkodi@utep.edu (T. Sarkodie-Gyan).

http://dx.doi.org/10.1016/j.trc.2016.02.009

event. In contrast, car-following typically involves two vehicles, one following another in the same lane. Therefore, the study of lane change is more complex and challenging than car-following.

In general, there are two types of lane change in freeways: mandatory and discretionary. Mandatory lane change is also known as forced or necessary lane change. It usually occurs, in the United States driving convention, when a vehicle is trying to move from the left or center lane to the rightmost lane in order to exit the freeway. Mandatory lane change may also happen when a vehicle has just entered the freeway from an on-ramp and is trying to move to the center or left lane to avoid a downstream exit lane. Mandatory lane change is a microscopic manifestation of the macroscopic route choice behavior. Discretionary lane change is also known as free lane change or desired lane change. It primarily occurs when a driver seeks to increase its speed or seeks a better driving environment (such as greater space ahead or behind his/her vehicle) by moving to an adjacent lane (Caliper, 2011; Zheng, 2014). Obviously, the motivations and resulting driving behavior for the two types of lane change are different. Therefore, a driver is expected have different decision rules and/or risking taking behavior for the two types of lane change. Since driving is a complex task, it is sometimes not possible to classify a lane change as mandatory or discretionary. For example, a driver may move from the left lane to the right lane on a freeway well upstream of an exit. This is a mandatory move in order for him/her to exit the freeway. However, since the exit is far ahead, he/she has time to make a discretionary move. This may be the reason that some models combine the two types of lane change. This paper makes a distinction between mandatory and discretionary lane changes, i.e., for a vehicle that is changing lane, the event is either mandatory or discretionary, not both.

A lane change might be modeled as a sequential four-step process: (1) motivation; (2) selection of target lane; (3) checking for opportunity to move; and (4) the actual move. The beginning and end of the four steps are marked by time instants t_1, t_2, t_3, t_4 and t_5, respectively, where $t_1 < t_2 < t_3 < t_4 < t_5$. At t_1, the driver begins to feel uncomfortable driving in the original lane. Between t_1 and t_2, external stimulus motivates him/her to want to change lane. At t_2, he/she has made up his mind to change lane, and begins to look for a target lane (the immediate left or immediate right lane). At t_3, the target lane is selected. From t_3 onwards, the driver actively seeks an opportunity in the target lane to make a lateral move. He/she begins the lateral move at t_4. The lateral move is completed at t_5. Keyvan-Ekbatani et al. (2015) further classifies the lane changing move (i.e., between t_4 and t_5 into four sub-steps) but this is not the focus of this research. This article focuses on the decisions at t_3.

The traditional lane changing decision models rely on deterministic mathematical equations and/or rules to replicate drivers' decisions. These models do not consider the uncertainties of drivers' perception and decisions (McDonald et al., 1997; Das and Bowles, 1999). Fuzzy logic incorporates a degree of uncertainty in the decision making process and therefore, reflects the drivers' natural or subjective perceptions of the inputs which influence their decisions. Therefore, the fuzzy logic approach is used in this research to model the lane changing decisions from t_3 to t_4.

The objective of this paper is to develop an improved binary decision tool for a discretionary lane changing move using the fuzzy logic approach. More specifically, a Fuzzy Inference System (FIS) is constructed to replicate a driver's binary decisions in the third step of the four-step lane changing process; that is, from t_3 to t_4. The FIS answers the question "Is it time to begin to move into the target lane?" It is expected that the FIS will produce a series of "no, do not change lane" recommendations from t_3 and the last and one recommendation of "yes, change lane" at t_4. Once developed, the FIS may be programmed into lane change advisory systems in actual human-driven vehicles. It also has the potential to be programmed into autonomous vehicles, and microscopic traffic simulation models. The FIS has the potential to improve freeway safety by reducing the number of crashes due to incorrect lane changing decisions.

This paper is organized as follows. After this introduction, important terms that are used in the subsequent presentation of the lane changing problem are first defined. The envisioned application of the FIS in a lane change advisory system are described, so that readers can have a proper context our developmental work for the rest of this paper. Literature reviews on conventional lane changing models, fuzzy logic and FIS, and fuzzy logic based lane changing models are made. The next section reports a survey conducted to understand drivers' lane changing behavior. This is followed by a description of the Next Generation SIMulation (NGSIM) vehicle trajectory data used in this research, and the development of the FIS. The accuracy of the developed FIS when applied to the calibration and test data sets are then reported. The performance accuracy of the FIS is also compared against an existing gap acceptance model. This article ends by highlighting the contributions of this research, limitations and future research directions.

2. Definition of terms

A lane change involves the interaction of several vehicles. This section defines the vehicles involved, potential variables that may influence the driver's decision to or not to change lane (i.e., begin a lateral move) and their mathematical symbols, so that consistent terms and symbols can be used throughout this paper.

A typical lane changing scenario is depicted in Fig. 1, which involves up to five vehicles. The subject vehicle *S* is trying to move from its original lane to the target lane. Vehicles *PA*, *FA*, *PB* and *FB* are the preceding vehicle after lane change, following vehicle after lane change, preceding vehicle before lane change and following vehicle before lane change, respectively.

The variables that describe the interactions between these vehicles may be divided into three groups: (i) distance or gap (in distance unit); (ii) headway or time-to-collision (in time unit); and (iii) speed. Ten potential variables have been identified in a focus group meeting and they are listed in Table 1. The gap, distance and time-to-collision are calculated from the