Driver Modeling for Simulation of Transportation Systems

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***Abstract*—This paper first reviewed the driver or driving models used in traffic simulation that were created mainly for generating the required mobility. Some commonly used models and the state-of-the-art technologies were discussed. In order to better study the effect of human driver on the transportation system, this paper introduced several other typical driver models and the related technologies that were developed for the purposes of studies on vehicle dynamics and controls during last decades. These models not only perform the tasks in generating the required mobility with better fidelity and flexibility for traffic simulation, but also provide more insight on the physics of drivers' driving nature and characteristics. Further research was suggested in the modeling of drivers' personal driving characteristics, in particular, drivers' habitual driving styles. These can be very valuable and important in the design and study of the modern transportation systems with vehicle-driver-environment taken into consideration.**

Keywords-human driver; driver modeling; transportation simulation

I. INTRODUCTION

Improving the efficiency and safety of the transportation systems is essential to the functioning and prosperity of modern societies. However, the limited road capacity and thus traffic congestion has become a severe problem in many countries [1]. Engineers are therefore seeking solutions to the questions of how the capacity of the road network could be used more efficiently and how operations can be improved by ways of intelligent transportation systems [2]. As the problems become increasingly complex, the development, test, evaluation and verification on these technologies largely via field test under real-world environment have become more and more impractical, if not impossible, mainly due to the cost and time spent, and many logistic barriers.

Driving simulation is an invaluable tool for studying a wide range of driving-related subjects, including driving safety, road and traffic infrastructure improvement, and many new transportation related technologies. Providing a realistic simulation of individual traffic elements, often referred to as microscopic traffic simulation, is a necessary component of high fidelity driving simulation. A microscopic traffic simulation model, rather than a statistical model, is necessary to ensure that the behavior of individual entities is generated in sufficient detail that the cueing subsystems can display the motion of each traffic element in real-time [3].

As one of the key elements in transportation system, human drivers play an important role in the safety and the efficiency of the transportation systems via interactions with other drivers, and by responding to the surrounding traffic and roadway design and to the human-vehicle interfaces, and by obeying traffic rules, etc. Therefore, driver models that describe human driving behavior and represent drivers' driving nature are critical in the driving simulation in order to simulate realistically the microscopic traffic conditions with physical characteristics such as time gaps, distances and velocities among vehicles in the traffic.

Existing driver models in the typical traffic simulation, however, are mainly, if not solely, for the purpose of mobility generation, and are mostly established on the basis of many external factors such as vehicle density, lane number, and vehicle dispatch model. They do not in general take much into consideration of neither "driving" characteristics nor vehicle dynamics. As a result, these types of driver models can hardly reflect the "driving" nature and represent the human driving behavior. In the mobility generation, these types of driver models typically do not model the "controls" with steering, braking or throttling for vehicles to track the desired trajectory including both path and speed. This may lead to artificial yet unrealistic simulation results of the traffic mobility.

Many other driver models were developed during last several decades for the purposes of studying vehicle dynamics, and human factors and impact on vehicle controls, driver assistance and active safety systems, etc. Although these models mainly capture driver's control characteristics, the capability in generating high-fidelity and flexible mobility required by traffic simulation can be very useful, in particular, in the microscopic traffic simulation.

Further research on the modeling of drivers' personal driving behavior and characteristics, such as habitual driving styles, and of broader driving spectrum, such as drivers' perception to the surrounding driving environment, mental and psychological judgment and decision making processes, neuromuscular actions and reactions further can be very valuable and important in the

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design and study of the modern transportation systems with vehicle-driver-environment taken into consideration.

The paper is organized as follows: in Section II, we present the state-of-the-art of the driver or driving modeling in traffic simulation; In Section III, we introduce other driver modeling methods and models. The paper concludes with some remarks in Section IV.

II. The state-of-the-art of the driver modeling in traffic Simulation

Driver models in the traffic simulation include car following models, which describe the resultant vehicle longitudinal driving characteristics, such as time gaps, distances and velocities when they are following a leading vehicle to maintain certain safe headway distance to the leader; lane changing models, which describe the resultant vehicle lateral driving characteristics in lane selection and gap acceptance; and driver distraction models, which describe diver's attention from the road to other tasks.

A. Car following model

The concept of car following was first proposed by Pipes [4] to evaluate traffic capacity and congestion. Pipes proposed a linear follow-the-leader model in which the driver follows the lead vehicle speed by controlling the acceleration with a linear proportional gain.

Gazis [5] developed a car-following model by replacing the proportional gain in the linear follow-the-leader model with a nonlinear gain. This model is known as nonlinear general motor (GM) model and has been calibrated on different data sets by many researchers [6].

Newell [7] suggested another nonlinear model where the desired speed is an exponential function of range error and is achieved in an exponential fashion.

Before the model developed by Helly [8], almost all car-following models describe driver behavior as regulating either zero range error or zero range-rate, though real drivers are likely to do both. The acceleration in Helly's model is a function of both range error and range-rate.

Gipps [9] proposed a model using a safe distance strategy rather than precisely following the leader. The model calculated a safe-distance as the desired distance by estimating the kinematic relationship between the lead vehicle and the following vehicle in congested traffic. A second mode was added in the Gipps' model to describe free flow condition.

Michael [10] modeled driver behavior as a sequential control in which the driver responds to the lead vehicle's size change when it exceeds some threshold. Some basic concepts and criteria were provided in Michael's work but no specific mathematic model was presented.

Lee's model [11] used time-to-collision as a threshold for braking and used τ (angular separation over separation rate) to estimate time-to-collision, with the brake force based on the time rate of change of τ.

Recently, Yang [12-13] and colleagues developed an errorable car-following driver model. An errorable driver model is one that emulates human driver's functions and can generate both nominal (error-free) as well as devious (with error) behaviors. This model is based on a model for longitudinal control that normally achieves car-following tasks. The stochastic car-following behavior was first analyzed and modeled as a random process. Three error-inducing behaviors were then introduced. Comparing with conventional car-following driver models that aim to approximate normal human driving, the errorable driver model is capable of producing accident and incident behavior that is statistically similar to field testing results.

B. Lane changing model

Traditionally, lane changing models often incorporate two steps: the lane selection process and the lane change execution process [14].

The most popular lane changing decision model intended for microscopic traffic simulation tools was presented by Gipps [15]. The model treated lane selection as a rule-based process and repetitively evaluated the set of lanes in the driver's choice set based on different considerations or rules prioritized through a deterministic sequence. The rules/considerations governing lane changes could be broadly classified as belonging to either a Mandatory (MLC) or Discretionary (DLC) category. MLC are performed when the driver must leave the current lane. DLC are performed when the driver perceives that driving conditions in the target lane are better, but a lane-change is not required.

Similar models were later developed by Hidas [16] et al. and Halati [17] et al. and implemented in the microscopic simulators SITRAS and CORSIM respectively.

Yang and Koutsopoulos [18] developed a rule-based lane changing model that is applicable only for freeways. The model used a probabilistic framework to model drivers' lane change behavior when they face conflicting goals. It thereby helped capture trade-offs between various factors influencing lane choice at any given instant. Their model is implemented in MITSIMLab, a microscopic traffic simulator developed at the Intelligent Transportation Systems Laboratory at MIT.

After selecting a lane other than his current lane to drive on, the driver should evaluate whether the gap between the lead and lag vehicles in the direction towards the selected lane is acceptable.

Kita [19] used a logic model to estimate a gap acceptance model for the case of vehicles merging from a freeway ramp.

Ahmed [20] assumed that the driver considers the lead gap and the lag gap separately and in order to execute the lane-change, both gaps must be acceptable.

C. Driver distraction model

Many driving models simulate a driver's interaction with a particular in-vehicle system and attempt to predict the resulting effects on driving performance and the in-vehicle task.

Levison [21] developed the integrated driver model to simulate driving performance while dialing and talking on a cell phone.

Salvucci [22] and colleagues presented a driver performance model that integrates ACT-R with a task analysis of vehicle control.

Liu [23] and colleagues simulated driving while completing an in-vehicle map reading task.

Model developed by Yang and colleagues [12-13] focus on simulating aggregate or average outcomes and is useful for activities such as evaluating and designing active safety technology.

D. Summary

The existing driver models used in the areas of microscopic traffic simulation were mainly to create traffic mobility. They were mostly established on the basis of many external factors such as vehicle density, lane number, and vehicle dispatch model without much consideration of neither "driving" characteristics nor vehicle dynamics. In this sense, these are not "driver" models, but more precisely, driving models to simply generating vehicle motions for traffic mobility. For simplicity or to serve the limited purposes, they generally ignored the important ingredients of vehicle dynamics and drivers' driving characteristics, which, however, are considered to be one of the most important factors in representing realistic and high-fidelity vehicle motions, not only for mobility simulation, but also for the large picture of vehicle-driver-environment system as a whole.

III. OTHER DRIVER MODELING METHODS AND APPROACHES

Although the existing driver models in traffic simulation are in general able to generate the vehicle motion for the purpose of the mobility simulation, there were many other driver models developed during last several decades that better represent the mobility in the traffic with vehicle dynamics and human driving characteristics taken into consideration. Although these models mainly capture driver's control characteristics, their high fidelity and flexibility can greatly enhance the mobility model in traffic simulation, in particular, in the microscopic traffic simulation.

A. Driver models for vehicle dynamics and stability control

Numerical simulation is an important tool for the development of nowadays vehicle and vehicle dynamics controllers. Besides a comprehensive vehicle model and a detailed representation of the road conditions, a technical driver model that allows implementing driving maneuvers during normal operation and at the driving limits is necessary to get realistic simulation results. Because of the driving maneuvers can be intuitively considered as a control task so that control theory based driver models have been successful, since the first driver models which extended from prior knowledge of pilot's manual control of aircraft have been introduced by Weir and McRuer [24]. This type of driver models primarily focused on driver steering control operation and extended to direction-speed hybrid control [25-26]. All these models can be classified into two basic categories: compensatory control model which do not use future path information, and preview control model which take the road ahead the driver into account.

1) Compensatory control model

The compensatory control model focuses on compensatory tracking tasks, in particular minimizing visually perceived errors by exercising continuous control. The well-known crossover model [27-29] developed in the operator/pilot study provides a very effective way to describe human regulation control tasks. The principle of the crossover model is that humans adapt their control to provide compensation that dependent on the vehicle dynamics to ensure closed loop stability, as shown in Figure 1. The crossover model points out that the loop transfer function gain of a stable closed loop system will drop off at a -20dB/decade in the crossover region. Although the crossover model does not provide a driver model that can be implemented directly, it provides a design principle and guideline for the driver model development and is the basis of some more complex models, such as precision mode in [30].

2) Preview control model

Early driver models based on compensation feedback only are difficult to ensure enough phase margin while still keep low frequency performance at different speeds for the reason that the driver's neural processing delay limits the bandwidth of control. One way to provide the desired phase lead especially for the modeling of driver activity at high speed is using the future path information. By previewing the road path ahead the driver is able to anticipate the necessary control input and compensate for the inherent time delay [26, 31].

There are various preview models based on different assumptions of driver control strategies. One of most well known preview models is proposed by Macadam in [31]. The model is formulated under the optimal control framework. Macadam's optimization algorithm is based on a continuous comparison between previewed road path and predicted vehicle path and its discrete form is more easily implemented. If the preview points are weighted using the Dirac delta function, the algorithm can be simplified to single point, linear preview control model which shows some characteristics predicted by the crossover model [32]. The original Macadam's model performs very well for normal lateral driving behaviors. To solve the near/at limit vehicle handling problems, Macadam proposed a more comprehensive driver model take more vehicle states such as steering angle, side slip, and roll angle into the cost function [33].

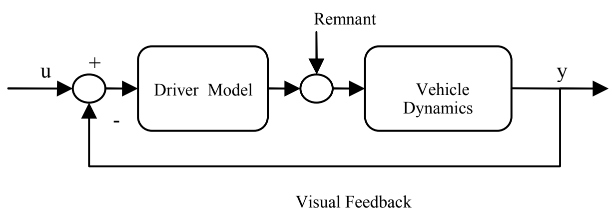

Figure 1. The basic structure of crossover model

The preview time has an important effect on Macadam's controller, increasing the preview time leads to the driver smoothing the vehicle response, and reducing the preview time leads to control instability [34]. It is not necessary to specify a preview time or distance in Sharp and Valtetsiotis' driver model based on Linear Quadratic Regulator (LQR) control theory because the value is inherent in the model [35]. Cole [36] carried out a study to compare preview control theory with LQR control theory and demonstrated that there are no fundamental differences other than mathematical formulations among those model designs.

B. Driver modeling for advanced driver assistance systems

Nowadays, more and more advanced driver assistance systems (ADAS) are available to improve longitudinal and lateral vehicle control, to automate driving operations, and to reduce the driver burden. In existing driving assistance systems, the driver remains the sole responsible of the driving task, thus the development and testing of new ADAS naturally raises questions about the driver activity and behavioral adaptation aspects [37] and needs some digital human models to estimate the consequences of performing tasks in a given work environment to determine if people are likely to become injured by the task requirements. Simulations using human models are much less expensive and dangerous than field testing. These features make them very useful in the ADAS design process.

Human models may be classified into two categories: physical and cognitive. Physical models focus on the body postures and the physical motions used to perform a task. Cognitive models research on the cognitive processing underlying the decisions made when performing a task.

1) Physical modeling of human driving

The principles and results obtained from a wide range of research relating to the neuromuscular system provide an insight into the likely control strategies employed by drivers. To better understand the role of the neuromuscular dynamics in the driving task, the key muscles involved in the driving control must be identified. Hillc [38] and Wilkie [39] represented the mechanical properties of muscles by a three-element model which is widely used to represent neuromuscular dynamics [40-42]. Research by Magdaleno and McRuer has shown that the measured frequency response of the combined limb and manipulator is consistent with the three-element muscle model and can be represented by a third order dynamics [43]. The neuromuscular model proposed by Magdaleno and McRuer is shown in Figure 2. Many other models of the neuromuscular system dynamics have been incorporated into models of driver steering control [44].

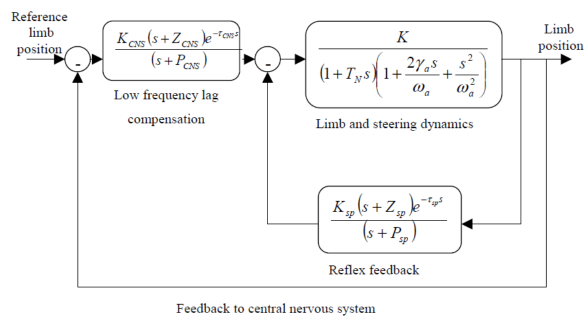

Figure 2. Magdaleno and McRuer's [43] neuromuscular system with feedback paths

Human models are now widely used for ergonomic analysis of products and workplaces. Porter et al. summarized applications of digital human models in vehicle ergonomics during the early years of personal computers [45]. Posture and motion simulation is very important for ergonomic analysis, so that a wide variety of methods for simulating human postures and motions [46-48]. The HUMOSIM [49] ergonomics framework developed by the University of Michigan is a modular system of algorithms that function together to produce realistic human motion in a wide variety of task scenarios but lacks a model of human information acquisition and processing.

2) Cognitive modeling of human driving

Cognitive models of the human aim to explain the mechanisms behind human actions and decision and to predict the decisions people will make in particular situations and the act timing [50].

Liu and Wickens [51] provide a cognitive model known as 'single-channel model' based on the common assumption that an operator can only do one thing at a time.

Wickens [52] discussed in detail the multiple-resource limited capacity theory that models based on which can handle information for concurrent tasks in parallel as long as the total processing load does not exceed the limited capacity.

Liu [53] developed an integrated computational framework based on the psychological support for both single-channel models and limited capacity models.

In 1973, Allen Newell [54] recognized that decomposing the cognitive system into many elements may cause one to miss important links and interactions among elements. Therefore, he called for the development of unified theories of cognition (UTC). Since then, many models and cognitive architectures fit with the goal of UTC have been developed, including the Model Human Processor (MHP) [55], the GOMS [56] family of models, and ACT-R [57].

C. Summary

While most existing driver models in vehicle dynamics and control areas can provide much more realistic vehicle motion by taken into consideration of high-fidelity vehicle dynamics and some drivers' driving characteristics, they were mainly focused on drivers' "control" aspect of the common driving characteristics. However, on the one hand, drivers' driving nature and characteristics are in general much broader than just "controls", such as drivers' perception to the surrounding driving environment, mental and psychological judgment and decision making processes, neuromuscular actions and reactions. On the other hand, all these characteristics carry much individuality from one driver to another, such as habitual driving styles, which can be complexly influenced by many factors like surrounding driving environment, individual driving experience, or even age, gender, emotion, to name a few. Although properly and comprehensively modeling these can be a big challenge, it is the fact that they are of great influential factors in the design and study of the modern transportation systems with vehicle-driver-environment taken into consideration. This can be good further research areas.

IV. CONCLUSIONS

This paper first reviewed the driver or driving models used in traffic simulation. While they were created mainly for the purpose of mobility simulation, they did not in general take much into consideration of the vehicle dynamics and drivers' driving characteristics. This paper introduced some commonly used models and the state-of-the-art technologies in the field of vehicle dynamics and controls, which may greatly enhance the microscopic traffic simulation with high-fidelity and flexible mobility simulation. In order to better study the effect of human drivers or human factors on the modern transportation systems when vehicle-driver-environment systems are of the ultimate concerns, this paper further suggested future research on the modeling of driver's personal driving characteristics, such as drivers' habitual driving styles. These can be of great influencing factors in the design and study of the modern transportation systems.

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