

Modeling and Simulation of Intelligent Driving with Trajectory Planning and Tracking

Mengxun Wu, Weiwen Deng, Sumin Zhang, and Hao Sun
State Key Lab of Automotive Simulation & Control, Jilin Univ

Bin Liu, Bingxu Shang, and Shaobo Qiu
R&D Center, China FAW Group

ABSTRACT

This paper proposes a novel modeling and simulation environment developed under Matlab/Simulink with friendly and intuitive graphic user interfaces, aimed to enable math-based virtual development and test of intelligent driving systems. Six typical driving maneuvers are first proposed, which are further abstracted into two atomic sub-maneuvers: lane following and lane change, as any maneuvers can be the combinations of these two. A generic trajectory planning and path tracking control algorithm are developed to deal with the generality and commonality of the lane change function with optimization among safety, comfort and efficiency in performing the lane change maneuver. Some typical simulations are conducted with results demonstrating the practical usefulness, efficiency and convenience in using this proposed tool.

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I. INTRODUCTION

In recent years, the research on intelligent driving systems including driver assistance, active safety and autonomous driving systems has attracted great attention, where trajectory planning and path tracking are two of the key constituent and enabling functions [1]. A well-planned trajectory and accurate trajectory tracking are required to achieve an optimal performance among safety in avoiding obstacles on the path, comfort throughout the maneuver, and the efficiency in completing the maneuver. Conventionally, the intelligent driving systems were developed, tested and validated largely based on intensive, in-vehicle, field experiment. Although this is often necessary, it can be much reduced with high-fidelity and high-efficiency modeling and simulation approaches, which have been widely adopted in other research areas to reduce the cost, shorten the development cycle, and more, to provide great insight to the systems to be developed [2]. For intelligent driving systems in particular, there is no way to guarantee the test repeatability, and more importantly, the safety when dealing with safety critical test scenarios, such as collision, crash, vehicle spin or rollover, etc.

This paper proposes a novel modeling method and a simulation environment aimed at enabling math-based virtual development, test and even validation of intelligent driving systems. The proposed modeling method and simulation environment are developed under Matlab/Simulink, a widely used modeling and simulation tool.

Under this environment, some typical driving maneuvers are first proposed, which represent most common daily driving cases, such as lane following, lane changing, overtaking, obstacle avoidance, intersection crossing, etc. To generalize the maneuvers for intelligence driving, these typical maneuvers are further abstracted into two atomic sub-maneuvers: lane following and lane changing. Since lane following maneuver is fairly straight forward in trajectory following and tracking, this paper mainly focuses on the lane changing sub-maneuver.

A generic trajectory planning and path tracking control algorithm are developed to deal with the generality and commonality of the lane change function with optimization among the requirements of safety, comfort and efficiency in performing the lane changing maneuver. Finally some typical simulations are conducted with the simulation results demonstrating the practical usefulness, efficiency and convenience in using this modeling and simulation tool.

The paper is organized as follows: the analyses on some typical maneuver are presented in [Section II](#). In [Section III](#), generic trajectory planning for lane change maneuvers is developed to deal with the generality and commonality of any complex driving scenarios. [Section IV](#) presents the proposed simulation environment with some simulation results shown in [Section V](#). The paper finally concludes in [Section VI](#).

II. ANALYSES OF TYPICAL MANEUVERS

Some typical maneuvers are investigated first with their behavioral natures that are common and representative in our daily driving scenarios, such as lane following, lane changing, lane changing with interference, overtaking, intersection crossing, and obstacle avoidance:

1. Lane following: the host vehicle maintains its position within the lane, and adjusts its speed to a desired set speed or to avoid potential collision with front traffic vehicles. [Figure 1](#) illustrates the lane following maneuver.

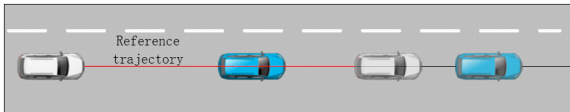


Figure 1. Lane following maneuver

2. Lane change: the host vehicle makes a lane change and enters to the adjacent lane, as shown in [Figure 2](#):

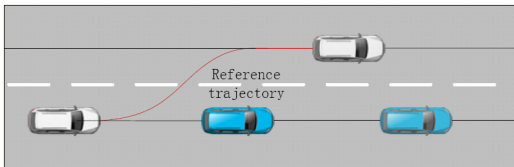


Figure 2. Lane changing maneuver

3. Overtaking: another type of lane (or double lane) change for the purpose of overtaking a slow traffic vehicle in front, as shown in [Figure 3](#).

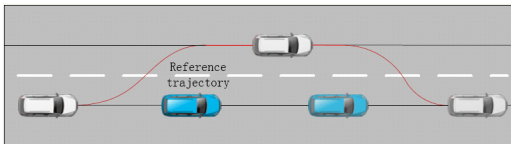


Figure 3. Overtaking maneuver

4. Lane change with interference: similar to a regular lane change, but with potential collision with traffic vehicles or obstacles on the course, as shown in [Figure 4](#).

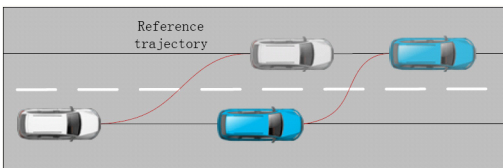


Figure 4. Lane changing with interference maneuver

5. Obstacle avoidance: can be either lane following or lane change, to avoid front obstacles, as shown in [Figure 5](#).

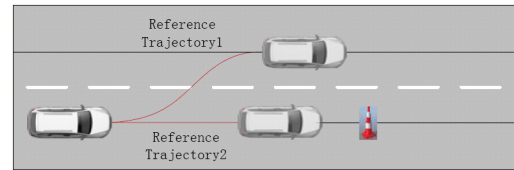


Figure 5. Obstacle avoidance

6. Intersection crossing: this maneuver can be considered as lane following except there are intrusive traffic vehicles from the crossing lane, as shown in [Figure 6](#).

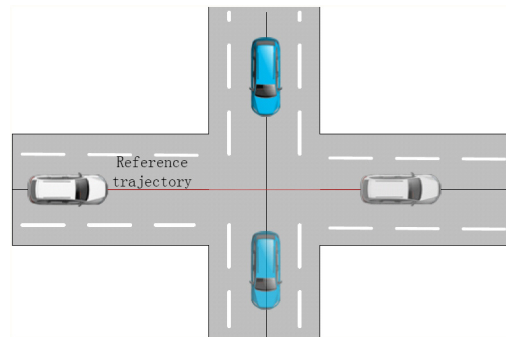


Figure 6. Intersection crossing maneuver

From these typical driving maneuvers, we may abstract them into two atomic sub-maneuvers: lane following and lane change. An overtaking maneuver, for example, can be decomposed into a series of combined atomic actions, or sub-maneuvers. [Figure 7](#) illustrates an overtaking maneuver, which is composed of a left lane change, lane following and a right lane change [3].

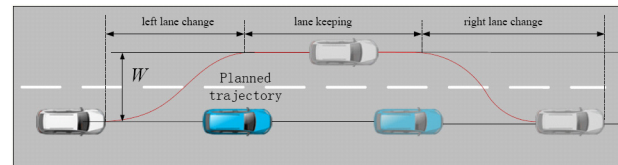


Figure 7. A maneuver consists of two atomic sub-maneuvers

Thus any arbitrary and complex driving scenarios can be reasonably represented by the combination of the two sub-maneuvers. A generic trajectory planning method is then proposed to deal with the sub-maneuvers, which can be broadly applied to any complex driving scenarios for trajectory planning and path tracking.

III. TRAJECTORY PLANNING AND TRACKING

In this section, the algorithm for intelligent driving is proposed with trajectory planning and tracking. We mainly focus on the lane change sub-maneuver, since lane following is fairly straight forward. A generic trajectory planning and path tracking control algorithm are developed to deal with the generality and

commonality of the lane change function with optimization among requirements of safety, comfort and efficiency in performing the lane changing maneuver.

Trajectory Planning

Figure 8 shows a typical and complete left lane change maneuver [3].

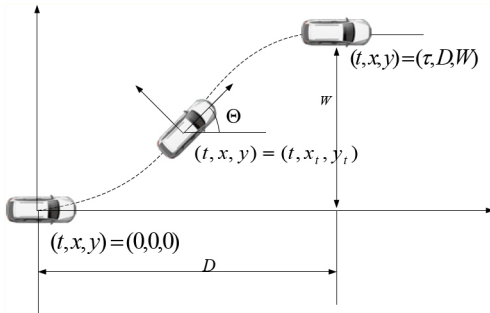


Figure 8. (Left) lane change as one of the atomic sub-maneuvers

First, an optimal steering angle should be determined to satisfy two conflicting objectives between vehicle performance and driving efficiency. The relationship between the traveling time period and the steering angle can be approximately derived as:

$$\tau(\delta) \approx \frac{\frac{W(t)}{u} - \tau_1 \sin \theta - \frac{u \tau_1^2 \delta}{2L(1+Ku^2)} \cos \theta}{\theta + \frac{u \tau_1 \delta}{L(1+Ku^2)} + \frac{\left(\theta + \frac{u \tau_1 \delta}{L(1+Ku^2)}\right)^3}{3}} \quad (1)$$

Also, the relationship between the steering angle δ and the lateral acceleration a_y is well known based on vehicle steady-state turn:

$$a_y(\delta) = \frac{u^2}{L} d \quad (2)$$

For driving comfort with good handling and stability, a smaller $a_y(\delta)$ is more desirable, which however may lead to undesirable longer time to complete the maneuver, and vice versa. Thus, this becomes an optimization problem. With proper weighting factors W_1 and W_2 , the cost function to be minimized can be defined in a quadratic form as:

$$\min(J) = \min \left[w_1 a_y^2(d) + w_2 t^2(d) \right] \quad (3)$$

Figure 9 shows different global optimal trajectories with different criteria:

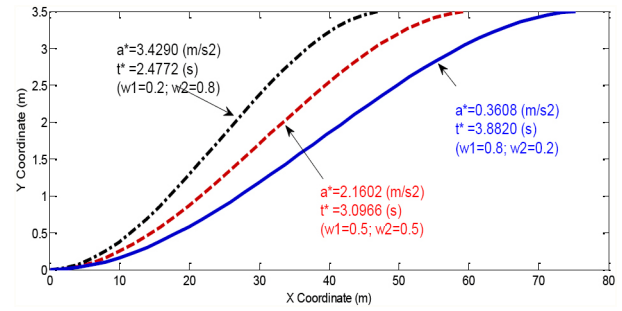


Figure 9. Optimal lane change maneuvers with different criteria

Taking the derivatives with respect to both a_y and τ respectively, the optimal steering angle at any time t can be obtained numerically that satisfies both vehicle performance and driving efficiency.

With this optimized steering angle input, an optimal vehicle trajectory can be obtained or predicted at a given vehicle speed. A kinematic vehicle model is used that has reasonable fidelity and computational efficiency within a short time interval [4]. The trajectory generated can be a candidate of the planned trajectory dynamically.

Assuming the traffic vehicle's current speed and heading angle are known from the host vehicle's on-board sensors, its movement likely will form a cluster of trajectories, mainly depending on the possible changes of its future speed and steering angle. These changes, however, are subject to physics laws of tire-road contact adhesion and vehicle structural limitations in steering. The traffic vehicle's movement, as with all vehicles, is governed by the following differential equation:

$$\dot{x} = f(x(t), u(t)) \quad (4)$$

where x is the state variables and u is the input, such as steering, braking or throttling, constrained by their maximum boundary set of U . Therefore, the possible vehicle movement within a short time interval τ can be expressed as:

$$R^e(r) = \left\{ x(r) \mid x(r) = x(0) + \int_0^r f(x(t), u(t)) dt, \right. \\ \left. x(0) \in X_0, u(t) \in U \right\} \quad (5)$$

Although each of the possible trajectories carries a statistical probability, in general, retention of the current status is more likely than a change of trajectory. Figure 10 is an illustration of an envelope of a traffic vehicle motion with a cluster of trajectories: