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Lane Change Scheduling for Autonomous Vehicles ⋆

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Abstract: The subject of this paper is the coordination of lane changes of autonomous vehicles on a two-lane road segment before reaching a given critical position. We first develop an algorithm that performs a lane change of a single vehicle in the shortest possible time. This algorithm is then applied iteratively in order to handle all lane changes required on the considered road segment while guaranteeing traffic safety. Various example scenarios illustrate the functionality of our algorithm.

Keywords: Autonomous vehicles, lane change, scheduling algorithms, intelligent transportation.

1. INTRODUCTION

Lane changes have a significant effect on the *traffic throughput* and *traffic safety* (Monteil et al., 2014; Lin et al., 2014). Hence, various studies in the existing literature address the simulation of lane changes, the safety of lane changes and the local coordination of lane changes. In this context, most of the approaches are based on human drivers and assume that the global traffic behavior is uncoordinated.

There are many recent advances in the research on *autonomous vehicles*. For example, autonomous vehicles support features such as Cooperative Adaptive Cruise Control (CACC) for safe *vehicle following* (Ploeg et al., 2014; Kianfar et al., 2014), *lane keeping* (Chen et al., 2014; Kim et al., 2015), the control of *lane changes* (Chen et al., 2013; Rucco et al., 2014) and the adjustment of *vehicle distances* (Deaibil and Schmidt, 2015).

This paper assumes the usage of autonomous vehicles with the features stated above and focuses on a specific traffic scenario with a two-lane road segment before a *critical position*. This can for example be an urban intersection or a highway ramp, where vehicles need to move to the appropriate lane before reaching the critical position depending on their destination. As the main contribution, the paper develops an original method for performing the required lane change maneuvers before the critical position, while ensuring traffic safety. The method comprises two main algorithms. The first algorithm handles the lane change of a single vehicle in the shortest possible time while keeping a safe distance to all neighboring vehicles. This algorithm is then applied iteratively starting from the vehicles closest to the critical position to obtain the trajectories of all vehicles on the road segment. Different from all the existing literature, the proposed method computes all vehicle trajectories and hence achieves coordination of the global traffic behavior. Various test cases illustrate the developed method.

Related work can be found in the literature on *lane change assistance*, *local lane change coordination* and *merging* at on-ramps. Tawari et al. (2014); Hou et al. (2015) determine when it is safe for a single vehicle to perform a lane change depending on the traffic situation. Local lane change coordination of autonomous vehicles is considered by Awal et al. (2015) and Hu et al. (2012). Hereby, coordination is restricted to local modifications of the traffic situation such as slowing down a lag vehicle. Wang et al. (2009) propose to redistribute vehicle distances in order to provide gaps for merging vehicles. Awal et al. (2013) determine an optimal merging order depending on the current and predicted traffic condition and Desiraju et al. (2015) try to determine the maximum number of lane changes depending on full knowledge of all vehicle trajectories on a road. Different from our scenario, these methods do not assume autonomous vehicles and do not compute the most appropriate trajectory for each vehicle. Finally, (Dao et al., 2007) proposes a method for the optimal lane assignment of vehicles on a highway in order to balance the traffic but without considering the actual required vehicle maneuvers.

The paper is organized as follows. The lane change problem is introduced in Section 2. Section 3 considers lane changes of a single vehicle and Section 4 develops our method for multiple lane changes. Conclusions are given in Section 5.

2. MOTIVATION AND PROBLEM STATEMENT

We focus on coordinated lane change maneuvers of multiple vehicles on two-lane road segments as shown in Fig. 1.

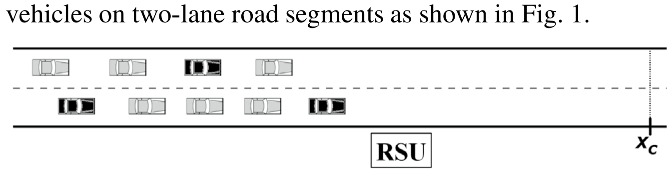

Fig. 1. Road segment before a critical position.

Here, x_c represents a critical position (CP), where a cooperative lane change maneuver should be completed. This can for example be an urban intersection (Ahmad et al., 2014; Cesme and Furth, 2014), the end of a vehicle queue, or an on-ramp/off-ramp on a highway (Awal et al., 2013; Desiraju et al., 2015). In order to avoid disruptions in the traffic flow and to ensure traffic safety, it is necessary that all vehicles safely move to their designated lane before reaching the CP.

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We address the stated problem in the framework of ITS. It is assumed that autonomous vehicles with the capability of automatic distance adjustments, automatic lane changes, lane keeping and vehicle following are used. In addition, all vehicles are equipped with vehicle-to-infrastructure (V2I) communication to provide state information such as position to a road side unit (RSU) and to receive maneuver commands from the RSU.

The subject of this paper is the development of algorithms for the RSU in order to coordinate the vehicle maneuvers on the road segment. That is, knowing the initial positions and the target lane of all vehicles on the road segment, we want to determine the trajectory of each vehicle and the timing of all lane changes such that all vehicles reach their designated lane before reaching CP, while ensuring safety.

3. COMPUTATION FOR A SINGLE VEHICLE

3.1 Notation and Assumptions

A single lane change maneuver is the basic building block of the problem stated in Section 2. Consider the scenario in Fig. 2 with four vehicles that are involved in a lane change maneuver in the time interval $[0, t_{\text{end}}]$. Here, t_{end} denotes the available time until the string leader reaches the CP when traveling at a given nominal speed v_{nom}. The *subject vehicle* (SV – black) with the unknown position x performs the lane change from the *current lane* to the *target lane*. The SV's *current leader* (CL – before the lane change) has the known trajectory x_{cl} and its *target leader* (TL – after the lane change) has the known trajectory x_{tl}. The *lag vehicle* (LV) with the unknown position x_{l} is the vehicle behind the SV on the target lane after the lane change.

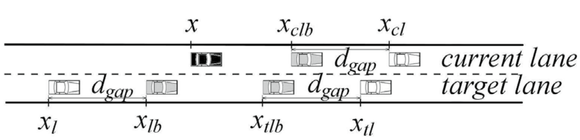

Fig. 2. Single lane change scenario with SV, CL, TL, LV.

In this setting, vehicles can travel at the given nominal speed v_{nom} or faster/slower than v_{nom}. In order to simplify the discussion, we perform fast and slow travel at the average velocity v_{up} and v_{dn}, respectively. In addition, lane changes have a duration of Δ_{LC} and should be performed when traveling with v_{nom}. Traffic safety requires to keep a minimum distance between the vehicles. Safe vehicle following can be achieved by using CACC (Ploeg et al., 2014) with a minimum distance

$$d_v = L + r + h \cdot v, \tag{1}$$

the vehicle length L, the distance at standstill r, the headway time h and the current vehicle speed v. We write $d_{\text{gap}} := d_{v_{\text{nom}}}$.

In the single lane change scenario, it is desired to determine the vehicle position $x(t)$ in the interval $[0, t_{\text{end}}]$ such that the lane change of the SV can be performed at the earliest possible time $\hat{t}$ and traffic safety is ensured for all times $t \in [0, t_{\text{end}}]$:

- CL: $x(t) \leq x_{\text{clb}}(t) := x_{\text{cl}}(t) - d_{\text{gap}}$ for $t \in [0, \hat{t} + \Delta_{\text{LC}}]$,
- TL: $x(t) \leq x_{\text{tlb}}(t) := x_{\text{tl}}(t) - d_{\text{gap}}$ for $t \in [\hat{t}, t_{\text{end}}]$,
- LV: $x(t) \geq x_{\text{lb}}(t) := x_{\text{l}}(t) + d_{\text{gap}}$ for $t \in [\hat{t}, t_{\text{end}}]$.

Here, x_{clb}, x_{tlb} and x_{lb} denote the *CL bound*, the *TL bound* and the *LV bound*, respectively. In particular, SV should be located between these bounds for performing a safe lane change as illustrated by the vehicles in gray in Fig. 2. Together, a lane change is possible at time $\hat{t}$ if the vehicle speed is v_{nom} between $\hat{t}$ and $\hat{t} + \Delta_{\text{LC}}$ and $x(\hat{t}) \leq x_{\text{clb}}(\hat{t})$, $x(\hat{t}) \leq x_{\text{tlb}}(\hat{t})$, $x(\hat{t}) \geq x_{\text{lb}}(\hat{t})$.

3.2 Possible Cases

Let v_{cl} and v_{tl} be the CL and TL speed, respectively, and introduce x_{min} as the minimum of the CL bound and TL bound: $x_{\text{min}}(t) := \min\{x_{\text{tlb}}(t), x_{\text{clb}}(t)\}$ for $t \in [0, t_{\text{end}}]$ with the corresponding velocity v_{min}. Let $\mathcal{W} := \{[t_1, t_2] | t_2 \geq t_1 + \Delta_{\text{LC}}$ and $v_{\text{cl}}(t) = v_{\text{tl}}(t) = v_{\text{nom}}$ for $t \in [t_1, t_2]\}$ be the set of time windows where the leader vehicles enable a lane change. We next consider all possible relative locations of the four vehicles at time $\hat{t}$ before a lane change.

Case 1 (Fig. 3 (a)): $x(\hat{t}) > x_{\text{min}}(\hat{t})$ The gap between the SV and the TL and/or CL vehicle is insufficient. In this case, the SV should slow down until the gap is sufficient. Hence, we compute the earliest time t_{next} such that $x(t_{\text{next}}) \leq x_{\text{min}}(t_{\text{next}})$ as

$$t_{\text{next}} = \min_{t > \hat{t}} \{x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{dn}} = x_{\text{min}}(t)\} \tag{2}$$

$$x(t) = x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{dn}}; \quad v(t) = v_{\text{dn}} \text{ for } t \in [\hat{t}, t_{\text{next}}] \tag{3}$$

Case 2 (Fig. 3 (b)): $x(\hat{t}) < x_{\text{lb}}(\hat{t}) \wedge x(\hat{t}) < x_{\text{min}}(\hat{t})$: The gap between the SV and the CL/TL is sufficient but the LV is too close to the SV. In this case, the SV can approach the leader vehicles as long as the gap remains sufficient and must wait until the LV opens a sufficient gap. This is achieved by computing

$$t_{\text{next}} = \min_{t > \hat{t}} \{x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{up}} = x_{\text{min}}(t) \vee x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{up}} = x_{\text{lb}}(0) + v_{\text{dn}} t\} \tag{4}$$

$$x(t) = x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{up}}; \quad v(t) = v_{\text{up}} \text{ for } t \in [\hat{t}, t_{\text{next}}] \tag{5}$$

Case 3 (Fig. 3 (c)): $x(\hat{t}) < x_{\text{lb}}(\hat{t}) \wedge x(\hat{t}) = x_{\text{min}}(\hat{t})$: The smallest allowable gap between the SV and the CL/TL is obtained but the LV is too close to the SV. Then, the SV follows the closest leader vehicle and waits until the LV opens a sufficient gap:

$$t_{\text{next}} = \min_{t > \hat{t}} \{x_{\text{lb}}(0) + v_{\text{dn}} t = x_{\text{min}}(t)\} \tag{6}$$

$$x(t) = x_{\text{min}}(t); \quad v(t) = v_{\text{min}} \text{ for } t \in [\hat{t}, t_{\text{next}}] \tag{7}$$

Case 4 (Fig. 3 (d)): $x_{\text{min}}(\hat{t}) > x(\hat{t}) \geq x_{\text{lb}}(\hat{t}) \wedge [\hat{t}, \hat{t} + \Delta_{\text{LC}}] \notin \mathcal{W}$: The gap between the SV and the CL/TL/LV is sufficient. Nevertheless, the CL/TL do not travel at the nominal speed for at least Δ_{LC}. In this case, the SV can approach the CL/TL as long as the gap remains sufficient and must wait until both CL and TL travel at nominal speed for at least Δ_{LC}:

$$t_{\text{next}} = \min_{t > \hat{t}} \{x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{up}} = x_{\text{min}}(t) \vee [t, t + \Delta_{\text{LC}}] \in \mathcal{W}\} \tag{8}$$

$$x(t) = x(\hat{t}) + (t - \hat{t}) \cdot v_{\text{up}}; \quad v(t) = v_{\text{up}} \text{ for } t \in [\hat{t}, t_{\text{next}}] \tag{9}$$

Case 5 (Fig. 3 (e)): $x_{\text{min}}(\hat{t}) > x(\hat{t}) \geq x_{\text{lb}}(\hat{t}) \wedge [\hat{t}, \hat{t} + \Delta_{\text{LC}}] \in \mathcal{W}$: The gap between the SV and the CL/TL/LV is sufficient. In addition, the CL/TL travel at the nominal speed for at least Δ_{LC}. In this case, the SV performs the lane change while following the leader vehicles at the nominal speed. That is, we set

$$x(t) = x(\hat{t}) + (t - \hat{t}) v_{\text{nom}}; \; v(t) = v_{\text{nom}} \text{ for } t \in [\hat{t}, \hat{t} + \Delta_{\text{LC}}] \tag{10}$$

Case 6 (Fig. 3 (f)): $x_{\text{min}}(\hat{t}) = x(\hat{t}) \geq x_{\text{lb}}(\hat{t}) \wedge [\hat{t}, \hat{t} + \Delta_{\text{LC}}] \notin \mathcal{W}$: The minimum allowable gap between the SV and CL/TL is obtained and the LV maintains a sufficient gap to the SV. Nevertheless, the leader vehicles do not travel at the nominal speed for at least Δ_{LC}. In this case, the SV should follow CL/TL until the leader vehicles travel at nominal speed for at least Δ_{LC}:

$$t_{\text{next}} = \min_{t > \hat{t}} \{[t, t + \Delta_{\text{LC}}] \in \mathcal{W}\} \tag{11}$$

$$x(t) = x_{\text{min}}(t); \quad v(t) = v_{\text{min}}(t) \text{ for } t \in [\hat{t}, t_{\text{next}}]. \tag{12}$$