Cooperative Lane-change on the Main-line of Highway in a Connected Vehicle Environment

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Abstract. The main-line lane-change (LC) and ramp LC are critical factors which decrease the mobility and safety of the transportation system. Connected Vehicle Technologies (CVTs) bring promising foundations for both types of LC to improve the traffic efficiency and reduce the crash risks by using real-time communication and systematic operation. Based on an 5G communication architecture, this paper proposes a novel CVT-based cooperative LC method which can be used for advanced traffic management to enhance the transport service. In the proposed approach, several Roadside Units (RSUs) are set up on the main-line of a highway to communicate with and manage connected client vehicles (CVs) for traffic flow smoothing. A mathematical model is developed to address the systematic maneuver of vehicles’ LC in the connected vehicle environment (CVE), and its solution algorithm is also proposed. In order to assess the proposed method, a simulation test-bed is developed using VISSIM COM, and a typical highway network is employed as the study case. The simulation results illustrate that the proposed method can increase 20.7% of traffic capacity in a two-lane highway. And when it is applied in dense traffic environment, it can reduce more than 90% of travel delay, more than 75% of maximum queue length, and more than 10% of fuel consumption and gas emission. Moreover, sensitivity analysis shows that the market penetration of CVT is a key factor that affects the result of CVT-based cooperative LC.

Keywords. Cooperative lane-change, Connected vehicle technologies, Traffic efficiency, VISSIM COM.

1. Introduction

Car following (CF) and lane-change (LC) are two primary driving behaviors in microscopic traffic theory. Vehicles attempting to achieve the desired speed, or avoid following a truck, will decrease the mobility and safety of the traffic system [1]. During the process of vehicle LC, the driver’s workload and stress are likely to significantly increase, which makes driving more error-prone and thus more dangerous. Some researchers suggest that LC is an important cause of traffic accident [2].

With the development of on-board sensors and communication technology like 5G, connected automated vehicles has gained gaining increasing amounts of attention from both industry and academic communities. Luo et al. [3] presented a trajectory planning method converts the planning problem into a constrained optimization problem using the lane change time and distance. Nilsson et al. [4] proposed an approach to solve two loosely coupled convex quadratic programs. Peng et al. [5] designed a new four-level automatic driving mode and an effective decision mechanism that considers
safety and ergonomics. Santos et al. [6] presented a Decentralized Bargaining Negotiation Process allowing that two conflicting vehicles negotiate when they perform coordinated lane change maneuvers. Liu et al. [7] established an autonomous lane change decision-making model based on benefit safety and tolerance with a support vector machine (SVM) algorithm solving the non-linearity problem. Xing et al. [8] used multiple low-cost cameras and VBOX vehicle data acquisition system to gain the inputs to deal with the time-series driving sequence and the temporal behavioural patterns. Li et al [9-10] proposed a machine learning method for the short-term prediction of lane-changing impacts (LCI) during the propagation of traffic oscillations. Peng et al.

This paper deals with the issue of cooperative vehicle lane-change on highways using connected vehicle technology. The new contents in this study mainly include: (1) a lane-change method for moving traffic flow on the main-line of a highway in CVE; (2) a mechanism for connected client vehicles to cooperate their movements; (3) assessment of the proposed approach in some dense traffic environment using CVT.

2. Methodology

2.1. Assumptions

The study is built on the following assumptions for cooperative lane-change under CVE: (1) The CVC can observe the microscopic traffic parameters by connected vehicle technology and other traffic detection technologies such as radar or LiDAR based sensors. (2) A vehicle equipped with connected-vehicle kit is called connected client vehicle (CV). A CV can exchange data with the CVC in real time. Each CV sends its destination, next link, position, and speed to the CVC periodically. Meanwhile, a vehicle which isn’t equipped with connected-vehicle kit is called human-driven vehicle (HDV). (3) There has no any packet drops, and the packet transmission delays are short enough to be ignored. (4) Communication protocol between RSUs and CVs is 5G. (5) When a CV received dynamics parameters (moving paces) from the CVC, it can execute exactly.

2.2. Lane-change on the Main-line of Highways

The cooperative strategy of LC in CVE is illustrated in figure 1. We can see that: V0 is the vehicle which needs lane-change. V1, V2 and V3 are the vehicles which will coordinate their movements with V0. The cooperative ways of V1 and V3 are to provide sufficient forward space for V0, while the cooperative way of V2 is to avoid rear-end collision with V0. V4 and V5 don’t take in involved in coordination directly, but their dynamic states will limit the movement processes of V1 and V3 (determine the velocity and acceleration ranges of V1 and V3).

Figure 1. Typical vehicle lane-change in a two-lane highway.

To achieve the optimal cooperation, the cooperative principles of vehicle LC include: (1) try not to change the velocities of the cooperative vehicles (V1, V2 and V3). (2) change the velocities of the cooperative vehicles as few as possible; (3) for the convenience of control, only constant acceleration (or deceleration) is permitted for the lane-changing vehicle and the cooperative vehicles during the processes of coordinative lane-change.
2.3. Mathematical Model

Essentially, the lane-change problem is to get a combination of four acceleration variables, \( a_0, a_1, a_2 \) and \( a_3 \) (corresponding to the accelerations of V0, V1, V2 and V3). Let \( a_{max}^d \) present the maximum acceptable deceleration of the vehicles, \( g_i \) means the variable coefficients. As discussed above, the optimization principle of vehicle LC is to change the velocity of the lane-changing vehicle itself rather than those of other vehicles, thus the objective function is presented as:

\[
\min G = \sum_{i=0}^{3} |g_i a_i|
\]  

Subjects to:

(1) \( g_0 < g_j \) (\( j = \{1,2,3\} \)), which means we’d better change the velocity of the lane-changing vehicle rather than those of the coordinative vehicles.

(2) Acceleration constraints: \( a_0, a_1, a_2, a_3 \in [a_{max}^d, a_{max}^u] \), where \( a_{max}^d \) represents the maximum acceptable vehicle deceleration, \( a_{max}^u \) represents the maximum acceptable vehicle acceleration.

(3) Speed constraints: \( v_0 + t_f a_0, v_1 + t_f a_1, v_2 + t_f a_2, v_3 + t_f a_3 \in [v_{min}, v_{max}] \). where \( t_f \) is the period of cooperative lane-change time, \( v_{min} \) and \( v_{max} \) respectively present the minimum and maximum acceptable speeds.

(4) Longitudinal constraints of V1:

\[
y_1 + \frac{1}{4} t_f (2v_1 + \frac{1}{2} a t_f) - \text{Len(V1)} \geq y_0 + \frac{L}{2} + \frac{(v_0 + \frac{1}{2} a t_f)^2 - (v_1 + \frac{1}{2} a t_f)^2}{2a_{max, nay}^d} + \Delta l
\]  

where \( y_0, y_3 \) present the longitudinal coordinates of V0 and V1 in the initial time of lane-change, \( L \) is the travel distance in the longitudinal direction during lane-change process, \( \Delta l \) means the basic safety distance, which is related to the travel speed. Len (V1) is the length of V1, \( a_{max, nay}^d \) represents the feasible maximum deceleration (to avoid collisions).

(5) Longitudinal constraints of V2:

\[
y_2 + \frac{1}{2} t_f (2v_2 + a_2 t_f) \leq y_0 + L + \frac{(v_2 + a_2 t_f)^2 - (v_0 + a_0 t_f)^2}{2a_{max, nay}^d} - \text{Len(V0)} + \Delta l
\]  

(6) Longitudinal constraints of V3:

\[
y_3 + \frac{1}{2} t_f (2v_3 + a_3 t_f) - \text{Len(V3)} \geq y_0 + L + \frac{(v_0 + a_0 t_f)^2 - (v_3 + a_3 t_f)^2}{2a_{max, nay}^d} + \Delta l
\]  

Symbols in expression 3and 4 are defined as those above.

(7) Indirectly acceleration range: \( a_{max}^d(V4) \) and \( a_{max}^u(V5) \) respectively present the maximum acceleration value of V1 and V3 constrained by V4 and V5. There are two types of strategy to confirm \( a_{max}^d(V4) \) and \( a_{max}^u(V5) \), including conservative strategy and aggressive strategy, as:

\[
\begin{align*}
&\begin{cases}
y_1 + \frac{1}{2} t_f (2v_1 + a_{max}^u(V4)t_f) + \frac{(v_1 + a_{max}^u(V4)t_f)^2}{2a_{max}^u} \leq y_i + \frac{v_i^2}{2a_{max}^u} - \text{Len(V4)} - \Delta l & \text{Conservative strategy} \\
y_1 + \frac{1}{2} t_f (2v_1 + a_{max}^u(V4)t_f) \leq y_1 + v_1 t_f - \text{Len(V4)} - \Delta l & \text{Aggressive strategy}
\end{cases}
\end{align*}
\]

\[
v_1 + a_{max}^u(V4)t_f \leq v_{max}
\]

Speed limit
In fact, the proposed method above can also be used for ramp LC. When used for ramp LC, the front-vehicle of the lane-changing vehicle on the same lane (like V1 in figure 1) can be ignored. And it should be pointed out that if there has no feasible gap between the front-vehicle and the rear-vehicle on the object lane (like V2 and V3 in figure 1), the lane-changing vehicle (V0) should try to stop in front of the stop-line of the ramp lane.

2.4. Trajectory of Lane-change

According to the study by Nelson [10], a 5th order polynomial trajectory can be used as the trajectory of the lane-changing vehicle. As:

\[
h(y) = d \left\{ 10 \left( \frac{y}{L} \right)^3 - 15 \left( \frac{y}{L} \right)^4 + 6 \left( \frac{y}{L} \right)^5 \right\}
\]

where \(d\) presents the width of lane, \(L\) means the longitudinal distance of the whole lane-change process, \(h\) stands for lateral position, \(y\) means the variant longitudinal position. Dynamic moving angles of the vehicle are calculated by:

\[
\theta(y) = \frac{d^2h}{dy^2} \left( \frac{1}{1 + \left( \frac{dh}{dy} \right)^2} \right)^{\frac{1}{2}}
\]

For computational convenience, we can get the average value of the dynamic angles by:

\[
\bar{\theta} = \alpha + \frac{v_{max} - v_0}{v_{max}} \beta
\]

where \(v_0\) stands for V0’s initial speed of lane-change, \(\alpha\) and \(\beta\) is undetermined parameters. By expression (9) we can use a triangle to roughly calculate the process time and the travel distance in the longitudinal direction during lane-change.

when \(a_0 \neq 0\), the process time of lane-change is:

\[
t_f = \frac{(v_0^2 + 2a_0d)^{\frac{1}{2}} - v_0}{a_0}
\]

when \(a_0 = 0\), the process time of lane-change is:

\[
t_f = \frac{d}{v_0} \csc \bar{\theta}
\]

2.5. Algorithm of the Proposed Model

For a N times attempt to get the optimal solution, the algorithm firstly set \(a_0 = 0 + n\Delta a\) and \(a_0 = 0 - n\Delta a\) \((n \leq N)\); then for a specific \(a_0\), the algorithm will search for the corresponding optimal values of
\(a_1, a_2, \text{ and } a_3\), and calculate the objective function by expression 1; based on those, we can obtain the optimal solution. The specific logic of getting the optimal solution is shown in Table 1.

In general, a traversal algorithm is needed to search for the optimal solution. But if some solutions have met the exit requirements, the algorithm can be terminated in advance. For example, when all vehicles can collaborate for lane-change without changing their speeds, the algorithm doesn’t need to finish the entire traversal action.

| Table 1. Specific algorithm of searching for the optimal solution. |
|-------------------------|
| For \((n=0; n < N; n++)\) |
| (1) \(a_0 = 0 + n\Delta a\) |
| Get the relative optimal values of \(a_1, a_2, \text{ and } a_3\) respectively using expression 2-6 |
| If \(\{a_0, a_1, a_2, a_3\}\) is a feasible solution |
| Get the evaluation index \(G^+\) using expression 1 |
| (2) \(a_0 = 0 - n\Delta a\) |
| Get the relative optimal values of \(a_1, a_2, \text{ and } a_3\) respectively using expression 2-6 |
| If \(\{a_0, a_1, a_2, a_3\}\) is a feasible solution |
| Get the evaluation index \(G^-\) using expression 1 |
| (3) Compare with \(G^+\) and \(G^-\) and noted the better one as \(G^#\) |
| (4) Compare and replace the former best solution \(G^*\) with \(G^#\) as: |
| If \((G^# < G^*)\) |
| \(G^* = G^#\) |

3. Model Implementation

We employ the standard microscope traffic simulation software VISSIM5.2 64bit edition as the traffic simulation environment.

3.1. Simulation Result and Data Analysis

3.1.1. Simulation Road Network. About 50% of the vehicles need to exchange their lanes in the 900 meters long highway, so the lateral disturbance is very serious for the mobility of the traffic flow. In order to improve the capacity of this traffic system, a section of the central highway (the two-lane link) with 600 meters long, is equipped by connected vehicle technology, and a CVC is set up to oversee and manage the movements of the CVs by real-time information exchanging. The exchanged information includes: current lane, object lane, current position and speed. The protocol of the communication will follow the 5G standard.

In the simulation case, conservative strategies (as discussed in expression 5 and 6) for nearby vehicles are employed. Simulation parameters are set as shown in table 2.
Table 2. Simulation parameters.

| Simulation parameter          | value     | Simulation parameter          | value     |
|------------------------------|-----------|------------------------------|-----------|
| $v_{\text{max}}$             | 72 km/h   | Car proportion               | 80%       |
| Desired speed                | 60(58-68) km/h | Bus proportion               | 10%       |
| $a_{\text{max}}$             | 4 m/s$^2$ | Truck proportion             | 10%       |
| $a_{\text{min}}$             | -4 m/s$^2$| Lane-change probability      | 50%       |
| Lane width                    | 3.75 m    | $\alpha$ in expression 9     | 18        |
| Min security space gap        | 5 m       | $\beta$ in expression 9      | 10        |
| Maximum length of queue for statistics | 1500 m | Other parameters             | VISSIM’S default setting |

3.1.2. Simulation Results. The main simulation results are demonstrated in table 3. We can see that connected vehicle technology can not only increase the capacity of the highway, but also decrease the fuel consumption, CO emission, maximum queue length and travel delay.

Table 3. Main simulation results$^a$.

| Average indexes               | 0%CV value | 70% CV value | Improved (%) | 100%CV value | Improved (%) |
|------------------------------|------------|--------------|--------------|--------------|--------------|
| capacity (veh/h.lane)        | 1110       | 1240         | 14.4         | 1340         | 20.7         |
| travel delay(s/person)       | 33.71      | 14.69        | 56.43        | 2.05         | 93.92        |
| CO emission(g/veh)           | 4.31       | 3.93         | 8.89         | 3.80         | 11.94        |
| fuel consumption (gal/veh)   | 0.06       | 0.06         | 8.52         | 0.05         | 11.93        |
| maximum queue length (m)     | 296.50     | 125.25       | 57.76        | 63.38        | 78.63        |

$^a$traffic volume is 500-1200 veh/h.lane, the interval is 100 veh/h. lane, so the indexes above are obtained by 8 groups of simulation data.

In the table above, 0%CV means the proportion of CVs in the traffic flow is 0%, 70%CV and 100%CV have the similar meanings. It should be pointed out that 1200 veh/h.lane is a very high traffic demand for 0%CV environment, so we don’t do any simulation in higher traffic demand.

In order to evaluate the performance of the proposed method at varied market penetration of connected vehicle technology (MPCVT), for each parameter setting, we carried out the simulations in 0%, 70% and 100% MPCVT environment respectively. The specific results are illustrated in figure 2 to figure 5: the curves of travel delay are demonstrated in figure 2, in where we can see that if the traffic volume is 1000 veh/h.lane or less, connected vehicle technology does not decrease the travel time obviously, but if the traffic volume is 1100 veh/h.lane or higher, the advantage of connected vehicle technology will be revealed. These phenomena can also be seen in figure 3 about the CO gas emission; figure 4 about the fuel consumption; and figure 5 about the maximum queue length, respectively.
In the sub-link where is set as the connected vehicle environment, vehicles will cooperate their movements for lane-change. Figure 6 shows the activities of all lane-change processes when the traffic demand is set to 1000 veh/h.lane in 100%CV environment. We can see that many lane-change actions take place at the front section of the CVE, which means that the CVC will guide the CVs to get in their object lanes as soon as they enter the sub-link with CVE.
3.2. Sensitivity Analysis
We find that the capacity of the highway increase as we enhance the market penetration of CVT. Figure 7 presents the increasing trend of the capacity.

Moreover, we evaluate the index of travel delay in different market penetration of CVT. As the traffic volume is set to 1000veh/h. lane, the reduction of traffic delay is not very apparent when the proportion of CVT is not larger than 70%, as illustrated in figure 8. While as the traffic volume is set to 1100veh/h. lane, the travel delay will decrease obviously as the proportion of CVT increases. Especially, when the market penetration of CVT is 40% or above, traffic delay will be much lower than that in 0%CV environment, as shown in figure 9.

![Figure 7. Traffic capacities in varied environment of CVT market penetration.](image)

![Figure 8. Travel delay when traffic volume is 1000 veh/h.lane.](image)

![Figure 9. Travel delay when traffic volume is 1100 veh/h.lane.](image)

4. Conclusions and Future Research
We address some strategies and principles for cooperative vehicle lane-change. To assess the proposed method, a simulation test-bed using VISSIM COM is developed. By simulation results, we find that: (1). connected vehicle technology can enhance 20.7% of highway capacity in a two-lane highway, and decrease more than 90% of travel time, more than 75% of maximum queue length, more than 11% of fuel consumption, and more than 11% of CO gas emissions in dense traffic environment. (2). the proportion of CVT will influence the efficiency of the proposed method. (3) In dense traffic demand (1100 veh/h. lane or above), travel delay will decrease significantly when the market penetration of CVT is higher than 40%. To sum up, CVT is an effective technology to enhance the capacity and efficiency of highways.
In this study, connected vehicle environment means that there are not any communication packet drops and the communication delays are short enough to be ignored. In the future study, we will consider real wireless communication technology environment, in which communication delay, packet drop and interrupt may occur. Moreover, for real applications, we will pay attention to accident occurrences, such as crashes, mechanical failures, and so on. Therefore, how to organize traffic flow in abnormal traffic situation is another topic for the improvement of the proposed method. Finally, the case study is based on a two-lane highway; the proposed method in this paper should be tested in some other highways with three or more lanes.

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