Journal of World Architecture, 2024, Volume 8, Issue 6
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Optimization Control Method of Inbound Traffic Flow on On-ramp

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Abstract: This study aims to optimize the inbound traffic flow on on-ramps by considering low time costs, good speed stability, and high driving safety for mixed traffic flow. The optimal inlet gap is identified in advance, and trajectory guidance for vehicles entering the gap is determined under safety constraints. Based on the initial state and sequence of vehicles entering the merging area, individual vehicle trajectories are optimized sequentially. An optimization model and method for ramp entry trajectories in mixed traffic flow are developed, incorporating on-ramp vehicle entry sequencing and ordinary vehicle trajectory prediction. Key performance indicators, including driving safety, total travel time, parking wait probability, and trajectory smoothness, are compared and analyzed to evaluate the proposed approach.

Keywords: Traffic flow; Optimization control method; On-ramp vehicle

Online publication: December 31, 2024

1. Introduction

With the implementation of intelligent bicycle systems, highways and urban expressways exhibit characteristics such as fewer nodes, continuous traffic flow, and simplified path selection behavior. Additionally, the cost of roadside network connection equipment is relatively low, and many cities have initiated pilot studies in specific areas. Therefore, studying the laws of traffic flow and developing control measures under intelligent network-connected scenarios hold significant practical value. This represents a necessary stage in achieving coordinated traffic management from localized points to broader areas [1]. Intelligent collaborative control of continuous traffic flow on highways is influenced by factors such as traffic flow guidance, lane selection at entry points, and on-ramp merging and exiting. The networking and communication capabilities between vehicles enable collaborative control and optimization of the vehicle flow system.

Currently, research on connected vehicles primarily focuses on technical aspects such as vehicle-road communication, lateral trajectory control, traffic flow parameter characteristics in connected environments, driving behavior, and traffic flow feature extraction. However, from a management perspective, studies on travel behavior are mainly limited to operational rules and control methods for single road sections or individual intersections, resulting in a relatively narrow research scope. Building on existing research, this paper uses expressways as the research setting, focusing on regional traffic flow optimization and achieving collaborative management.

Traffic flow organization in ramp merging areas plays a crucial role in improving the traffic efficiency of both the main road and the ramp. The on-ramp vehicle optimization method involves signal control and optimization algorithms to organize the merging sequence and trajectories of on-ramp vehicles. By projecting on-ramp vehicles onto the main road, the required gap is calculated in advance, determining the merging point and time intervals for vehicles. A speed adjustment strategy is then proposed to ensure that on-ramp vehicles reach the merging point smoothly and complete the merging process seamlessly [2]. The longitudinal control of on-ramp vehicles was designed using a fuzzy controller. By adjusting the speed of on-ramp vehicles, the controller ensures they enter the main road smoothly and stably, thereby avoiding traffic congestion [3]. To ensure on-ramp vehicles enter the main road smoothly, vehicles on the main road can create appropriate gaps in advance by adjusting their speed through acceleration, deceleration, or lane changes. A novel merging strategy is proposed, leveraging the communication capabilities of intelligent vehicles [4].

In this method, the speed and trajectory of the connected vehicles on the main road are adjusted by the cooperation of the connected vehicles to generate a safe inbound gap, and the inbound trajectory of the on-ramp vehicles is calculated during the traffic time released by the traffic light. The collaborative optimization algorithm of on-ramp and trunk road vehicles can be further divided into optimal control and feedback control [5]. The objective of the optimal control is to optimize the parameters of the total passing time, average speed, acceleration, fuel consumption, and so on. A vehicle longitudinal trajectory optimization model was established to deal with maximizing energy efficiency and driving comfort and achieve optimal speed organization by minimizing the first and second derivatives of acceleration and speed [6]. Therefore, the on-ramp vehicle merging organization can be transformed into a vehicle following problems with safety and kinematics constraints.

This paper presents a collaborative optimization method for mixed flow at the on-ramp. The on-ramp driving rules and driving models of ordinary vehicles and connected vehicles are given respectively, and a speed guidance method to ensure the smooth entry of on-ramp vehicles is proposed, which realizes the safe and efficient entry of on-ramp vehicles under a connected environment. The ramp inlet optimization algorithm is based on the driving model to generate mixed traffic flow and plan the trajectories of the vehicles on the ramp one by one. Based on the principle of safe and efficient import, the import gap on the main road is sorted, and collaborative trajectory optimization is given to verify the import feasibility of alternative gaps. The uncertainty of the import point of each vehicle is considered in the model, and the import time breaks the first-in-first-out rule. The overall framework calculation method of on-ramp traffic import is constructed, which can be used for the centralized management of traffic flow under the intelligent network.

2. Ramp inbound optimization algorithm

The on-ramp inbound scenario considered in this paper includes an inlet on-ramp, on which there is a side road. The traffic flow on the main road and on-ramp is mixed, and the vehicle types include ordinary vehicles, single-car connected vehicles, and Cooperative Adaptive Cruise Control (CACC) vehicles in the fleet. On-ramp traffic merging is a process in which the vehicles on the on-ramp seek to merge into the gap or communicate with the vehicles on the main road to obtain a safety gap, to enter the main road before the end of the service road. For traditional roads and vehicles, the ramp merges into the distance and speed observations within the field of view to artificially adjust the speed and obtain a safe distance before entering. Due to the asynchronous decision-making and lack of communication, it is difficult to ensure that the vehicles do not experience delays, do not collide, and smoothly merge onto the main road.

(1) Step 1: The purpose of this step is to determine whether the current vehicle can successfully merge into the selected gap before reaching the end of the auxiliary lane, without requiring a speed adjustment. If the gap is suitable for the vehicle to merge without adjusting its speed, the vehicle's position at that moment must be precisely mapped to the gap on the main road, and the vehicle distance must meet safety requirements. Additionally, the vehicle is restricted to the auxiliary lane, and exiting is prohibited. Therefore, if the gap can be entered onto the main road without speed adjustment, the following constraints must be satisfied:

$$x_i(t') + h_s(t') \le x_j(t') < x_{i-1}(t') - h_s(t') \quad (1)$$

$$2 \times L_c < x_j(t') < 2 \times L_c + L_a \quad (2)$$

(2) Step 2: Based on the mapped position and spacing of vehicle j on the main road, it is further divided into the following subsets.

$$G_s(t) = \{G_{sf}(t), G_{sb}(t)\} \quad (3)$$

$$G_u(t) = \{G_{uf}(t), G_{ub}(t)\} \quad (4)$$

$$G_{sf}(t) = \{g_i(t) | g_i(t) > g_m(t) \& x_i(t) > x_j(t)\} \quad (5)$$

$$G_{sb}(t) = \{g_i(t) | g_i(t) > g_m(t) \& x_i(t) < x_j(t)\} \quad (6)$$

$$G_{uf}(t) = \{g_i(t) | g_i(t) \le g_m(t) \& x_i(t) > x_j(t)\} \quad (7)$$

$$G_{ub}(t) = \{g_i(t) | g_i(t) \le g_m(t) \& x_i(t) < x_j(t)\} \quad (8)$$

(3) Step 3: When none of the intervals within the detection area can be successfully entered without a speed adjustment, the algorithm will be activated to achieve the necessary conditions through coordinated speed adjustments between the main road and on-ramp vehicles. It will then publish details to the side unit, including the merge location, merge time, and speed. The basic idea is to verify the feasibility of each interval in order of distance. Once verified, the relevant main road vehicle i and ramp vehicle j will receive speed guidance, while other vehicles will maintain their natural behavior and follow.

3. Examples and analysis of results

The algorithm was experimentally validated in a highway scenario with on-ramps, as shown in **Figure 1**. To ensure generality, it is assumed that the traffic flow of drivers arriving at the entrance of the inbound area follows a Poisson distribution, with an average interval time of three seconds on the main road and five seconds on the on-ramp to generate random traffic flow. Specifically, if a steady flow has formed on the main road at the entrance of the ramp, it can be assumed that the vehicle interval on the main road is constant. In this experiment, vehicles are assumed to enter the road according to a Poisson flow from the detection point. The proportion of connected vehicles on the main road and on-ramp is set as =70% and =40% respectively. The distribution and arrangement of different models on the main road and on-ramps are randomly generated. The simulation duration is 120 seconds, and the time range is divided into 120 sections.

In the example, the trajectory and speed changes of the vehicle at the ramp inlet are shown in **Figure 1** and **Figure 2**. The horizontal axis indicates the travel time, the vertical axis indicates the location of the vehicle, and the main road and ramp are calculated from the monitoring point. A total of 72 vehicles entered, including 48 vehicles on the main road and 24 vehicles on the on-ramp. Among them, the red, blue, yellow, and green lines respectively represent the driving tracks of connected vehicles on the main road, ordinary vehicles on the main road, connected vehicles on the on-ramp, and ordinary vehicles on the on-ramp. In **Figure 1**, the trajectory line with a constant slope indicates a direct import process with no velocity change. Some vehicles on the main road must slow down to widen the gap and allow on-ramp vehicles to enter, such as some track lines with small amplitude track shocks.

Another phenomenon that oscillates even more strongly is that associated vehicles cooperate with other vehicles following an optimized trajectory, which is achieved by adjusting the speed of multiple vehicles in front of the speed. Additionally, in this example, no vehicles were observed stopping for inbound traffic, and none of the vehicles slowed to zero. Simultaneously, it can be seen that the rear vehicles join in advance and then move to the front, and the connected vehicles on the ramp (yellow curve) can merge with the main road-connected vehicles to form a team. **Figure 2** shows the speed change of vehicles. It can be observed that on the corresponding main road, connected vehicles and ordinary vehicles on the on-ramp, a small number of vehicles accelerate directly to a comfortable speed and then drive at a constant speed, and some vehicles need to adjust their speed but the changes are relatively gentle, with no instances of prolonged stopping or waiting.

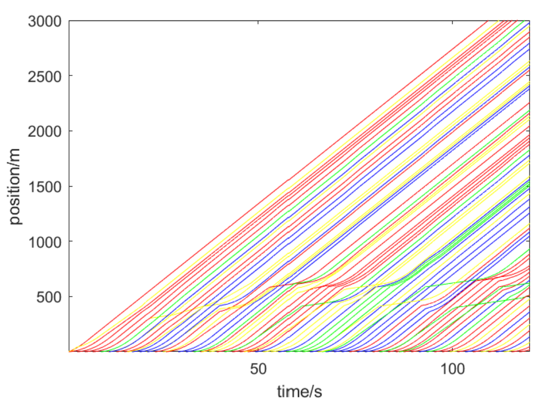

Figure 1. Vehicle track at ramp entry

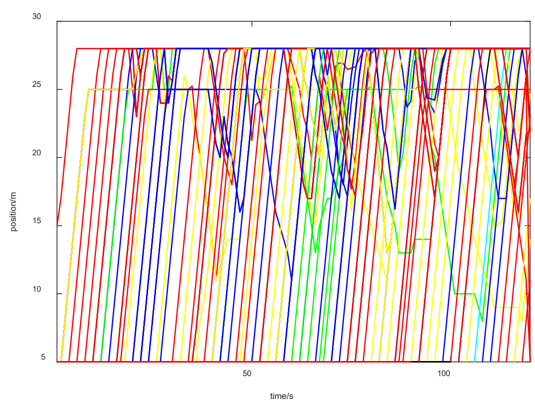

Figure 2. Vehicle speed at ramp entry

Figure 3 and **Figure 4** show the total capacity of the road network under different inbound traffic volumes of the main road and on-ramp. In the experiment, the number of driving hours is first converted to the average time between vehicles. As can be seen from **Figure 3**, in the case of low ramp flow (as shown on the left side of the figure), the total capacity on the main road increases rapidly with the increase in traffic. It can be seen that in this case, the impact of vehicles on the on-ramp on the main road is small, and the speed change of vehicles is also small. With the increase of ramp flow, the increase or decrease of capacity is slow and presents an irregular trend. Concurrently, the traffic flow of the main road is severely affected, and the merging of vehicles can lead to dramatic speed fluctuations and unsmoothness of the track. When the traffic flow of the main road increases to 1,800 veh/h, and the traffic flow of the on-ramp is 500 veh/h to 1,000 veh/h, the traffic capacity decreases due to the high traffic density and is accompanied by congestion. As shown in **Figure 4**, the total number of outgoing vehicles always increases with the increase of the number of incoming vehicles on the main road, and when the on-ramp traffic is large, the incremental rate gradually slows down. It shows that due to the high speed and driving priority on the main road, the main road flow is the key factor affecting the traffic capacity, and too much on-ramp flow will lead to congestion, speed deceleration, and traffic capacity reduction, and vice versa.

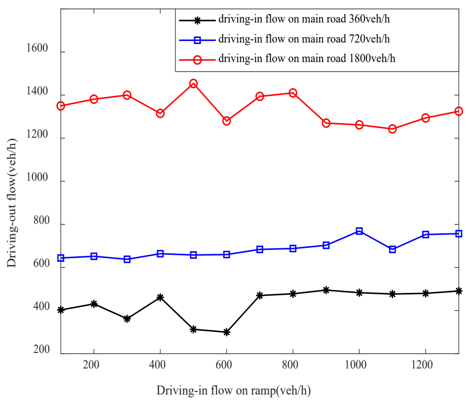

Figure 3. Impact analysis of ramp flow

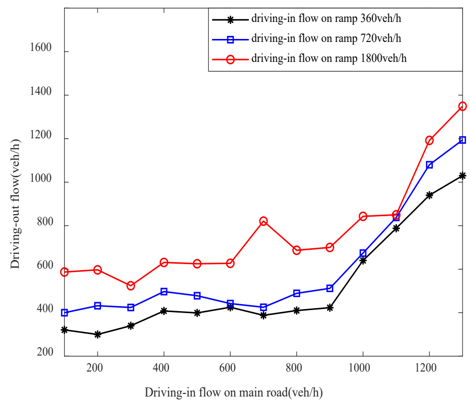

Figure 4. Impact analysis of main traffic

4. Conclusion

This paper presents a trajectory optimization algorithm for ramp entry of mixed traffic in a networked environment. Considering constraints such as vehicle safety distance, kinematic characteristics, and driving performance, Vehicle-to-Everything (V2X) communication is used to stabilize the speed of on-ramp inbound traffic and increase the total number of off-ramp vehicles. In the proposed method, the trajectories of connected vehicles are optimized based on the arrival order of on-ramp vehicles. The optimization plan for the vehicle in front is stored and used as input for the following vehicle, while the trajectory of ordinary vehicles is predicted using a driving model. For each vehicle, the process involves first identifying an appropriate gap and determining priority, then verifying the feasibility of the gap based on constraints and calculating the driving trajectory. The vehicle entry point in the algorithm is not fixed, and the entry time of the rear vehicle can be earlier than that of the front vehicle. Additionally, the rear vehicle is allowed to move ahead and become the leading vehicle once it merges into the main road. The model and algorithm are validated through numerical examples and comparative experiments. The results show that the method achieves relatively smooth vehicle trajectories, ensures safe distances, and improves entry efficiency. On-ramp vehicles are allowed to merge into the main road before reaching the auxiliary lane exit, avoiding stops and delays, while keeping speed fluctuations minimal.

Disclosure statement

The authors declare no conflict of interest.

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