Research on Vehicle Control Strategy at Weaving Area under Vehicle-Infrastructure Cooperative Environment

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Abstract. In this paper, the typical driving behavior of vehicles at urban road weaving area is studied and the causes of low safety and efficiency are analyzed. To improve traffic efficiency, the vehicle control strategy at weaving area is proposed through the vehicle-infrastructure cooperative technology. The simulation scenario is built in VISSIM, and the control strategy and input parameters are simulated and compared. The simulation results showed that the dangerous driving behaviors can be avoided such as forced parallel and emergency braking caused by the lack of proper driving decisions. The speed and passing rate at weaving area were obviously increased and the delay was obviously reduced. It is of great significance to improve traffic efficiency, ensure traffic safety and reduce energy consumption.

1. Introduction
Vehicle-Infrastructure Cooperative System is a safe, efficient and environmentally friendly transportation system, which adopts advanced wireless communication and new generation internet technologies. It implements all-round real-time dynamic information exchange among vehicles, vehicle-infrastructure and people-vehicle, and achieves effective collaboration between people, vehicles and infrastructure on the basis of collection and integration of full-time dynamic traffic information and guarantees traffic safety and improves traffic efficiency [1]. With the rapid development and application of the new generation of information and communication technology, vehicle-infrastructure cooperative system has become a hot research topic in the field of intelligent transportation. Internationally, CVIS in Europe, IVHS in the United States, Smart Way in Japan and other systems established effective information communication between vehicles and infrastructure to achieve intelligent transportation management and information services [2]. Road weaving area is one of the most common complex traffic scenarios, which has poor speed stability and is prone to a large number of traffic conflicts leading to traffic accidents. In 2007, Hyoungsoo Kim studied the application of Ad Hoc Network in the confluence area [3]. In 2009, Hyungjun Park studied a solution to the conflict at the weaving area of the highway [4], which made the vehicles on the main road change lanes to the left in advance, provided more traversable gap for the vehicles coming from the ramp. Vehicles total running time reduced by 4.6%, and average velocity increased by 9.3%.

With the continuous breakthroughs in key technologies of C-V2X, the problems of delay, false alarm, missing packet, shielding and transmission mode in the information interaction process are gradually solved. In order to cope with the autonomous vehicles safely and efficiently through the weaving area, this paper studied the control strategy of autonomous vehicles at weaving area based on vehicle-infrastructure cooperative system. Through the analysis of driving behaviors in typical scenarios, the factors that affect the efficiency and safety of operation were found and a reasonable and
effective control method was proposed. In order to improve the operation efficiency of the weaving area and reduce traffic conflicts, the suggestions on lane change, acceleration or deceleration were provided to the vehicles at weaving area timely and appropriately.

2. Analysis of driving behaviors at weaving area

Weaving area refers to the road with two or more traffic flow sections in the same driving direction. The weaving area can be divided into confluence area, lane change area and diversion area without the aid of other traffic control facilities [5], as shown in figure 1. Usually the length of general weaving areas is less than 750 meters and greater than 110 meters. When the length is short, the driver often does not have enough time to complete the whole process from foresight, perception, seeing, deciding action, starting action to completing action [6]. Therefore, it is necessary to provide timely and necessary route guidance for vehicles going in all directions at weaving area.

![Figure 1. Structure map of urban road weaving area](image)

Video acquisition and analysis of vehicle behaviors at weaving area shows that the proportion of normal driving, deceleration driving, left parallel, right parallel and continuous right parallel is 14%, 17%, 11%, 49% and 9% respectively. Nearly half of the traffic on the main road paralleled to the right. The main driving behaviors of on-ramp vehicles are divided into eight categories: non-parallel, uniform driving, accelerated merge, decelerated merge, left-to-right decelerated merge, stopping merge, forced parallel, and continuous left parallel, and the proportion is 13%, 8%, 6%, 46%, 3%, 4%, 5% and 15% respectively. Nearly half of the vehicles slowed down and drove into the main road.

![Figure 2. Analysis of driving behaviors in urban weaving areas](image)

The above results show that the special driving behaviors of vehicles at weaving area reduce the traffic efficiency and safety compared with the normal road. At weaving areas, the following vehicles search for the appropriate traversable gap in the traffic flow of adjacent lanes while driving. There is a large distance to follow the car, and usually the car slowed down to wait for the gap to cross [7]. Non-following vehicles want to increase the speed as much as possible, narrow the space, and reduce the interference of vehicles. Therefore, it is a problem to eliminate weaving interference for the vehicle-infrastructure cooperative control strategy. At weaving area lane change behavior must be completed within a limited distance. If there is not suitable traversable gap during driving at the weaving area, forced parallel, stopping parallel and accelerating parallel will occur [8]. Therefore, trying to solve the unsafe merging behavior of main road vehicles and on-ramp vehicles is another problem.
3. Control strategy and evaluation index in weaving area

The control strategy of weaving area is to control the speed and space of vehicles by means of vehicle-infrastructure interaction communication, with the control of vehicle longitudinal driving behavior as the main part and the control strategy of lane-changing as the supplement [9]. This paper studies the control of main road vehicle platoon in confluence area and the import control of single on-ramp vehicle to improve the operational efficiency of road resources through the cooperative control of the main road and on-ramp.

The traffic scenario at weaving area is shown in figure 1. The main road is the urban expressway, and the on-ramp vehicles come from the interchange. There are 3 lanes on the main road and 1 lane on the ramp. Some of the vehicles on the main road leave the exit while some of the vehicles on ramp converge into the main road, or some of them leave the exit. Seven detection sections are set up in this scenario. Section 1 is in the upstream area of the main road, 1000 meters away from the confluence point. At this section, the traffic path of each lanes of the main road is adjusted to eliminate the influence of continuous parallel, sudden parallel and forced parallel at weaving area. Section 2 is located in the proximity area of the main road, 500 meters away from the confluence point. It detects the state of vehicles on the main road, and adjusts the space to form a platoon and enlarge the gap. Section 3 is the main road confluence section. Vehicles on the driveway of the main road drive in platoon at this section and the traffic on ramp remitted. Section 4 is located in the vicinity of the ramp, 100 meters away from the confluence point. This section detects the state of the ramp vehicles, sends the inward demand to the main road vehicle, and adjusts the speed according to the gap. Section 5 is located at the ramp confluence section, and vehicles on the ramp car are preferred. Section 6 is a vehicle information detection section for main road and weaving area vehicles, located 200 meters downstream of confluence point. Section 7 is the exit section of main road vehicles and weaving area vehicles, located 200 meters downstream of confluence point.

Figure 3. Diagram of vehicle-infrastructure cooperative information Interaction

Figure 4. Flow chart of main road driving control
3.1 Confluence area control strategy

Under the vehicle-infrastructure cooperative environment, it is assumed that the roadside units can collect the information of the identity, speed, location and destination of all vehicles passing through the cross-section, and exchange information. Through the background control operation, the roadside units send the speed adjustment and lane adjustment suggestions to the target vehicles.

3.1.1 Main Road Driving Control Strategy

Step 1: On the basic section of the weaving area shown in figure 1, the roadside unit of the main road collects the status information of vehicle \( i \) \( f(i) = \{ ID, v, n, x, y, des \} \) at section 1, representing the identity number, speed, Lane number, abscissa, ordinate and destination of vehicle \( i \) respectively. Destination =1, far away; Destination =2, the next exit; Destination =3, this exit.

Step 2: According to the status of \( Des \) at destination and the lane of vehicle location, it judge whether the vehicle needs to change lane or not.

Step 3: Decision output. Output each vehicle operation suggestion function \( o(i) = \{ ID, \text{nc}, \text{nl}, nr \} \), respectively, representing the vehicle \( i \) identity number, target lane number, the number of changes to the left or right.

Step 4: Send the operation suggestion to the display terminal of vehicle \( i \) through the control platform, and the vehicle will carry out the operation.

3.1.2 Main road platoon control strategy

Step 1: Gather information. In section 2, the roadside unit of the main road collects the status information \( g(i) = \{ ID, v, a, x, y, des \} \) of vehicle \( i \) in lane 3, representing identity number, vehicle speed, acceleration, abscissa, ordinate and destination respectively. At the same time, the on-ramp road side unit at section 4 collects the state information of vehicle \( j \) in lane \( 4 \) \( g(j) = \{ ID, v, a, x, y, des \} \).

Step 2: Main road vehicle group in platoon. It is judged whether the distance \( d_{i+1} \) between vehicle \( i \) and front vehicle in main road lane 3 is larger than the distance threshold. If it is larger, vehicle \( i \) will be the head of the next group of platoon. If it is less than or equal to the distance threshold, the vehicle will catch up with front vehicle until the distance between this vehicle and front vehicle is less than the distance threshold within the group.

Step 3: Main road vehicle yield. The time when the rear of the main road platoon passes through the confluence point and the time when the ramp vehicle arrives at the confluence point without changing the speed are calculated. If the ramp vehicle arrives first, the ramp vehicle passes through the confluence point first; if the main road platoon passes first, the speed of the ramp car arriving at the confluence point before the main road platoon is calculated.

Step 4: Decision output. Output main road vehicle and ramp vehicle suggested function. \( ID, v, v_{r+1} \) respectively represents vehicle number, current velocity and target velocity.

Step 5: Send the operation suggestion to the display terminal of vehicle \( i \) through the control platform, and the vehicle will carry out the operation.

When the distance between the vehicle on the main road and the front vehicle is larger than the threshold of platoon distance, it is considered that the vehicle is not restricted by the front vehicle and is in a state of free running. The speed and acceleration are calculated according to formula 1[10].

\[
\begin{align*}
    a_j &= \begin{cases} 
    \min \left\{ a, a_{\text{max}} \left[ 1 - \left( \frac{V}{V_{\text{exp}}} \right)^2 \right] \right\} (V_{\exp} > V) \\
    \min \left\{ a, a_{\text{min}} \left[ 1 - \left( \frac{V}{V_{\exp}} \right)^2 \right] \right\} (V_{\exp} \leq V) 
    \end{cases} 
\end{align*}
\]

In formula 1: \( a \) is acceleration for free driving,
\( a \) is acceleration for the current state,
\( a_{\text{max}}, a_{\text{min}} \) is maximum acceleration and deceleration of the vehicle,
The current speed of the vehicle, $V$, is the expected speed of the vehicle, $V_{exp}$.

Section 2 Vehicle information collection
- Vehicle number, velocity, longitude and latitude, destination, Lane number

Step 1: Information collection
- Roadside unit

Step 2: Decision making
- The distance between main road vehicle and front vehicle is larger than threshold?
  - Y: as head car
  - N: Accelerate to a distance less than the threshold

Step 3: Main road vehicle yielding
- The distance between vehicle and vehicle is less than the threshold?
  - Y: Platoon completed
  - N: Calculate the time for the rear of the platoon to pass the confluence point

Step 4: Decision output
- Output operation suggestion
  - Target lane number, lane change direction and times

Step 5: Control execution
- Steering control and velocity control

Section 4 Vehicle information collection
- Vehicle number, velocity, longitude and latitude, destination, Lane number

Calculate the time of ramp passing the confluence point

Is it longer than the time for the main road vehicles to pass the confluence point?
- Y: Calculate the time required for the ramp car to pass before the platoon
- N: Output operation suggestion
  - Target lane number, lane change direction and times
  - Steering control and velocity control, information broadcasting

The calculation of acceleration and speed of the rear car when the main road forms a motorcade is based on the KFTM model [11] proposed by Tanveer.

\[
v_i(t + \tau) = \min \left[ v_i(t + \tau) \right]
\]
(2)

\[
v_{h, i}(t + \tau) = \max \left[ 0, \min \left( v_{i, i}(t), v_{i, i}^{\text{off}}(t) \right) \right]
\]
(3)

\[
p = 2\left( x_{i, i}(t) - x_i(t) - l \right) - v_i(t)\Delta t - \frac{v_i(t)^2}{b}
\]
(4)

Figure 5. Flow chart of Main road platoon control strategy
\begin{equation}
v_{i+1,t}(t) = v_i(t) + A \Delta t \left[ 1 - \left( \frac{v_i(t)}{V} \right)^4 - \left( \frac{v_i(t) - v_{i-1,t}(t)}{V_{i-1,t}} \right)^2 \right] \end{equation}

\begin{equation}
q = \sqrt{b^2(\Delta t)^2 - bp} 
\end{equation}

\begin{equation}
v_{i,j-1}^{\text{safe}}(t) = \begin{cases} 
b \Delta t + q & (q \geq 0) \\
b \Delta t + v_j(t) & (q > 0) 
\end{cases} 
\end{equation}

\begin{equation}
s_{i,j-1}^{\text{des}}(t) = s_0, \max \left[ 0, v_i(t)T + \frac{v_i(t)\{v_i(t) - v_{i+1,t}(t)\}}{2\sqrt{AB}} \right] (i - j) 
\end{equation}

$s_{i,j-1}^{\text{des}}(t)$ represents the desired distance between the $i$ and $i-1$ vehicles. $v_{i,j-1}^{\text{safe}}(t)$ is the velocity when the distance between the front vehicle $i-1$ and the rear vehicle $i$ is greater than the safe distance. $v_{i,j-1}(t)$ is the velocity when the distance between the front vehicle $i-1$ and the rear vehicle $i$ is less than the safe distance.

After the formation of the main road platoon, the time to reach the confluence point is calculated as follows. Distance is set at 500 meters in the scenario.

\begin{equation}
t_i = \frac{500}{v_i(t)} 
\end{equation}

If the ramp vehicle velocity remains, the time to reach the confluence point is calculated as follows. The distance from the ramp detection point to the confluence point is 100 meters in the scenario.

\begin{equation}
t_j = \frac{100}{v_j(t)} 
\end{equation}

3.2 Control strategy at weaving area

The control strategy needs to solve the unsafe parallel behavior of main road vehicles and ramp vehicles at weaving area. It is to subdivide the upstream vehicles on the main road and guide them to different lanes according to different destinations. Vehicles in the outermost lane of the main road form a platoon, so that the ramp vehicles can import into the main road. Then the ramp vehicles destined for the exit form a platoon, and some of the main road vehicles drive out at this exit.

Step 1: Gather information. In section 6, the roadside unit of the main road collects the status information $g(i) = \{ID,v,a,x,y,des\}$ of vehicle $i$ in lane 3, representing identity number, vehicle speed, acceleration, abscissa, ordinate and destination respectively. At the same time, the roadside unit of the main road at section 6 collects the state information of vehicle $j$ in lane 4 $g(j) = \{ID,v,a,x,y,des\}$.

Step 2: Main road vehicle group in platoon. It is judged whether the distance $d_{i,j-1}$ between vehicle $i$ and front vehicle in lane 4 is larger than the distance threshold. If it is larger, vehicle $i$ will be the head of next platoon. If it is less than or equal to the distance threshold, the vehicle will catch up with front vehicle until the distance between vehicle and front vehicle is less than the distance threshold.

Step 3: Ramp vehicle. At this time, the vehicles in lane 3 of the main road still run in platoon. The time when the rear of platoon in lane 4 passes through the confluence point and the time when the platoon in main road lane 3 leaves to reach the confluence point without changing the speed are calculated. If the main road out of the team first arrives, the main road vehicles pass the junction first. If the ramp platoon passes first, it needs to calculate the speed of the main road platoon driving out of the area before the ramp platoon arrives at the junction.

Step 4: Decision output. Output the suggested function $a(i) = \{ID,v_i,v_{i+1}\}$ of interleaving vehicles and outgoing vehicles. $ID, v_i, v_{i+1}$ represents vehicle number, current velocity and target velocity.

Step 5: Send the operation suggestion to the display terminal of vehicle $i$ through the control platform, and the vehicle will carry out the operation.
3.3 The evaluation index

The evaluation based on vehicle-infrastructure cooperation system is mainly divided into three aspects: safety, efficiency and energy consumption. Subdivided indicators involve vehicle spacing, velocity, queue length, waiting time, acceleration or deceleration, delay, pass rate, traffic volume, mileage, travelling time, number of conflicts, braking distance, number of congestion waves and energy consumption emission and so on.

3.3.1 Efficiency evaluation index

Traffic flow $Q(t)$ is the average traffic flow through the section at $t$ time. When the traffic volume in time $\Delta t$ is $n$, $Q(t)$ is calculated as follows.

![Figure 6. Flow chart of Control strategy in weaving area](image-url)
Travel velocity, also known as interval velocity, is the ratio of the vehicle's travel distance to the total time required to pass the distance, including parking time. It reflects the velocity of the main road and ramp, which is used to evaluate the degree of road smoothness and estimate the traffic delay.

\[
Q(t) = \frac{n}{\Delta t}
\]

(11)

Delay. Vehicles are blocked and need to queue up for release. The total delay time is the sum of the delay time of m vehicles.

\[
d = \sum_{i=1}^{m} t_i
\]

(13)

3.3.2 Safety Evaluation Index

Velocity difference. The velocity difference between the front vehicle and the rear vehicle is \(\Delta v_i = v_i - v_{i-1}\). Velocity difference reflects the stability of the vehicle and can reflect the degree of safety to a certain extent. The average velocity difference can be calculated as follows[8].

\[
\overline{\Delta v} = \frac{1}{n} \sum_{i=1}^{n} \Delta v_i
\]

(14)

Vehicle-following distance. The distance difference between the car in front and the car behind is \(\Delta d_i = d_i - d_{i-1}\). The following distance also reflects the stability of the vehicle and can reflect the degree of safety to a certain extent. The average car-following distance can be calculated as follows.

\[
\overline{D} = \frac{1}{n} \sum_{i=1}^{n} d_i
\]

(15)

Stopping times. Stopping behavior occurs because of accidents or traffic capacity exceeding. Stopping causes queues, delays and congestion waves.

3.3.3 Energy Consumption Evaluation Index

Energy consumption, also known as emissions, fuel economy or driving costs. Velocity changing as smoothly as possible can reduce emissions. The fuel consumption is calculated by a method of instantaneous fuel consumption of light vehicle, _EMIT_[12]. The calculation formula is as follows.

\[
FR = \begin{cases} 
\alpha + \beta v + \gamma v^2 + \delta v^3 + \zeta v^4 & P_{\text{net}}>0 \\
\alpha & P_{\text{net}}=0
\end{cases}
\]

(16)

\(FR\), \(V\), \(a\), \(P_{\text{tract}}\) are fuel consumption rate, speed, acceleration, total traction power. Gasoline density is 0.73722g/ml at 15.56 °C.

| Table 1. Main Parameters for Fuel Consumption Calculation |
|-----------------------------------------------|-------------------------------|----------------|-------|
| parameters                        | values                        | parameters         | values |
| Rolling resistance \(A\)            | 0.1326 kW/(m/s)               | coefficient \(\alpha\) | 0.365  |
| Rolling resistance velocity correction \(B\) | 2.7384 e-3 kW/(m/s)^2        | coefficient \(\beta\) | 0.00114|
| Air resistance \(C\)                | 1.0843 e-3 kW/(m/s)^3        | coefficient \(\gamma\) | 0     |
| Gravity acceleration \(g\)         | 9.8m/s^2                      | coefficient \(\delta\) | 9.65e-7|
| ramp angle \(\theta\)              | 0°                             | coefficient \(\zeta\) | 0.0943 |
|                                 |                                | coefficient \(a\)   | 0.299  |
4. Simulation scenario building and analysis

4.1 Simulation scenario building

In this study, VISSIM basic model, COM component object model and EDM external driver model were selected for secondary development to realize the simulation of Internet of vehicles and automatic driving technology. Specific functions include: vehicle formation, automatic driving, road communication. The communication module can realize information exchange, and extract the vehicle's identity information, speed, acceleration, position, time, destination and other information from time to time. It can also control and track the vehicle's horizontal behaviors such as upstream lane change, parallel alignment of the main road allowed, and longitudinal behaviors such as team formation and vehicle acceleration. The simulation system consists of four parts: parameter input, VISSIM Simulation scenario, control strategy secondary development and parameter output.

The expected speed of the main road lane and lane 2 is defined as 80km/h, the expected speed of lane 3 is defined as 60km/h, and the expected speed of the weaving area is defined as 50km/h. Wiedemann 99 psycho-physical car following model was selected. The expected distance is 15.2m, the reaction time is 3s, and the expected acceleration is 2.5m/s². The forward apparent distance is 250m, and the rear apparent distance is 150m. Lane transformation model selects free transformation. The maximum deceleration is -3 m/s².

4.2 Simulation analysis

4.2.1 Effect of control strategy on main road at weaving area

This section evaluates the average speed, delay, queuing and stopping times before and after the implementation of the control strategy. The upstream lane-splitting control strategy aims at solving the situation that the car-following behavior of the main road is affected by interlacing and changing lines. It is the main evaluation direction to improve the traffic volume, speed, reduce queue length and time, and reduce the traffic time of the main road. The main road platoon concession control strategy aims at solving the problem of queuing and long waiting time when ramp vehicles converge into the main road, focusing on the velocity of the main road platoon.
Average velocity. In the main road of weaving area, the velocity changes before and after the control strategy are shown in figure 8. The main road input traffic volume is 3000 vehicles/h, the ramp input traffic volume is 600 vehicles/h, and the simulation time is 3600 seconds. The average velocity of the main road raised from 16.67 km/h to 27.48 km/h, increasing by 64.8%. After the change of upstream lane, the traffic disturbance of vehicles destined for this exit to the three lanes of the main road is reduced and the average velocity is significantly increased. For the weaving lane, the change in velocity of vehicles at the destination is shown in figure 9 before and after the control strategy. The average velocity raised from 16.9km/h to 19.86km/h, increasing by 17.8%.

Figure 10. Average delay of main road in weaving section

Figure 11. Average delay of interlaced lanes

Delay time. The change of delay at main road of weaving area before and after the control strategy is shown in figure 10. The average delay of main road at weaving area is reduced from 299s to 110s, decreasing by 63.1%. For the weaving lane, the change of delay before and after the control strategy is shown in figure 11. The average delay of weaving lane is reduced from 169s to 25s, decreasing by 85%. The effect is remarkable.

Traffic volume. The traffic volume changes at main road of weaving area before and after the control strategy are shown in figure 12. The main road volume at weaving area raised from 56.5 to 75.4, increasing by 33.5%. The control strategy guides the main road out of the rear section of the weaving area and the weaving lane volume decreases, as shown in figure 13. The traffic volume of weaving lane reduced from 21.4 to 14.4, decreasing by 32.8%.

4.2.2 Effect of Control Strategy on ramp
Average velocity. The main road platoon control strategy aims to provide more gap for the ramp vehicle importing into the main road, so that the ramp vehicles can merge smoothly and quickly. Figure 14 shows the velocity change of ramp vehicles before and after the implementation of the control strategy. The average velocity raised from 29.9 km/h to 48.2 km/h, increasing by 61%.

Delay time. Figure 15 shows the delay change of ramp vehicles before and after the implementation of the control strategy. The average delay changed from 3.24s to 0.25s, decreasing by 92%. The reason for the short delay is that the traffic volume of on-ramp vehicles is small.
Passing volume. Figure 16 shows the change of on-ramp vehicle volume before and after the implementation of the control strategy. The average number of vehicles passing in 100s changed from 16 to 18.8, an increase of 17%.

Stopping times. Figure 17 shows the stopping times of on-ramp vehicles before and after the implementation of the control strategy. The number of stopped vehicles decreased by 41% from 7.71 to 4.5 in 100s.

4.2.3 Effect of control strategy on energy consumption
The instantaneous energy consumption is directly related to the change of vehicle speed and acceleration. The instantaneous fuel consumption distribution of the main road and on-ramp at weaving area calculated by velocity and acceleration is shown in figure 18 and figure 19. The average instantaneous fuel consumption of main road vehicles changed from 0.47g/s to 0.40g/s, which decreased by 14.9%. The average instantaneous fuel consumption of on-ramp vehicles changed from 2.67 g/s to 0.76 g/s, which decreased by 71.5%. The control strategy can effectively reduce fuel consumption and emissions.

5. Conclusion
In this paper, vehicle control strategy under vehicle-infrastructure environment is proposed to solve the interference of main road upstream interleaving, weaving area lane changing and ramp confluence by
studying the driving behavior at urban road weaving area. Based on the logical rules and algorithms, the simulation scenario of vehicle-infrastructure cooperative and auto-driving was established, which realized vehicle lane allocation, vehicle platoon, vehicle-infrastructure communication and vehicle-vehicle communication. On the basis of simulation scenarios, the operation status of the weaving area before and after the implementation of the control strategy is compared and analyzed. After the implementation of the strategy, the velocity was significantly improved and the delay was significantly reduced, and the traffic volume increased except for the reduction of weaving lane traffic.

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