The merging control method of on-ramp vehicles based on cooperative vehicle infrastructure system for highway entering ramp

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Abstract. As one of the most important part of the modern comprehensive transportation system, highway plays a critical role in national traffic system, which bears the most of traffic load. Whereas, ramp areas may become bottleneck areas of highway if the control is inappropriate or ineffective. The cooperative vehicle infrastructure system (CVIS) brings great opportunities for ramp control to address many tricky problems, among which the merging control of on-ramp vehicles is one of the most prominent problem related to traffic efficiency and safety. In this paper, we apply the technology of cooperative vehicle infrastructure control in the highway ramp area to enhance the traffic efficiency and safety, and propose a merging control method for on-ramp vehicles. At last, a simulation is conducted to evaluate this control method.

1. Introduction
Highway is a sign of the modernization transportation, which promotes the development of many modern industries, such as automobile industry and civil engineering industry, and has a profound and extensive impact on the modern socio-economic development and urban layout. Since highway occupies an extremely important position in the modern transportation system, it has been paid much attention to traffic construction and planning and become the measure of a country economic development and an indicator of the degree of modernization.

In past years, highway construction has experienced a rapid development period in China, by the end of 2018, there are 14.3 million kilometers highway, and it has reached the first place in the world. Even so, the pressure of transportation for highway remains at large due to the speed of highway construction falls behind the rapid growth of passenger and cargo traffic demand. Moreover, there are still many problems in highway control and management. As an important part of highway, ramp area often becomes a bottleneck place leading to traffic efficiency dropping and high frequency traffic accident where ramp vehicles merge in and bear off main lane, which further exacerbates the contradiction between the traffic demand and highway capacity. Thereby, seeking the effective control and management method for highway to solve traffic problems in ramp area becomes an important urgent problem.

However, there is no effective control in the ramp area in China yet. Although there are a lot of researches for ramp control in western developed countries, these researches and implications mainly focus on the control of traffic entering the highway from ramp on the macro level[1-5], however, the researches about merging control in ramp area from a relative microscopic aspect are insufficient. A critical reason for this research gap is that the merging control of on-ramp vehicles must rely on the real-
time and detailed information about the traffic condition in the ramp area, apparently, it is impossible just based on traditional roadside-based detector system and communication technologies. Fortunately, the recently developed technology of cooperative vehicle infrastructure system (CVIS) provides a new opportunity to fill this research gap[6].

The CVIS can obtain detailed information of vehicles and traffic on the road by using many technologies, such as information processing, communication, location, electronic sensor, artificial intelligence and etc[7]. Active safety control of vehicles and cooperative control of road traffic operation can be easily realized based on the dynamic whole space-time traffic information to improve traffic efficiency and safety[8-11]. According to this, in this paper, we propose a merging control method for ramp vehicles to improve the traffic efficiency under the prerequisite of guaranteeing safety, in which these on-ramp vehicles are given advisory speed according to traffic condition in the ramp area.

2. Methodology

2.1. Vehicle merging process in ramp area

Above all, we should analyze the merging process of a ramp vehicle in the ordinary way. The structure of a general ramp area is shown in figure 1, where the ramp has two parts, one is the guidance region (or separation region), and another part is the transition region whose length is \(x_{acc}\). The ramp vehicles start to move (the initial speed is equal to zero) from the location of signal at the zero time and then enter the control area. After that, they drive into the main lane from the guidance ramp (i.e., control area in figure 1), then accelerate in the transition region to match the speed of traffic flow in the main lane, and finally move into the main lane at the end of acceleration area, denoted by \(E\).

It is generally known that the main task of highway transportation is undertaken by the main lane, so one principle must be insisted that vehicles on the main lane have the higher priority than these vehicles on the ramp. This requires that on-ramp vehicles must merge into the main lane during a suitable time through control without affecting the normal driving vehicles on the main lane. In this paper, the speed control for ramp vehicles only happens during the control area with a length of \(l\) as denoted by the light red area in figure 1. Additionally, only a certain number of vehicles are permitted to enter the ramp if there are already too many vehicles on the ramp.

2.1. Merging control for ramp vehicles

According to the analysis above, a ramp vehicle should keep a gap acceptance from the normally driving vehicle behind, simultaneously, a suitable distance from the vehicle before so as not to be affected when it merges into the main lane. We assume that the traffic and average speed of vehicles on the main lane are \(q\) and \(v_m\), and then the distance headway \(D\) can be expressed as equation (1), which can be taken as the minimum distance acceptable.

\[
D = \frac{1}{k} = \frac{v_m}{q}
\]
The ramp vehicle (denoted by \( V_0 \) in the following) starts to enter the ramp area at time \( t = 0 \), and the initial distance between vehicle \( n \) on the main lane and the location of \( E \) is \( x_{ni} \). The time taken for \( V_0 \) to merge into the main lane can be calculated by equation (2). We assume that \( V_0 \) would merge into the main lane in the quickest way if it is not controlled, which can be seen in figure 2. This means that it would accelerate to the limit speed of ramp \( v^r \) and drive at this speed on the ramp, then it speeds up again to match the normal traffic speed after reaching the acceleration area. Therefore the shortest time for merging can be derived by equation (3), where \( a \) represents the acceleration of vehicle. During this period of time, the travelling distance of vehicle \( n \) can be expressed by \( v_{mt} \). At the time \( t = t_{min} \), the vehicle \( n \) would be in front of \( V_0 \) if \( v_{mt} > x_{ni} \), called \( V_1 \); otherwise, behind it, called \( V_2 \).

\[
t = f(v) = \frac{v}{2a} + \frac{l}{v} + \frac{(v^n - v)^2}{2av^n} + \frac{x_{acc}}{v^n}
\]

\[
t_{min} = f'(v')
\]

For a ramp vehicle without speed control, there are three cases according to the traffic condition on the main lane as follows: I. there is no vehicle before and behind; II. there is no vehicle behind; III. there is no vehicle before. Apparently, there is no need to conduct control for \( V_0 \) in case I, then what we really care about is the remaining cases.

For case II as shown in figure 3, the distance \( x_1 \) between the location of \( E \) and \( V_1 \) is equal to \( v_{mt} - x_1 \) at \( t = t_{min} \). As mentioned above, there is no influence on \( V_0 \) from \( V_1 \) if \( v_{mt} - x_1 > D \), and speed control is only necessary when \( v_{mt} - x_1 < D \). Given \( x_1 = v_{mt} - x_1 \), increasing the value of \( t \) from \( t_{min} \) would be the simplest way to enlarge \( x_1 \). That is to say, in this case, \( V_0 \) should reach the location of \( E \) later to acquire an acceptance distance from \( V_1 \) which equals to \( D \) at least (i.e., \( x_1 \geq D \)). Then now the control object is the required retardation time \( \Delta t \), which can be obtained by equation (4).

\[
\Delta t = \frac{D - (v_{mt} - x_1)}{v^n}
\]

Obviously, this control object can only be realized by controlling the speed of \( V_0 \), then we need to find the relation between \( \Delta t \) and the target speed of \( V_0 \), denoted by \( v' \) as shown in figure 2. According to the function of \( t \) and \( v \) shown in equation (2), we can easily get the differential relation expressed as equation (5) by using the full differential formula, then we have the relation between \( \Delta t \) and \( \Delta v \) based on the geometrical meaning of differential expressed by formula (6), where \( \Delta v = v' - v' \). Finally, the target control speed can be obtained by equation (7).

\[
dt = df(v) = \left( \frac{v}{av^n} - \frac{l}{2v'^2} - \frac{1}{2a} \right)dv
\]

\[
\Delta t \approx \left( \frac{v'}{av^n} - \frac{l}{2v'^2} - \frac{1}{2a} \right) \Delta v
\]

\[
v' = v' - \Delta t \left( \frac{v'}{av^n} - \frac{l}{2v'^2} - \frac{1}{2a} \right)^{-1}
\]
For case III as shown in figure 4, there is no need to conduct speed control for \( V_0 \) if \( x_2 > D \), which is similar to case II. What differs from case II is \( x_2 \), the distance between location of \( E \) and \( V_2 \), which is equal to \( x_2^i - v^w t_{\text{min}} \) here. Besides, in this case, \( V_0 \) is no longer the one being affected but as the one exerting influence if \( x_2 < D \). As discussed above, this influence is not permitted in this paper. We should also adjust the value of \( t \) by speed control to enlarge \( x_2 \). However, the value of \( t \) cannot be reduced further from \( t_{\text{min}} \) in this case, meaning that the target control speed is not allowed larger than \( v^r \). In this case, a longer retardation time \( \Delta t \) is needed to acquire a sufficient distance separation in front of \( V_0 \), which is determined by equation (8). Then we can get the target control speed by equation (7) similarly.

\[
\Delta t = \frac{D + (x_2^i - v^w t_{\text{min}})}{v^w}
\]

(8)

Through the analysis above, we can find that the segment of main lane with distance from the location of \( E \) falling in the interval of \( [x_{\text{max}}, x_{\text{min}}] \) is the region of interest (ROI) in the process of merging control as shown in figure 5, where \( x_{\text{min}} = v^w t_{\text{min}} - D \) and \( x_{\text{max}} = v^w t_{\text{min}} + D \). Thereby, only these vehicles satisfying the condition (9) at \( t = 0 \) are related to the merging control. Besides, it should be noted that the formula (6) is workable only with the necessary condition \( \Delta v \to 0 \), or that the curve of \( f(v) \) is approximately linear. Figure 6 shows the graph of function of \( f(v) \), from which we can find that the relation between \( t \) and \( v \) is approximately linear when the value of \( v \) is in the interval of (8 m/s, 30 m/s). In general case, the speed of ramp vehicles ranges from 30 km/h (8.3 m/s) to 60 km/h (16.7 m/s). Therefore, we can confirmed that the proposed control method in this paper is reasonable theoretically.

\[
v^w t_{\text{min}} - D \leq x_n^i \leq v^w t_{\text{min}} + D
\]

(9)
3. Evaluation of the control method

3.1. Simulation environment
A simulation environment is developed by AnyLogic to illustrate the effectiveness of the proposed merging control method in this paper as shown in figure 7. Additionally, the main parameters used in this simulation environment are listed in table 1. AnyLogic is the leading simulation software for business, utilized worldwide in many industries, such as logistics, manufacturing, mining, healthcare, etc. AnyLogic is a multi-method simulation tool, meaning that developers can choose the suitable system modeling methods to build their models, including agent-based method, discrete event-based method and system dynamics method.

For the purpose of comparison, a button is set to make the switchover between on and off of merging control, and the simulation data is collected by the dataset plug-in unit during the process of simulation and exported to Excel files at the end of the simulation. We conduct the simulation experiments with or without merging control respectively, and the corresponding results are collected for analysis.

Figure 6. The graph of function \( t = f(v) \).

Figure 7. Simulation environment developed by AnyLogic.
Table 1. Main parameters of the simulation environment.

| Parameters | value |
|------------|-------|
| $l$        | 180 m |
| $x_{acc}$  | 125 m |
| $a$        | 2 m/s² |
| $v^m$      | 100 km/h |
| $v^r$      | 60 km/h |
| $q$        | 800 veh/h |

3.2. Analysis of results

Since the desirable object of the merging control is to make sure that the traffic flow on the main lane is not affected by the merging vehicles from the ramp. Thereby, the evaluation parameter should be characterization parameters of traffic flow on the main lane. In this paper, we use average speed and travel time of vehicles on the main lane to evaluate the effectiveness of the merging control method.

Figure 8 shows the changing of the average speed of vehicles on the main lane. We can find that the average speed with merging control is generally higher than that without control although it fluctuates in the process of simulation due to various reasons, such as uncertainty of vehicle arrival, fluctuation of vehicle speed and etc. Apparently, this result should be expected. Through merging control, ramp vehicles are designed to arrive the merging location acquiring an acceptance distance from these vehicles on the main lane. Then it can merge into the main lane silently and what’s more, it can immediately integrate into the traffic flow on the main lane owing to that it already has the normal traffic speed after accelerating on the acceleration area as shown in figure 1. As a result, the traffic flow would not be disrupted by this merging vehicle which has found a good chance to cut in.

Figure 8. Average speed of vehicles on the main lane.

Another evaluation parameter is travel time of vehicles on the main lane, which are recorded by each vehicle. As we can see in figure 9 that the probability distribution of travel time with merging control is approximately in the form of Gaussian curve, which is in accordance with the fact that the travel time of vehicles on a certain road presents normal distribution approximately without external interference. This illustrates that the ramp vehicles produce little interference on the traffic flow with merging control. As a contrast, the travel time of vehicles without control is relative abnormal distributed, illustrating the influence of ramp vehicles on the traffic flow. Besides, there are several vehicles with relative long travel time (> 32 s) without merging control compared to that with merging control. These vehicles may be severely disrupted by merging vehicle, meaning that they are forced to slow down for avoidance until there is a safety distance and then speed up to return to normal traffic speed, which leads to much delay. These conclusions can also be confirmed by the statistics of travel time as shown in table 2.

Figure 9. Travel time of vehicles on the main lane.
Figure 9. Histogram of travel time distribution.

Table 2. Statistics of travel time.

| Statistics  | Without control | Merging control |
|-------------|-----------------|-----------------|
| Mean        | 24.68 s         | 24.26 s         |
| Maximum     | 34.92 s         | 33.72 s         |
| Minimum     | 17.82 s         | 17.82 s         |
| Variance    | 15.53 s²        | 10.88 s²        |

Through the analysis above, the effectiveness of the proposed merging control method is verified. Therefore, vehicles on the main lane can go through the ramp area with little disrupt when these ramp vehicles are controlled and guided to merge into the main lane at an appropriate time. As a result, the bottleneck problem of ramp area can be alleviated.

4. Conclusion
Highway plays an important role in modern transportation system, while it has been suffering the problem of bottleneck on the ramp area for a long time. In this paper, the cooperative vehicle infrastructure control technology is applied to solve this problem. A feasible resolution is proposed in this paper by controlling the speed of ramp vehicles to merge into the main lane without interference on the traffic flow. In order to choose a good choice to cut into the main lane, a vehicle entering the ramp is given an advisory speed according to the traffic condition on the ramp area. Then the on-ramp vehicles can merge into the main lane silently with little influence on the traffic flow. To test the merging control method, a simulation environment is developed by AnyLogic, and comparison experiments are conducted by this simulation environment. Finally, the effectiveness of this merging control method is verified by simulation results.

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