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Study on Main Road Capacity Influenced by Harbor Style Bus Stop

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Abstract

Harbor-style bus stops have large capacity, little influence on the main road, which is also safe and convenient for passengers to get aboard or getting off. However, the capacity of main road was reduced when buses arriving or departing the bus stops. Based on the analysis of procedure of bus arriving and departing the harbor station, with the combination of queuing theory with gap theory, we analyzed the influence of harbor style bus stop on main road capacity, which is studied by normal and spillover scenarios. For the normal scenario, with the procedure analysis of arriving and departing bus stop, influence model on main road was established, for the spillover scenario, we established the corresponding model, with the considering of the influence of lane change behavior of other vehicles on the outmost lane. The simulation analysis shows that the error of the model in two scenarios are 2.8% and 2.9% respectively, which is satisfied to reflect the influence of harbor style bus stop on main road capacity. From the case study, we can conclude that in the normal scenario, with the increasing of bus arrival and volume in outmost lane, the reduction coefficient of main road increased slowly, in the spillover scenario, when the bus arrival rate is more than 40veh/h , and volume in outmost lane more than 900veh/h, the reduction coefficient of main road shows accelerating trend.

Keywords: *Harbor-style bus stop; capacity of main road; stop spillover; queuing theory; reduction coefficient*

1. Introduction

Bus stop is an important infrastructure in urban transit system, among which harbor style bus stop extends the road, which is convenient for bus stopping, passenger getting on or off safely, meanwhile, the harbor style bus stop also separate the bus from other vehicles, which can minimize the disturbance of traffic flow. So it plays important rule in traffic management, and can improve safety of bus operation.

However, with the fluctuation of volume in main road and stochastic bus arrival time, the influence of harbor bus stop on capacity of main road can also be variable, which will be studied in this paper, and the conclusion is also useful for configuration optimization of bus stop.

The capacity of main road influenced by bus stops means the practical capacity of main road near the bus stop which is influenced by bus boarding and alighting. About the relationship between capacity of main road and bus stop, much research work got good suggestions. For example, Herbert S. Levinson and Kevin R.St.Jacques[1] studied the capacity of main road and intersection when the capacity of the normal bus stop is smaller than the demand of bus arrival, in which they discussed the relationship between parking lot of bus stop in real world and its effective park lot because of disturbance of other buses or vehicles. Padmanaban[2] analyzed the capacity of main road near bus stop taking bus stop duration into account. Liu Jianrong[3] studied the relationship between

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capacity reduction of the main road and the delay of intersection near the bus stop, in which the concluded that delay was related to bus stop style, distance from the bus stop, volume of main road and bus arrival interval, etc.. Feng Taiqun[4] established the reduced road capacity model of normal style and harbor style bus stop based on the fundamental capacity model, in which characteristics of bus operation and traffic flow around the bus stop was discussed. Yang Xiaokuan[5] studied the capacity of main road, in which they use the practical data to calibrate the impact factor, without considering the real influence of bus stop.

In the real world, the capacity of main road near bus stop is reduced because of frequent arriving and departing of buses, so in this paper, we first analyzed this procedure, then capacity reduction coefficient of main road and the corresponding model were established, which were studied by normal and spillover scenarios.

2. Procedure Analysis of Arriving and Departing the Harbor Style Bus Stop

Harbor style bus stop widens the lane adjacent to curb, and in this area there is bus stop for boarding and alighting [6].

This procedure includes 4 steps: “arriving”, “stopping”, waiting for gaps”, “departing”, if the queue at bus stop spill over, there is other step named “waiting before arriving”, see as fig 1.

About the step of “arriving”, there are 3 sub-steps: decelerating, lane change and stop. About the step of “stopping”, there are also 3 sub-steps, door open, boarding and alighting, and door close. The step “waiting for gaps” means when start, the bus must wait for the enough gaps among vehicles in the outmost lane at the main road. About the step of “departing”, 3 sub-steps are also included: merging, acceleration, and normal running, arriving and departing the harbor style bus stop.

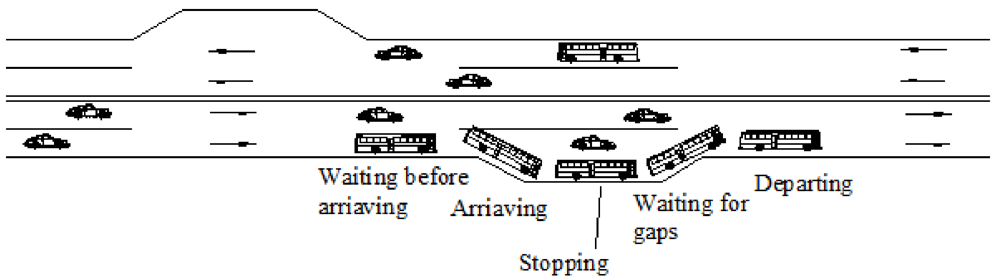

Figure 1. Procedure Analysis of Arriving and Departing at the Harbor-style Bus Stop

The influence of harbor style bus stop on main road capacity means the delay of vehicles because of disturbance of bus stop[7]. In the procedure of “arriving” and “departing”, 2 steps may conflict with the outmost lane, which will slow down the vehicle speed at the main road because of the lane change of buses, which finally impact the capacity of main road. About the step of “stopping” and “waiting for gaps”, the impact can be neglected.

In the step of “arriving”, because of bus deceleration and lane change, the following vehicles have to decelerate. If distance between buses and follow cars is long enough, the impact of capacity of main road can be neglected, of course, there must be no spillover of harbor style bus stop, or a lane of main road is occupied, the capacity of main road sharply decreased.

When “departing” from the bus stop, the bus has to wait for gaps at the main road, in this step if the queue of bus spill over, the capacity of main road is also decreased. Moreover, because of merging, the vehicles on the main road decelerate to avoid rear-end collision with bus, the capacity of main road is also decreased. Of course, if the gap is long enough for bus merging, the impact can also be neglected.

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In peak hours, the number of parking lot may not satisfy the demand of buses, which result to a more step "waiting before arriving", and spillover to the main street. In this case, the impact of harbor style bus stop on capacity of main road can be divided in to 2 parts. First, the waiting bus occupied the outmost lane at the main road, which will delay vehicles in this lane. If the situation comes worse, vehicles on the outmost lane will change to the left lane, which will delay vehicles in this lane, and decrease the capacity of main road.

3. Capacity Model of Main Road Influenced by Harbor Style Bus Stop

3.1 Fundamental Capacity Model of Main Road

There are 2 scenarios at harbor style bus stop. One is the situation that the number of parking lot is more than buses who need stop, in this case, boarding and alighting can be finished at the harbor style bus stop, so there is no influence of bus stop on the outmost lane of the main road, we called this scenario as "normal". The other scenario is that the number of parking lot is less than buses who need stop, in this case, buses have to wait, if the queue is long enough, the outmost lane will be occupied by buses, we called this scenario as "spillover".

Since interval of bus arrival time is an exponential distribution, in the "normal" scenario, we assume it as M/M/S queue service system [8]. In the "spillover" scenario, we just need calculate the probability of arrival buses which is more than the number of parking lot of harbor style bus stop as follow:

$$P=[1-\frac{1}{c!}(\frac{\lambda}{\mu})^{c}]\times P_{0} \tag{1}$$

$$P_{0}=[\sum_{k=0}^{c-1}\frac{1}{k!}(\frac{\lambda}{\mu})^{c}+\frac{1}{c!}\times\frac{1}{1-\rho}(\frac{\lambda}{\mu})^{c}]^{-1} \tag{2}$$

Where P the probability of spillover is, c is the number of parking lot of harbor style bus stop, λ is the bus arrival rate, μ is the stop interval of bus at the stop (service rate), k is the number of vehicle in the queue, $\rho=\lambda/\mu$ is the service intensity of bus stop, P_0 is the probability of no bus waiting.

So the capacity of main road influenced by harbor style bus stop can be expressed as follow:

$$C=C_{1}\times(1-P)+C_{2}\times P \tag{3}$$

Where C_1 is the capacity of main road without spillover, C_2 is the capacity of main road in the situation of spillover.

When bus arriving or departing the harbor style bus stop, it needs run at the outmost lane of main road (we called "outmost lane"), and the decelerate or accelerate to change the lane to arrive or depart the bus stop, it's obviously impact vehicle in the same lane, so the capacity of this lane will decrease, about the other lanes, the impact can be neglected [9].

About capacity of outmost lane, we definite a reduction coefficient δ_b to express it, which equals to impact duration divided by the total interval, as follow:

$$\delta_{b}=1-\frac{T}{3600} \tag{4}$$

So the capacity of outmost lane can be definite as:

$$C_{\alpha}=Q\times\delta_{b}=Q\times(1-\frac{T}{3600}) \tag{5}$$

Where C_α is the capacity of outmost lane influenced by harbor is style bus stop, Q is the possible lane capacity, here we assume that every lane has the same possible capacity, no matter it's the outmost lane, or second outmost lane, or other lanes at the main road, δ_b is the reduction coefficient, T is the duration of influence of bus at bus stop.

3.2 Scenario without Spillover

The procedure of bus arriving and departing the harbor style bus stop can be divided into four steps. 1. When bus approaching the bus stop, it decelerate first, and the following vehicles also decelerate for rear-end avoidance. 2. Stop for boarding and alighting at bus stop. In this step, there is no apparent disturbance to vehicles at main road. 3. Waiting enough gaps of traffic flow for merging to the main road.4.accelerating to the speed of traffic flow at outmost lane, which takes certain time, so it will make following vehicles deceleration.

Because there is no spillover at harbor step, the influence is mainly on the outmost lane.

In these 4 steps, there are 2 steps that may influence the traffic flow of the outmost lane: the deceleration in the 1st step and acceleration in the 4th step. In the 1st step, procedure of deceleration is partly finished at the harbor style bus stop, we assume that half is done at the outmost lane. In the 4th step, all procedure of acceleration is finished at the outmost lane.

So the impact duration which caused by deceleration in 1st step can be expressed as follow:

$$t_b = \frac{1}{2} \times \frac{v}{a_b} = \frac{v}{2a_b} \tag{6}$$

The impact duration which caused by acceleration in 4th step can be expressed as follow:

$$t_a = \frac{v}{a_a} \tag{7}$$

The total impact duration of one bus on the outmost lane is:

$$t_{ab} = t_a + t_b = \frac{v}{a_a} + \frac{v}{2a_b} = v(\frac{1}{a_a} + \frac{1}{2a_b}) \tag{8}$$

Where t_{ab} is the total impact duration, t_a 、 t_b are the impact duration of acceleration and deceleration respectively. v is the speed of traffic flow at the outmost lane; a_a , a_b are the acceleration and deceleration rate respectively.

The total impact duration of buses on the outmost lane is:

$$T_1 = \lambda(t_a + t_b) = \lambda v(\frac{1}{a_a} + \frac{1}{2a_b}) \tag{9}$$

So the capacity of main road in the scenario without spillover can be expressed as follow:

$$\begin{aligned} C_1 &= Q \times (1 - \frac{\lambda v(\frac{1}{a_a} + \frac{1}{2a_b})}{3600}) + Q \times (n-1) \\ &= Q \times [(n - \frac{\lambda v(\frac{1}{a_a} + \frac{1}{2a_b})}{3600})] \end{aligned} \tag{10}$$

Where n is the number of lanes at the main road.

3.3 Scenario of Spillover

When arriving buses is more than capacity of harbor style bus stop, they have to queue at the outmost lane of the main road (we call it spillover), which will block the vehicles in this lane. In this case, the capacity of outmost lane decreases sharply, so vehicles have to change lane to the second outmost lane.

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So in the scenario of spillover, we concentrate the analysis on the outmost lane and the second outmost lane. About the outmost lane, the impact duration of bus spillover can be expressed as follow:

$$t_d = \frac{L}{\lambda} = \frac{1}{\lambda} \times [\sum_{k=c}^{\infty} \frac{k-c}{c^{k-c} c!} \times (\frac{\lambda}{\mu})^k \times P_0] = \frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda} \tag{11}$$

Where t_d is the average waiting time of buses spilling over at the outmost lane, L is the average queue length.

So the capacity of the outmost lane can be inference as follow:

$$C' = Q \times (1 - \frac{\frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda}}{3600}) \tag{12}$$

Where C' is the capacity of the outmost lane of the main road.

About the second outmost lane, since vehicles at the outmost lane change to this lane, vehicles at this lane have to decelerate to avoid rear-end, which may decrease its capacity. The procedure of lane change from outmost lane to the second outmost lane is similar as the vehicle at minor street merging into the main street without signals at intersection, so the capacity of second outmost lane is similar with the capacity of main street[10], in this way, the capacity of the second outmost lane can be expressed as follow:

$$C'' = Q + Q \times \frac{e^{-Q_2 \tau}}{1 - e^{-Q_2 h_t}} \tag{13}$$

Where is C'' the capacity of second outmost lane in the spillover scenario, τ is the critical gap of merging traffic flow, h_t is the headway of traffic flow at the second outmost lane.

Therefore, the capacity of main road in spillover scenario can be expressed as follow, which was composed of outmost lane, second outmost lane and other lanes.

$$\begin{aligned} C_2 &= Q \times (1 - \frac{\frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda}}{3600}) \\ &+ Q \times (1 + \frac{e^{-Q_2 \tau}}{1 - e^{-Q_2 h_t}}) + Q \times (n-2) \\ &= Q \times (n + \frac{e^{-Q_2 \tau}}{1 - e^{-Q_2 h_t}} - \frac{\frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda}}{3600}) \end{aligned} \tag{14}$$

Where C_2 is the capacity of main road in scenario of spillover of harbor style bus stop; n is the number of lanes at the main road, in which $n \geq 2$

Finally, taking C_1、 C_2 into equation (3), we get Main Road Capacity influenced by Harbor Style Bus Stop as follow:

$$\begin{aligned} C = C_1 \times (1-P) + C_2 \times P &== Q \times [(n - \frac{\lambda v (\frac{1}{a_a} + \frac{1}{2a_b})}{3600})] \times (1-P) + Q \times (n + \frac{e^{-Q_2 \tau}}{1 - e^{-Q_2 h_t}} - \frac{\frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda}}{3600}) \times P \\ &= Q \times \{n - \frac{\lambda v (\frac{1}{a_a} + \frac{1}{2a_b})}{3600} \times (1-P) + [\frac{e^{-Q_2 \tau}}{1 - e^{-Q_2 h_t}} - \frac{\frac{\rho (c\rho)^c P_0}{c!(1-\rho)^2 \lambda}}{3600}] \times P\} \end{aligned} \tag{15}$$

3.4 Reduction Coefficient of Capacity of Main Road

To evaluate the impact of harbor style bus stop on capacity of main road, reduction coefficient is defined as follow:

$$R_C = 1 - \frac{C_h}{C_0} \tag{16}$$

Where is C_h the capacity of main road with the impact of harbor style bus stop, C_0 is the capacity of the same road section without harbor style bus stop, which is decided by road conditions (such as number of lanes, lane width, design speed, vertical alignment, sight distance, etc.) and traffic conditions (such as traffic composition, traffic distribution in different directions and lanes, etc.)[11].

4. Case Study Analysis and Model Verification

Road section of Ningxia, which is from Road Baiyu to Road Caoyang in Putuo District, Shanghai, was selected as the field test site, see as Figure 2, from which we can see that there are dual direction 4 lanes at the main road, and there are two dual direction harbor style bus stop (40 meters long), and each have 5 bus routes stopping. About the capacity of selected harbor style bus stop, each can hold 3 buses boarding at the same time. The bus and vehicles arrival rate at the main road, and boarding and alighting passengers at each stop in four scenarios (morning peak, evening peak, off peak and valley) were collected as table 1.

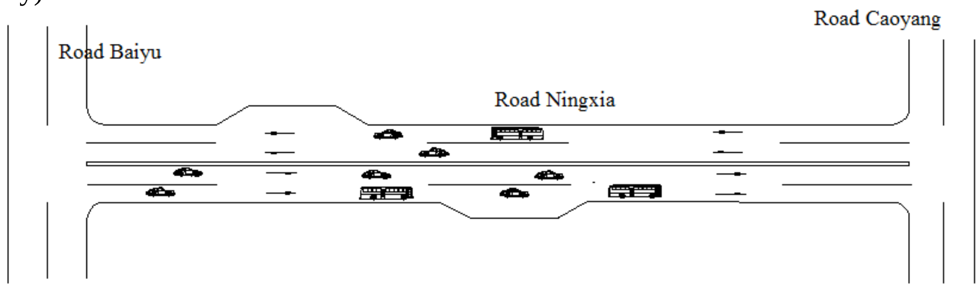

Figure 2. Configuration of Ningxia Road Bus Stop

Table 1. Survey Data of Bus Stop at Road Ningxia

	Direction	morning peak（7:30-8:30）	evening peak (17:30-18:30)	off peak (11：00-13：00)	valley (14：00-16：00)
Bus arrival rate	Westbound	39 bus/h	40 bus/h	19 bus/h	10 bus/h
	Eastbound	38 bus/h	39 bus/h	17 bus/h	9 bus/h
Vehicle volumes at main road	Westbound	1185 veh/h	1156 veh/h	805 veh/h	488 veh/h
	Eastbound	1015 veh/h	1091 veh/h	759 veh/h	472 veh/h
Number of boarding and alighting passengers	Westbound	449persons/h	452 persons/h	108 persons/h	36 persons/h
	Eastbound	406 persons/h	416 persons/h	89 persons/h	34 persons/h

Moreover, about the bus stop interval at the bus stop, 5 to 10 seconds at scenarios of off peak and valley, in which there were no spillover. At the morning peak and evening

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peak, bus arrival rate and vehicle volume at main road raised up to 40 bus/h, 1200 veh/h respectively, and the corresponding bus stop interval also extended to 20 to 30 seconds, in which it occurred spillover at the harbor style bus stop frequently.

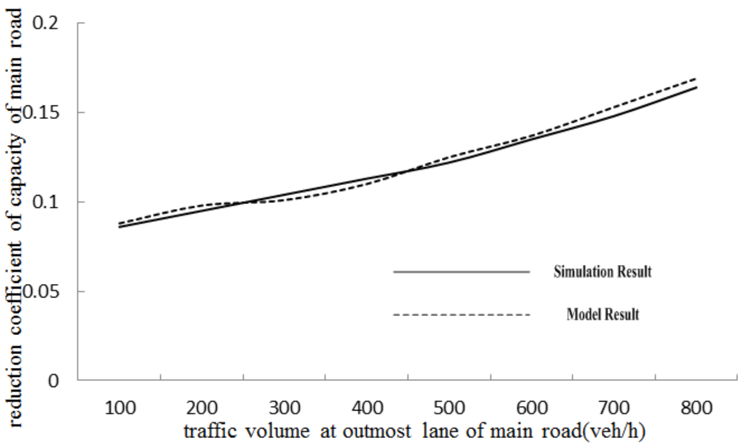
So we analyzed the impact of harbor style bus stop on main road with different bus arrival rates in normal and spillover scenario via traffic simulation software VISSIM 4.3.

4.1 Capacity Verification of Main Road Influenced by Harbor Style Bus Stop in Normal Scenario

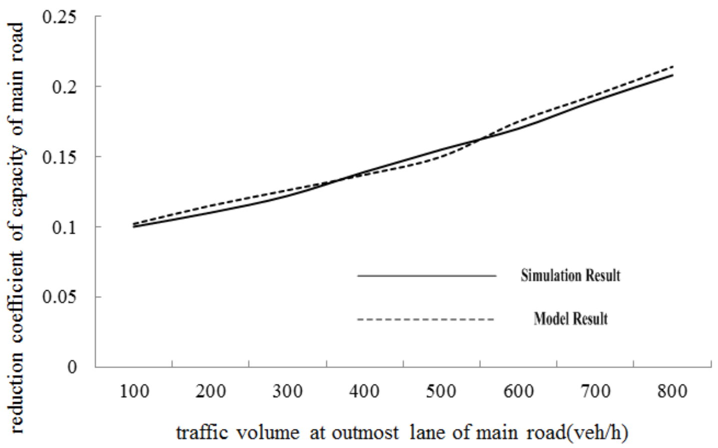
The factors that influence on capacity of main road main include parking lot of bus stop, stop interval at the bus stop, bus arrival rate and traffic volume at main road, etc.. In normal scenario, the parking lot is satisfied, so other factors were considered in following discussion.

Based on the survey data, we set fundamental simulation parameters of harbor style bus stop in normal scenario at off-peak and valley period as follow: average of bus speed was 35km/h, bus decelerated rate a_b when departing and accelerated rate a_a when arriving were 1 m/s^2 and 0.8m/s^2 respectively. In the simulation, we loaded traffic volume at outmost lane from 100veh/h to 800veh/h, and bus arrival rate from 10veh/h to 30veh/h.

Comparing the reduction coefficient of capacity of main road in simulation, which was the truth value, with of data calculated with models in this paper in different bus arrival rates and traffic volumes, results can be seen in Figure 3.



(a) Bus arrival rate 10 bus /h



(b) Bus arrival rate 20 bus /h

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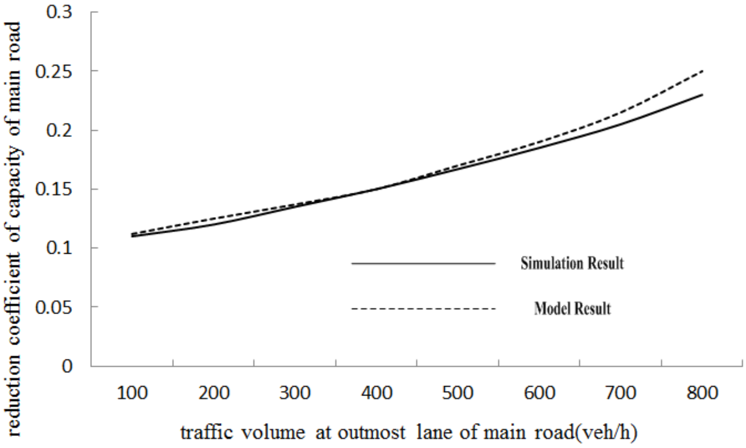

（c）Bus arrival rate 30 bus /h

Figure 3. Harbor-style Bus Stop Un-overflowed Model Checking with Different Bus Arrival Rate

From the figure, we can see that when the bus arrival rate was 10 bus/h, the maxim error of model occurred at the volume of 800 veh/h, and the tolerance was 3.1%; the minimal error occurred at the volume of 100 veh/h, and tolerance was 1.3%; and the average tolerance was 2.7%. With the increase of volumes at adjacent lane, the reduction coefficient of capacity of main road increased slowly, the maxim value was 0.16.

When the bus arrival rate was 20 bus/h, the maxim error of models occurs at the volume of 600 veh/h, and the tolerance was 2.8%; the minimal error occurs at the volume of 400 veh/h, and tolerance was 0.7%; and the average tolerance was 2.6%. And when the traffic volume of adjacent lane was more the 600 veh/h, the reduction coefficient of capacity of main road was more than 0.17.

When the bus arrival rate was 30 bus/h and the traffic volume of adjacent lane was more than 600 veh/h, the error between simulation results and models in this paper became greater, when the traffic volume of adjacent lane was more than 700veh/h and 800veh/h, the errors were 3.5%,7.6% respectively. So we can conclude that we bus arrival rate is more than 30 bus/h, traffic volume of adjacent lane is more than 700veh/h, model in normal scenario in this paper may not be suitable, because it may occurs spillover at the harbor style bus stop.

4.2 Capacity Verification of Main Road Influenced by Harbor Style Bus Stop in Spillover Scenario

In the spillover scenario, the fundamental simulation parameters were same as the normal scenario. Since the traffic increase in morning and evening peak, we loaded traffic volume at outmost and second outmost lanes from 500veh/h to 1200veh/h, and bus arrival rate from 10veh/h to 30veh/h, in which spillover of harbor style bus stop may occur frequently. And we set the stop interval at bus stop as 20 seconds.

Comparing the reduction coefficient of capacity of main road in simulation, which was the truth value, with of data calculated with models in this paper in different bus arrival rates and traffic volumes, the results can be seen in Figure 4.

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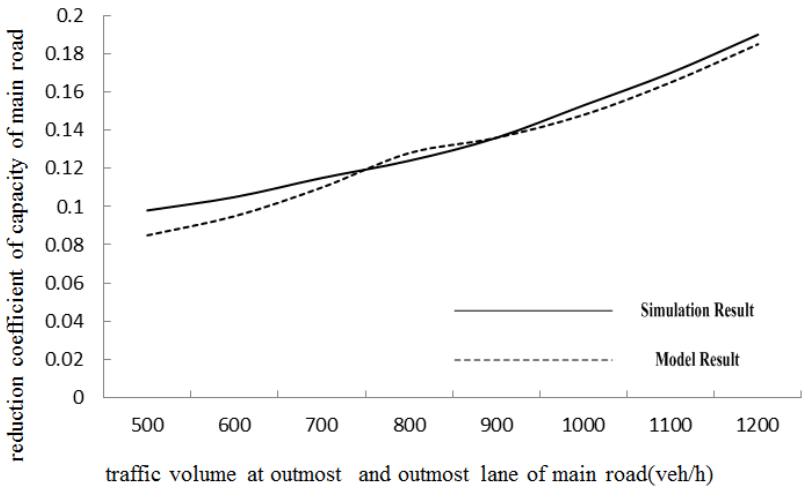
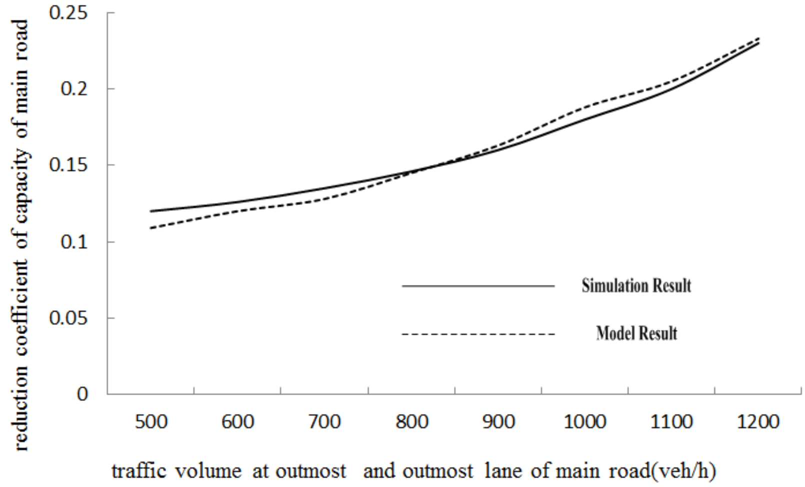
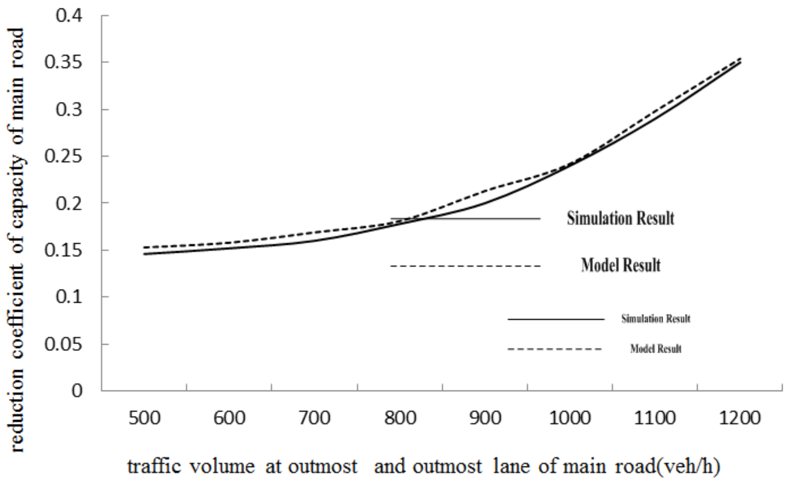


（a） Bus arrival rate 20 bus /h



（b） Bus arrival rate 30 bus /h



（c） Bus arrival rate 40 bus/h

Figure 4. Harbor-style Bus Stop Overflowed Model Checking with Different Bus Arrival Rate

From the figure, we can see that when the bus arrival rate was 20 bus/h, the traffic volume at outmost and second outmost lane is 500veh/h, the error of model in this paper was 7.5%, which was unacceptable; when the traffic volume increased to 800 veh/h, this number decreased to the acceptable area. And when traffic volume was smaller than 800 veh/h, the simulation results were always smaller than the results of model in this paper, maybe there was no spillover occurred, so the model was not suitable.

When the bus arrival rate was 30 bus/h, the maxim error of model occurred at the volume of 500 veh/h, and the tolerance was 5.4%; the minimal error occurred at the volume of 900 veh/h, and tolerance was 0.9%; and the average tolerance was 3.1%. The impact in spillover scenario is greater than normal scenario, the maxim reduction coefficient value is 0.23.

When the bus arrival rate was 40 bus/h, the maxim error of model occurred at the volume of 900 veh/h, and the tolerance was 3.3%; the minimal error occurred at the traffic volume of 1200 veh/h, and tolerance was 0.9%; and the average tolerance was 2.7%. When traffic volume was more than 900veh/h, the reduction coefficient of capacity of main road is more than 0.2, the maxim value was 0.35. In this situation, the harbor style bus stop can't satisfy the arriving buses, queue became longer and longer, with the increase of traffic volume on the main road, spilled buses blocked the main road, so the capacity decreased sharply.

5. Conclusion

In this paper, based on the configuration characteristics of harbor style bus stop, with whose influence we established capacity model of main road, considering factors such as bus arrival rate, bus deceleration and acceleration rate when arriving or departing, number of lanes at main road. Two scenarios (normal and spillover) were studied and verified by simulation in VISSIM, from which we get conclusions as follow:

（1）With the increase the volume at main road, reduction coefficient of capacity of main road also raised up, the average error between simulation value and model value were 2.65% in normal scenario and 2.9% in spillover scenario.

（2）In normal scenario, when the bus arrival rate was less than 20 bus/h, with the increase of traffic volume at adjacent lane, reduction coefficient increased slowly, the errors between model in this paper and the simulation value was little, when the bus arrival rate was more than 30 bus/h, traffic volume at outmost lane was more than 700 veh/h, this value became larger.

（3）In the spillover scenario, when the bus arrival rate was less than 20 bus/h, traffic volume at outmost and second outmost lane was less than 800 veh/h, the errors between model in this paper and the simulation value was unacceptable; when traffic volume at outmost and second outmost lane was more than 800 veh/h, bus arrival rate was more than 30 bus/h, the error is little enough to acceptable. And when traffic volume at outmost and second outmost lane was more than 900 veh/h, bus arrival rate was more than 40 bus/h, reduction coefficient showed trend of accelerated growth.

（4）When traffic volume of outmost lane was more than 700 veh/h, bus arrival rate was more than 30 bus/h, model in normal scenario in this paper is not suitable; when traffic volume of outmost lane and second outmost lane was less than 800 veh/h, model in spillover scenario in this paper is undesirable. Maybe transition model need be studied.

Furthermore, in real world, bicycle especially electric bicycle disturb the bus arriving and departing seriously, impact of the conflict between bicycles and buses on capacity of main road need be further studied.

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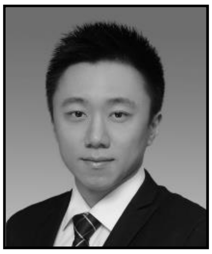

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