

Full Length Research Paper

Towards the pedestrian delay estimation at intersections under vehicular platoon caused conflicts

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This paper attempts to develop a pedestrian delay estimation model for intersections considering automobile-pedestrian conflicts induced by driver's bad behaviour of not giving way to pedestrians. Firstly, level of service (LOS) divisions for signalized and unsignalized intersection crosswalks for pedestrians in China are proposed and 6 levels are ranked using the pedestrians' perceptions of comfort, safety and psychological limitation as well as acceptable delay. Then pedestrian delay is analyzed at non-signalized intersection and signalized intersection, and the latter is divided into two parts: signal delay and interrupted delay based on whether pedestrian signal and vehicle signal are separated thoroughly. For the case of signal control, delay estimation model is constructed with pedestrian gathering and dissipating characteristics. In order to test the effectiveness of this proposed delay estimation model, we use Vissim to simulate the pedestrian delay at signalized and unsignalized intersections. Compared with the simulated delay, the delay values derived from this proposed model has better performance of EI (error indicator) in response to the observed ones, providing useful reference in improving pedestrian crossing environment at intersections.

Key words: Pedestrian delay estimation, signalized intersection, level of service, Vissim simulation.

INTRODUCTION

Pedestrian delay is the key performance indicator to evaluate a signalized intersection's Level-of-service (LOS) for pedestrians (Eboli and Mazzulla, 2008). Till now, based on the studies conducted in developed cities, several models for estimating pedestrian delays at signalized intersections have been developed based on pedestrian space and pedestrian delay (Cheng et al., 2008; Li et al., 2005; Chilukuri et al., 2005; Virkler, 1998; Pretty, 1979), under a broad range of traffic conditions. In 2005, Petritsch et al. published their article to discuss pedestrians' perceptions of crossings at signalized intersections through a LOS model, which considered "perceived safety and comfort (that is, perceived exposure and conflicts) and operations (that is, delay and signalization)". However, right turning traffic also could bring negative impact on

pedestrian's crossing behaviour and increase their delay at signalized intersection. Hubbard et al. (2009) developed a binary logit model to describe the factors (e. g., traffic flow, signal plan, location, etc) affecting pedestrian's crosswalk likelihood. However, mostly common used delay estimation methods and models are mostly derived from Highway Capacity Manual (HCM) and are relatively simple, without enough attention on the effect of platoon, especially for the mixed traffic in Chinese cities.

Generally, pedestrians are allowed to enter crosswalk during green phases and they are forbidden to do so in red and clearance phases. However, in China, traffic situations and signal system for pedestrian are significantly different (Li et al., 2005). Because of low quality of traffic politeness, limited education or poor traffic safety awareness, arrival pedestrian are often willing to comply with the traffic signals during non-green phases. Since drivers affected by mental workload and road geometry generally start and run slowly in the beginning, and give more patience to pedestrians'

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crossing behaviour (Pellegrino, 2009; Martinez et al., 2009), pedestrians usually can cross successfully over these time. According to the research by Bian et al. (2009), pedestrian LOS at signalized intersections is significantly influenced right-turning vehicle and bicycle volume in Chinese cities. Therefore, the intersection involved traffic is very crowded and conflicts exists among pedestrians, vehicles and non-motorized vehicles resulting in the decline of capacity, increase of pedestrian delay, or pedestrian involved collisions in some extraordinary instances.

Generally, a driver changes his/her behaviour for safety driving while information (that is, forward or following vehicle, road geometric, traffic lights, pedestrian's crosswalk, etc) is recognized to have been change (Hong et al., 2009). Therefore, the conflicts between platoon and pedestrian are dynamic and easy to induce fatal crashes. Thus, just from the consideration of preventing pedestrians from being hit by a motor vehicle, how to provide a safety crosswalk environment for pedestrian is the key issue to ensure the traffic safety at intersections (Pei et al., 2006; Srinivasan and Walker, 2009). From the point of pedestrian psychology, pedestrians pass through grade intersections irregularity when delaying time is longer than waiting psychological limit time of the pedestrian. With this, pedestrians become impatient, and engage in risk taking behaviour (Tiwari et al., 2007). Therefore, research on the grade of intersection's pedestrian crossing delay can help improve LOS of pedestrian crossing facility and reduce traffic accident (Feng et al., 2009).

However, pedestrians' perceptions of comfort and safety are the main considered factors, while estimating the delay of pedestrian at intersections in China's developing cities. (Feng et al., 2009). Yang et al. (2005) have developed a Monte Carlo model to estimate pedestrian delays at signalized intersections providing various kinds of pedestrian facilities, and validated the model with the field data collected in developing cities. Lu et al. (2002) have developed a Monte Carlo model to estimate pedestrian delays in a network of highways and walkways (with a signalized T intersection as an example), but no validation was performed. Wang et al. (2008) used software to test the effectiveness of constructed models, which provide some reference for our further research operation. However, since the conflicting vehicle flows that pedestrians encounter at signalized intersections are periodically changing, it is difficult to work out an analytical model to estimate pedestrian delays when most pedestrians have no respects toward traffic signals

Despite the previous researches on delay estimation models, particular mixed traffic condition is generally not taken into consideration while estimating pedestrian's delay at signalized intersections. In most China's metropolitan areas, drivers and pedestrian are not willing to comply with the traffic signals and drivers always do not consider the pedestrian priority (Li et al., 2007). More

seriously, there are still some vehicles conflicting with pedestrians during pedestrian green phases in some situations, thus, pedestrians may still receive delays, even crossing during green phase. In some China cities, pedestrian signal configurations are also somewhat different, e.g., signal cycles are usually longer (more than 100 s). Thus, because of the significant differences between traffic conditions in developed cities (e. g. London, New York, Tokyo) and developing cities in China, the existing models developed in response to traffic conditions in developed cities may not be applicable here (Guan et al., 2005). The ignorance of some factors, such as the delays received by pedestrians arriving during green phases, may cause only negligible error in developed cities, but big error in developing cities (Lazda et al., 2009).

Upon the agent requirement, it is necessary to develop a new model to estimate pedestrian delays at signalized intersections in China's developing cities. Therefore, the primary purpose of this paper is to address an effective method of pedestrian delay estimation at intersections. It is organized as follows: Los of crosswalk facilities is developed firstly and then delay estimation models are proposed for unsignalized intersection and signalized intersection, respectively. The paper concludes consequently with general remarks and comments about the overall works in the final section.

LOS OF FACILITIES SERVING PEDESTRIAN

Uninterrupted pedestrian facilities include both exclusive and shared pedestrian paths designated for pedestrian use. Such facilities accommodate the highest volumes of pedestrians; they also provide the best levels of service, because pedestrians do not share the facilities with other travel mode. LOS of facilities serving pedestrian is divided into six ranks through pedestrian delay and psychological waiting limit, according to HCM, 2000. Because the difference of psychological waiting, response is significant at unsignalized and signalized intersections. Therefore, the corresponding LOS standards are also different (Botma, 1995). At intersections with high conflicting vehicle volume, pedestrians have little choice but to wait for the walk signal, and observed noncompliance is reduced (Guell, 1984). On the basis of HCM, 2000, we develop the LOS of facility serving pedestrian, as shown in Table 1, at unsignalized intersection and signalized intersections, respectively.

Pedestrian delay at unsignalized intersection

Gap acceptance

While the time between two following automobiles is enough in the stream of vehicular platoon, it gives the

Table 1. LOS of crosswalk facilities at intersections.

Average delay / s		LOS	Description
Signalized	Unsignalized		
<10	<5	A	very small delay, none crossing irregularity
10~20	5~10	B	Small delay, almost no one crossing irregularity
20~30	10~20	C	Small delay, very few pedestrian crossing irregularity
30~40	20~30	D	Big delay, someone start crossing irregularity
40~60	30~45	E	Very big delay, many pedestrians crossing irregularity
>60	>45	F	Very big delay, almost every waiting pedestrians crossing irregularity

pedestrian a gap to pass through intersection by crosswalk successfully and safely (Rodriguez et al., 2009). Such a gap τ_0 has a minimum value, namely, acceptable gap, below which a pedestrian will not attempt to do the crosswalk and this critical threshold is the minimum headway among vehicle flow in essence that it guarantees a pedestrian passes through the intersection safely. Let's neglect the pedestrian's own influences (Zhang et al., 2006), we reach the acceptable gap τ_0 united s the pedestrian need to make crosswalk safely:

$$\tau_0 = \frac{d}{v} + t_R + t_0 \quad (1)$$

Where,

d - the average width of roadway in m;

v - the walking speed of pedestrian in m/s and here we consider $v = 1.2$ m/s;

t_R - the waiting time for pedestrian to decide whether to cross, and here we consider $t_R = 2$ s;

t_0 - the passing time of vehicle, and here we choose $t_0 = 0.72$ s for standard car.

Interrupted delay

At unsignalized intersections, pedestrian delay mostly contributes to vehicle interrupted delay, including the waiting time at the beginning sidewalk and in the middle road during crossing. Let say, suppose the headway of vehicular platoon complies with negative exponential distribution and vehicle arrival rate is q , then, the probability for pedestrian passing can be obtained among the overall platoon as:

$$P(t > \tau_0) = \sum_{i=1}^n e^{-q_i \tau_0} \quad (2)$$

Where, q_i is the i^{th} arriving vehicle; n is the total vehicle

number in platoon. If x is the number of acceptable gap occurrence, thus its distribution satisfies:

$$P(x = k) = (1 - e^{-q_1 \tau_0}) \sum_{k=2}^n e^{-q_k \tau_0} \quad (3)$$

Re-considering Equation (3), we yield the average value for acceptable gap:

$$\bar{x} = \sum_{k=1}^{\infty} k \times P(x = k) = \frac{(1 - \sum_{k=1}^n e^{-q_k \tau_0})}{\sum_{k=1}^n e^{-q_k \tau_0}} \quad (4)$$

For headway t , its density of probability is defined as:

$$f(t) = \begin{cases} qe^{-qt}, & t \geq 0 \\ 0, & t < 0 \end{cases} \quad (5)$$

Let make a hypothesis that headway of the first lane during crossing is smaller than τ_0 , then we obtain the waiting time of pedestrian as:

$$\bar{t}_x = \frac{\int_0^{\tau} tf(t)dt}{\int_0^{\tau} f(t)dt} = \frac{\frac{1}{q} - (\tau_0 + \frac{1}{q})e^{-q\tau_0}}{1 - e^{-q\tau_0}} \quad (6)$$

If the above mentioned headway is smaller than τ_0 resulting in pedestrian's not crossing intersections, so the corresponding waiting time is:

$$\bar{t}_d = \frac{\int_{\tau}^{\infty} tf(t)dt}{\int_{\tau}^{\infty} f(t)dt} = \frac{(\tau_0 + \frac{1}{q})e^{-q\tau_0}}{e^{-q\tau_0}} = \tau_0 + \frac{1}{q} \quad (7)$$

However, if the headway at other lanes is smaller than τ_0 , pedestrian can still not cross the intersection, and total waiting time is calculated by:

$$\bar{t} = \bar{t}_x P(t < \tau_0) + \bar{t}_d P(t > \tau_0) \quad (8)$$

On the basis of research findings (Zhang et al., 2006), the interrupted delay D_g in s of pedestrian at unsignalized intersection can be expressed as:

$$D_g = \bar{x} \times \bar{t} = \frac{\frac{1}{q_1} - (\tau + \frac{1}{q_1}) \prod_{i=1}^n e^{-q_i \tau}}{\prod_{i=1}^n e^{-q_i \tau}} \quad (9)$$

Where,

q_i - the average vehicle arrival rate of each lane in vehicle/s.

If we attempt to assess the LOS of pedestrian crossing facilities at intersections without signal control, the acceptable gap τ_0 is determined as well as the average delay of pedestrian crossing firstly and then come to the LOS evaluation value, through Table 1.

Pedestrian delay at signalized intersection

Pedestrian delay at signalized intersections is more complicated and less easily formulated, because it involves intersecting sidewalk flows, pedestrians crossing behaviour, and others queue waiting for signal. Therefore, the LOS is measured by average delay experienced by pedestrians, which is not only constrained to capacity (Virkler, 1998). Generally, pedestrian delay contributes to not only signal cycle time, but pedestrian green time and vehicle crossing delay. Thus, while pedestrian signal and vehicle signal are not separated thoroughly, the pedestrian delay includes delay, the interrupted delay by vehicle stream besides signal delay. Here, pedestrian delay at signalized intersection is divided into two types: pedestrian crossing delay under ideal case and interrupted condition.

Pedestrian delay in ideal case

If intersection has special signal for crosswalk, pedestrians will cross in ideal case. That's to say that, pedestrians arriving during red phase need to wait and begin to pass through the intersection during the green phase. While pedestrian stand at the intersection, he or she decides whether to cross according to the comparison between surplus green time and acceptable gap. Suppose

pedestrian arrival rate is q , Figure 1 presents the schematic model of pedestrian delay estimation with red signal (Dai et al., 2008). Considering Figure 1, we reach the average pedestrian delay in s within one signal cycle time t_c in ideal case as

$$\left\{ \begin{aligned} D_x &= \frac{S_{\text{delay tria.}}}{Q_{\text{pedes}}} = \frac{(t_c + t_h - t_c + \tilde{\tau}_0) \cdot q \cdot (t_h + \tilde{\tau}_0)}{2t_c q} = \frac{(t_h + \tilde{\tau}_0)^2}{2t_c} \\ \tilde{\tau}_0 &= \frac{D}{v} + t_R + t_0 \end{aligned} \right. \quad (10)$$

Where,

t_c - the signal cycle time in s;

t_h - the red time pluses yellow time in s;

D - the average width of single direction in m.

Acceptable gap

Let say, suppose the headway of vehicle platoon complies with negative exponential distribution, pedestrian interrupted delay is determined by the following expression:

$$D = D_x + D_g \quad (11)$$

The LOS of pedestrian crossing facility at signal controlled intersections follows the similar procedure as that of unsignalized intersection, and Table 1 summarizes the appraisal standards.

Case analysis

Here, we give two examples at peak hour (17:00 - 18:00): the first one for T unsignalized intersection and the other for orthogonal signalized intersection, according to two intersections in Xi'an. The unsignalized intersection has two 4.0 m lanes in each direction and two side crosswalk. The signalized intersection is regular type and the width of lane is also 4.0 m. Table 2 presents the signal condition and thus, we can reach $t_c = 60$ s, and $t_h = 30$ s. Something should be pointed out that this signal program is just the actual set used in intersection control.

Vissim can simulate the actual stream of vehicles movement. In order to check the effectiveness of this proposed model, we use Vissim 3.6 to simulate these two intersections and real survey is carried out at October 16, 2009, so as to observe the signal program and pedestrian delay. Table 3 shows the calculated delay, simulated delay and observed delay, respectively.

The LOS_s of the unsignalized and signalized intersection belong to level C and F, respectively, and we can see that,

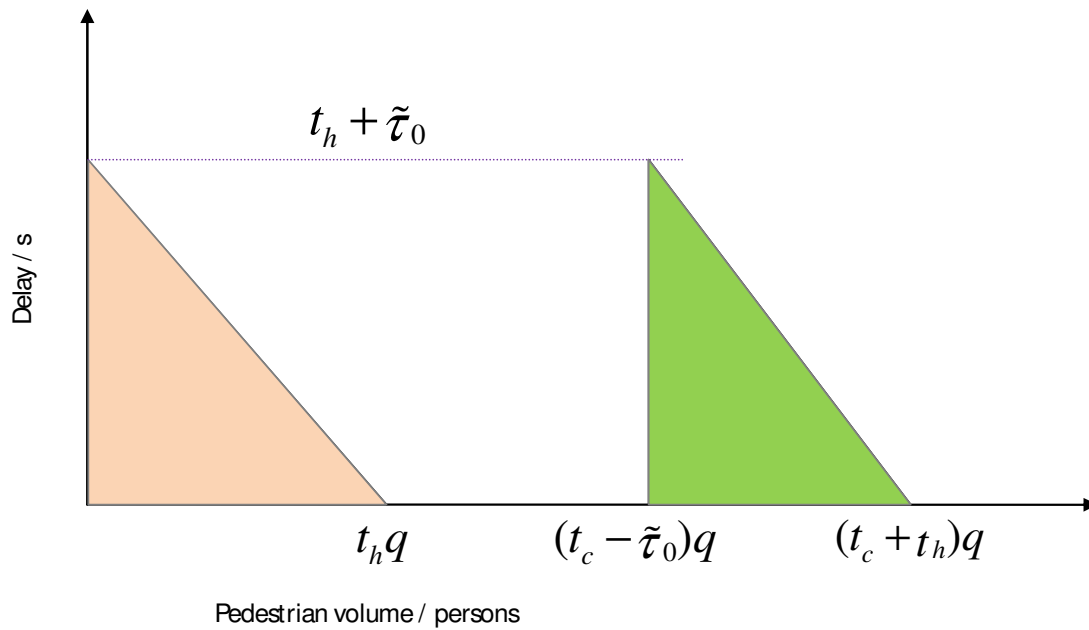


Figure 1. Pedestrian delay in ideal case.

Note: Over the time of one circle t_c , pedestrians that arrive the intersection satisfy $(t_c + t_h)q - t_h q = t_c q$, thus the total delay of these pedestrian willing to make crosswalk can be estimated by the area of delay triangle, marked in green.

Table 2. Signal program of research signalized intersection.

Phase	Symbol	Signal	Parameters
The 1st		<div style="display: flex; align-items: center;"> <div style="text-align: center; margin-right: 10px;"> Red <div style="width: 27px; height: 15px; background-color: red; margin: 0 auto;"></div> 0 s </div> <div style="text-align: center; margin-right: 10px;"> Yellow <div style="width: 3px; height: 15px; background-color: yellow; margin: 0 auto;"></div> 27 s </div> <div style="text-align: center;"> Green <div style="width: 30px; height: 15px; background-color: green; margin: 0 auto;"></div> 30 s </div> </div> <div style="text-align: right; margin-top: 10px;">60 s</div>	$t_c = 60$ s $t_h = 30$ s
The 2nd		<div style="display: flex; align-items: center;"> <div style="text-align: center; margin-right: 10px;"> Green <div style="width: 30px; height: 15px; background-color: green; margin: 0 auto;"></div> 0 s </div> <div style="text-align: center; margin-right: 10px;"> Yellow <div style="width: 3px; height: 15px; background-color: yellow; margin: 0 auto;"></div> 30 s </div> <div style="text-align: center;"> Red <div style="width: 27px; height: 15px; background-color: red; margin: 0 auto;"></div> 33 s </div> </div> <div style="text-align: right; margin-top: 10px;">60 s</div>	

This unsignalized intersection provides a high level walking environment. However, the signalized intersection is under a low level in servicing pedestrian, for the significant conflicts between crossing pedestrians and vehicular platoon. All these need change the signal program with more consideration and attention on the benefit of pedestrians. For easier explanation, we define the error indicator (EI) as Equation (12):

$$EI = \left| \frac{D_{\text{analytical}} - D_{\text{observed}}}{D_{\text{observed}}} \right| \times 100\% \quad (12)$$

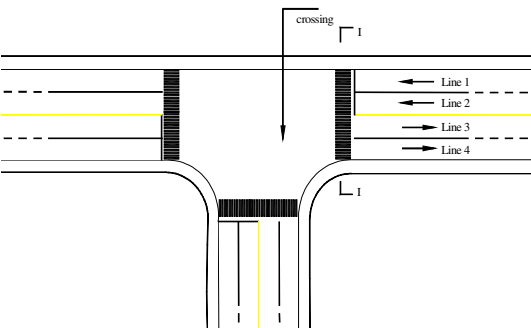
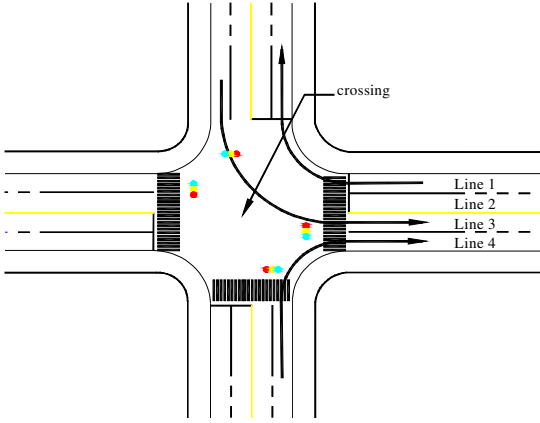
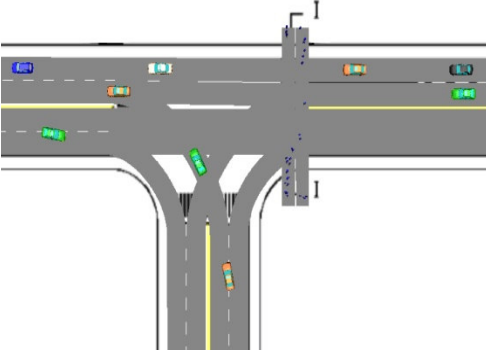
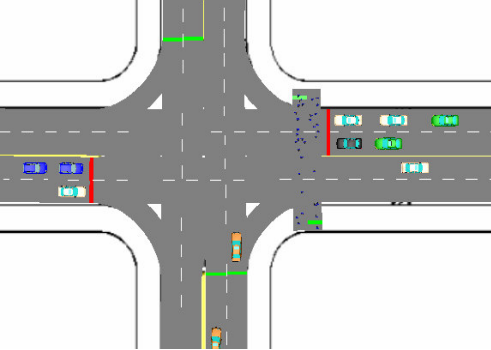
Where,

$D_{\text{analytical}}$ – the delay calculated or simulated,

D_{observed} – the delay observed.

Let say, suppose the observed delay as the just actual value in reality, then EIs of pedestrian's estimated delay for unsignalized and signalized intersections are 7.56 and 2.98%, respectively, through this proposed estimated model. However, the according EI values simulated by Vissim are 13.33 and 7.83%. We can see the simulated delay values are smaller than expected, which contributes to the ideal processing operation by Vissim (disconsidering the behaviour of individual entities and their intersection

Table 3. Case study analysis and comparison for delay estimation and model appraisal of effectiveness.

Item	Unsignalized intersection	Signalized intersection
Lane width / m	$d = 4.0$	$D = 8$
Traffic flow / pcu.h^{-1}	$Q_1 = 400, Q_2 = 245, Q_3 = 350, Q_4 = 204$	$Q_1 = 380, Q_2 = 216, Q_3 = 405$
Intersection condition		
Vissim		
Acceptable gap / s	$\tau_0 = 6.05$	$\tau_0 = 9.39$
Vehicle arrival rate / veh.s^{-1}	$q_1 = 0.111, q_2 = 0.068, q_3 = 0.097, q_4 = 0.057$	$q_1 = 0.106, q_2 = 0.06, q_3 = 0.113$
Delay / s	$D_{12} = 11.55, D_{34} = 7.81, D_{\text{total}} = 19.36$	$D_g^{12} = 26.01, D_g^3 = 8.43, D_x = 12.93, D_{\text{total}} = 47.37$
LOS	C	F
Simulated delay / s	$D_{\text{simu}} = 15.6$	$D_{\text{simu}} = 42.4$
Observed delay / s	$D_{\text{obse}} = 18$	$D_{\text{obse}} = 46$
EI of proposed model / %	7.56	2.98
EI of simulation / %	13.33	7.83

effects). Because the observed delay is surveyed during peak hour, the right turning and left turning vehicles do not give way to pedestrian, more seriously than ever at the surveyed T signalized intersection, which causes a bigger simulation error by Vissim (Leng et al., 2008). However, intersection types, weather conditions, pavement conditions, pedestrian behaviour, driver behaviour are not regarded in this research and all these concerns will be considered in the future works.

CONCLUSION

The pedestrian travel holds the important position in the transportation trip mode, therefore research on pedestrian crossing delay of intersections is necessary and important to improve the LOS of pedestrian facilities (Melkert and Van, 2009). On the basis of HCM, 2000, we define the LOS of pedestrian crossing facilities, dividing into six levels. According to delay survey, we consider that, the pedestrian

delay consists in two parts: delay in ideal case and delay in interrupted case and we develop the delay estimation models for unsignalized intersection and signalized intersection. Finally, a case example is performed to check the effectiveness of this proposed model of delay estimation, compared with the Vissim simulation and actual observation results.

The authors believe that, it as an important topic that has not ever drawn intensive attention in past and further research will become heated (Chatterjee and Ma, 2009), helps to formulate a system design of safety management and improvement for intersection locations in the overall urban areas, just as Arthur (2009) had argued to use human oriented technique (combining social theory and GIS) to create a safer road environment for all involved.

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