Method to Estimate The Speed and Density of The Pedestrian Sidewalk

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Abstract: This paper describes the models of fundamental characteristics for pedestrian flow movement. The actual data were investigated in Bangkok, Thailand. A sidewalk in the CBD in Bangkok is separated into six sub-sections in order to model the density-speed relationships. Nonlinear weights of instant density are assumed equal for each case for this study. The authors found that multi sub-sections analysis increase accuracy of speed-density-travel time relationship more than single section analysis but there is limitation of section separation. The final section of sidewalk does not give a significant impact on the speed of the whole section.

Key Words: speed estimation, pedestrian, sidewalk

1. INTRODUCTION

For short-distance trips, walking is a major travel mode. Tanaboriboon and Jing (1994) studied walking characteristics in China and found that pedestrian trip to work (22.7 %), to school (15.2 %), to shopping (22.8 %), to business (1.3 %), to transit stations (15.1 %), returning home (3.1 %), recreation (9.8 %) and others (7.2 %). In addition, there have been researches on the pedestrian walking characteristics on the sidewalk and walkway in Singapore (Tanaboriboon et al., 1986), China (Lam et al., 1994) and India (Laxman et al., 2010).

Pedestrian walking is also studied in rush hour and panic in building such as Nelson and McLennan (1996) found that the movement of people depends on their personnel characteristics when density is lower than 0.5382 person/m². On the other hand, when density is between 0.5382 and 3.5 person/m², movement of people is function of the occupation density. In addition, this model is applied by Pursals and Garzon (2009) for pedestrian evacuation in building.

The knowledge of the properties of the typical pedestrian flow in general, rush hour and panic not only important in our life style but also investment, the pedestrian investment should be
directed toward places “to improve connectivity where proximity is provided”, so we need the indicators such as regression models for planning pedestrian facilities (Matley et al., 2000)

To understand the real behavior of pedestrians on the types of facilities is complicated and heterogeneous. Therefore, modeling various traffic flows in terms of an unique model is nearly impossible. However, a complex model does not always guarantee a good result. If we want to emulate the average state of traffic flow, a simple modeling structure can give a reasonable performance. A fundamental diagram of traffic flow characteristics has the rationale (Kim, 2010)

The aim of this study is to develop a macroscopic pedestrian flow model based on pedestrian speed-density relationship. In this regard, the authors investigated that whether multi-subsection of sidewalk has the accuracy of the speed estimation of a whole sidewalk. This study proposes the modification process of data collection. This study conducted in Bangkok, a city of more than 5.7 million registered people (National Statistical Office, 2009) is one of the most densely populated cities in the world. The authors would like to address the characteristic the function of density of pedestrian speed. Actual data were recorded by video cameras to evaluate the density in seven time intervals for each point data. The speed-density models excluding non-linear weight were proposed.

2. LITERATURE REVIEW

In general, pedestrian flow is different from vehicular flow problem. The speed of pedestrian depends on their surrounding including others pedestrians and environment objects (Teknomo, 2002) but the current behavior is influenced by that of others in the past on the downstream conditions that have been formed ahead them along a trajectory (Han, 2003). Pedestrians try to move forward to crowded or try to avoid crowded areas (Bauer et al., 2007).

Traffic flow studies are classified as static and dynamic of macroscopic, mesoscopic and microscopic models.

![Figure 1 Schematic of pedestrian studies](image-url)
Microscopic model: these models consider individual characteristics of each person as an agent, a cell, and a molecular. For example, Cellular Automata (CA) by Von Neumann and Burks in 1940s, CA is a discrete model that consists of a regular grid of cells, each cell in one of a finite number of states. In a CA model, time is also discretized into a finite number of steps, and the current state of a specific cell is determined by the states of its neighboring cells at the last time step (Yuan and Tan, 2007). Social Force model, it simulates pedestrian behaviors which consist of three parts such as a term describing the acceleration towards the desired velocity of motion. Second, two terms reflecting that a pedestrian keeps a certain distance to other pedestrians and borders. Lastly, a term modeling attractive effects (Helbing and Molnar, 1995). Lattice gas model is discrete-time fine network system made up of a series of grid cells, in which one occupant that can move forward, left, and right directions (Li et al., 2008), can only occupy one point. Isobe et al. (2004) studied pedestrian counter flow by experiment and lattice gas simulation where each person is simulated by a biased random walker follow the front person with the same direction. Agent-based model, Toyama et al. (2006) propose an agent-based model based on cellular automata technique. This model represents different pedestrian characteristics such as gender, speed, room shape familiarity, and group and obstacle avoidance behavior. This model shows that when the pedestrian population is heterogeneous, the macroscopic behavior is different from a uniformly modeled population of pedestrians. The pedestrian groups with different features have different escape probabilities and contribute in different ways to the macroscopic behavior. Braun et al. (2005) propose agent-based model based on the social force model. The model focuses the treatment of complex environments and their implications on agents' movement. They use social force for describe interaction between environment and agents, and they assign the skill to each agent to make decision. Experimental analysis is conducted on animal and human such as Saloma et al. (2003) conducted mice escape from water pool to dry plate and found that the results of experiment on mice are similar results in CA modeling.

Mesoscopic model: queuing models are included in this type. Group of individuals are model as a separate objects allocated to one of several delineate tract. Time progression is typically modeled using discrete time, where in the time update it is decided how the distribution of people changes by transferring people form one region to another region (Bauer et al., 2007).

Macroscopic model: The main objective of macroscopic model is the temporal of the crowd density and evaluates flow using fundamental diagrams as a continuum. Macroscopic models use some relationship between density and speed (Kachroo, 2009). Macroscopic pedestrian models have been developed since 1968 by Older, Fruin (1971) and applied in HCM (2000). Survey models were studied since 1986 in Singapore by Tanaboriboon et al. They found that density at 0-1 person/m$^2$ have the high variance from 52-75 m/min and maximum speed is 73.9 m/min which less than the studied in US and Britain respectively. Pedestrian walking in China were studied by Tanaboriboon and Jing (1994) and Lam et al. (1995) in Hong Kong, walking speed in indoor and outdoor were monitored for speed-density relationships that are similarly to those developed for Singapore by Tanaboriboon et al. (1986).

Huang et al. (2009) modified Hughes’ two dimensional of continuum walking model and developed a solution algorithm that based on fluid dynamics. Laxman et al. (2010) studied mixed traffic condition (the motorized and non-motorized road) for pedestrian flow and found that the pedestrian tries to move forward out of mixed condition as fast as possible because of the pedestrian hazard risk situation. Moreover, free flow speed is higher than reports for Britain, China and Singapore.
3. DATA COLLECTION

To conduct the speed-density study in the concentrated area, CBD sidewalk in Silom Street, Thailand was selected as the observation site. Surrounding along the Silom Street, there are central offices, banks, hotels, offices, shopping centers, mass rapid transits and recreation zones for tourists. Figure 2 shows layout of study site which separated to 6 sub-sections. Grey hatch area is effective area for pedestrian walking (2.45 m. width and 25 m. long). Figure 3 (a) shows map of Thailand and figure 3(b) shows a one frame of video recording.

![Figure 2 Layout of study site](image1)

![Figure 3 Map of Thailand and a one frame of the video recordings](image2)

<table>
<thead>
<tr>
<th>Section</th>
<th>Length (m)</th>
<th>Effective Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>5.00</td>
<td>2.45</td>
</tr>
<tr>
<td>2-3</td>
<td>5.00</td>
<td>2.45</td>
</tr>
<tr>
<td>3-4</td>
<td>2.50</td>
<td>2.45</td>
</tr>
<tr>
<td>4-5</td>
<td>2.50</td>
<td>2.45</td>
</tr>
<tr>
<td>5-6</td>
<td>5.00</td>
<td>2.45</td>
</tr>
<tr>
<td>6-7</td>
<td>5.00</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Video records were used to gather data for the study on speed and density relationships at the observation sites. Pedestrians were manually count over a measured observed length for 6 sub-sections and speeds were then calculated. The recordings were analyzed frame by frame to minimize the errors for extracting travel time data with frame rate 25 FPS (accuracy = 0.04 s). These recordings were playback in laboratory to show limits of the measured sections, time, and frame number. The data for movements were separated in two groups (Estimated
4. METHODOLOGY

The macroscopic of pedestrian flow model has been widely used the continuum approach for whole section or network. When a pedestrian move towards and generate an occupation density in the sidewalk then speed and flows are determined from the density.

In a macroscopic simulation, the speed is only dependent on density. In reality, speed is a function of density and time but we assume speed depends on density. The density recorded at a sidewalk depends on the number of people who use it and if we assume that the density is directly proportional to the number of occupants assigned to the sidewalk and inversely proportional to its sidewalk area.

Density is high, the walking speed has to slow down, and travel time is increasing but the characteristics of pedestrian different from motor vehicle. Pedestrian require less space for accelerate the walking speed. In whole section, the density is random fluctuant density, and the condensed area may occur in many points as shown in Figure 5. A pedestrian have to change to speed depend on degree of density for each condensed sections and general sections.

In conventional data collection, density is measured once time from beginning line to ending line. For example, in figure 5(a), the density is 0.14 $p/m^2$ and we may estimate travel time is less and the pedestrian may increase walking speed because of loose density. However, in fact the density of sidewalk is uncertain increase and decrease over the time. For example in figure 5(b), a density at a 2nd line is 0.28 $p/m^2$, in figure 5(c) a density at 3rd line is 0.44 $p/m^2$, in figure 5(d) a density at 4th line is 0.44 $p/m^2$ and in figure 5(e) a density at 5th line is 0.32 $p/m^2$. Therefore, the accuracy of speed estimation could be improved by determine the average density by combining the values of an instant density which collect from every interest lines on a sidewalk. A single number of an average density is calculated the travel speed and travel time.

Figure 4 Illustration of the density.
Figure 5(a) Example of pedestrian walking for density 0.14 $p/m^2$ at 1st line

Figure 5(b) Example of pedestrian walking for density 0.28 $p/m^2$ at 2nd line

Figure 5(c) Example of pedestrian walking for density 0.44 $p/m^2$ at 3rd line

Figure 5(d) Example of pedestrian walking for density 0.44 $p/m^2$ at 4th line

Figure 5(e) Example of pedestrian walking for density 0.32 $p/m^2$ at 5th line
Notation \((i)\) is an id number for every sample pedestrian. The different 5 cases \((c)\) were test for speed estimation model. Sidewalk was separated by 7 lines \((n)\) or 6 sub-sections.

We collect the arrival time \((t_{i,\text{in}})\) and the departure \((t_{i,\text{out}})\) time of every sample pedestrian. An instant area \((A)\) of sample pedestrian is \((w \times l)\). Number of pedestrian in instant area of sample pedestrian on line \((n)\) is \((N_{i,n})\). An instant density of sample pedestrian on line \((n)\) is \((k_{i,n}^{\text{inst}})\). Both of arrival time and departure time were calculated the individual velocities \(v_i\). The instant density of sample pedestrian on line \((n)\) was calculated by \(\frac{N_{i,n}}{A}\) that called \((k_{i,n}^{\text{inst}})\). The following steps were used to collect the pedestrian movements in the video tapes.

1. Random a sample pedestrian \((i)\)
2. Notice the arrival time \((t_{i,\text{in}})\) of a sample pedestrian
3. At the sample pedestrian’s foot on the line \((n)\), pause the video file and count a number of pedestrian \((N_{i,n})\) in an instant area \((A)\).
4. Dividing a number of pedestrian by an instant area \((A)\) then give an instant density \((k_{i,n}^{\text{inst}})\).
5. Repeat the processes 3 and 4 until a sample pedestrian arrives on every line (1-7).
6. Mark the departure time of a sample pedestrian on line 7.
7. The walking time of a sample pedestrian in influential length is subtract of \((t_{i,\text{in}})\) from \((t_{i,\text{out}})\)
8. A sample pedestrian walking velocity is then dividing the length by the walking time
9. Repeat the processes until the required sample size is completely analyzed.

Figure 6 shows a sample pedestrian walking through the measurement section. After we finish the processes, the average density of each sample pedestrians was analyzed.

\[
K_i^{\text{avg}} = |\alpha_1 k_{i,1}^{\text{inst}}| + |\alpha_2 k_{i,2}^{\text{inst}}| + |\alpha_3 k_{i,3}^{\text{inst}}| + |\alpha_4 k_{i,4}^{\text{inst}}| + |\alpha_5 k_{i,5}^{\text{inst}}| + |\alpha_6 k_{i,6}^{\text{inst}}| + |\alpha_7 k_{i,7}^{\text{inst}}| \tag{1}
\]

All parameters are following:
Currently, authors study the density effect of the 5 cases with 457 data points to determine density-speed-travel time relationships. However, we assume all nonlinear weights are equal for each section for this study. All study cases are following.

Case 1, the average density in equation (2) is an instant density of sidewalk when a sample pedestrian arrives at the 1st line.

\[
K_i^{avg} = k_{i,1}^{inst}
\]  

(2)

Case 2, the average density in equation (3) is the average value of instant density on sidewalk when a sample pedestrian arrives at 1st, 4th line and 7th line.

\[
K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,4}^{inst} + k_{i,7}^{inst}}{3}
\]  

(3)

Case 3, the average density in equation (4) is the average value of instant density on sidewalk when a sample pedestrian arrives at 1st, 4th and 6th line.

\[
K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,4}^{inst} + k_{i,6}^{inst}}{3}
\]  

(4)

Case 4, the average density in equation (5) is the average value of instant density on sidewalk when a sample pedestrian arrives at 1st, 2nd, 3rd, 5th and 6th line.

\[
K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst}}{5}
\]  

(5)

Case 5, the average density in equation (6) is the average value of instant density on sidewalk when a sample pedestrian arrives at 1st, 2nd, 3rd, 5th, 6th and 7th line.

\[
K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst} + k_{i,7}^{inst}}{6}
\]  

(6)
5. RESULTS

In this part, speed estimation models are presented for each case. The density was counted in every line from 6 sub-sections and authors calculate the average of density and speed of individual for 5 cases. Actual data were separated in 2 groups: group 1 for speed estimation and group 2 for model validation that shown in this part. Model validation were conducted by MAPE (Mean Absolute Percentage Error).

5.1 Case 1:  \( k_{i}^{\text{avg}} = k_{i,1}^{\text{inst}} \)

Figure 7(a) and 7(b) show the average density of instant density of sidewalk related with speed and travel time respectively. The \( R^2 \) in figure 7(a) 0.2808, \( R^2 \) in figure 7(b) 0.2988.

5.2 Case 2:  \( k_{i}^{\text{avg}} = \frac{k_{i,1}^{\text{inst}} + k_{i,4}^{\text{inst}} + k_{i,7}^{\text{inst}}}{3} \)

Figure 8(a) and 8(b) show the average density of instant density of sidewalk related with speed and travel time respectively. The \( R^2 \) in figure 8(a) 0.3555, \( R^2 \) in figure 8(b) 0.4021.
5.3 Case 3:  
\[ K_{i}^{avg} = \frac{k_{i,1}^{inst} + k_{i,4}^{inst} + k_{i,6}^{inst}}{3} \]

Figure 9(a) and 9(b) show the average density of instant density of sidewalk related with speed and travel time respectively. The $R^2$ in figure 9(a) 0.3667, $R^2$ in figure 9(b) 0.4092.

5.4 Case 4:  
\[ K_{i}^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst}}{5} \]

Figure 10(a) and 10(b) show the average density of instant density of sidewalk related with speed and travel time respectively. The $R^2$ in figure 10(a) 0.3775, $R^2$ in figure 10(b) 0.4208.

5.5 Case 5:  
\[ K_{i}^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst} + k_{i,7}^{inst}}{6} \]

Figure 11(a) and 11(b) show the average density of instant density of sidewalk related with speed and travel time respectively. The $R^2$ in figure 11(a) 0.3645, $R^2$ in figure 11(b) 0.4146.
Figure 11(a) Density and speed relationship of case 5

Figure 11(b) Density and travel time relationship of case 5

Table 2 shows comparison of linear density-speed relationship and $R^2$. Table 3 shows comparison of linear density-travel time relationship and $R^2$.

### Table 2 $R^2$ comparison of density-speed relationships.

<table>
<thead>
<tr>
<th>Case</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $K_{i,1}^{avg} = k_{inst}$</td>
<td>$s = -0.7143k + 1.3793$</td>
<td>0.2808</td>
</tr>
<tr>
<td>2. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,4}} + k_{inst_{i,7}}}{3}$</td>
<td>$s = -1.0851k + 1.4752$</td>
<td>0.3555</td>
</tr>
<tr>
<td>3. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,4}} + k_{inst_{i,6}}}{3}$</td>
<td>$s = -0.9908k + 1.4527$</td>
<td>0.3667</td>
</tr>
<tr>
<td>4. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,2}} + k_{inst_{i,3}} + k_{inst_{i,5}} + k_{inst_{i,6}}}{5}$</td>
<td>$t = 13.517k + 17.831$</td>
<td>0.2988</td>
</tr>
<tr>
<td>5. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,2}} + k_{inst_{i,3}} + k_{inst_{i,5}} + k_{inst_{i,6}} + k_{inst_{i,7}}}{6}$</td>
<td>$t = 19.961k + 16.074$</td>
<td>0.4146</td>
</tr>
</tbody>
</table>

Where $s$ is pedestrian speed ($m/s$) and $k$ is density ($p/m^2$)

### Table 3 $R^2$ comparison of density-travel time relationships.

<table>
<thead>
<tr>
<th>Case</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $K_{i,1}^{avg} = k_{inst}$</td>
<td>$t = 13.517k + 17.831$</td>
<td>0.2988</td>
</tr>
<tr>
<td>2. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,4}} + k_{inst_{i,7}}}{3}$</td>
<td>$t = 21.171k + 15.85$</td>
<td>0.4021</td>
</tr>
<tr>
<td>3. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,4}} + k_{inst_{i,6}}}{3}$</td>
<td>$t = 19.203k + 16.321$</td>
<td>0.4092</td>
</tr>
<tr>
<td>4. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,2}} + k_{inst_{i,3}} + k_{inst_{i,5}} + k_{inst_{i,6}}}{5}$</td>
<td>$t = 19.124k + 16.279$</td>
<td>0.4208</td>
</tr>
<tr>
<td>5. $K_{i,1}^{avg} = \frac{k_{inst_{i,1}} + k_{inst_{i,2}} + k_{inst_{i,3}} + k_{inst_{i,5}} + k_{inst_{i,6}} + k_{inst_{i,7}}}{6}$</td>
<td>$t = 19.961k + 16.074$</td>
<td>0.4146</td>
</tr>
</tbody>
</table>

Where $t$ is travel time (second) and $k$ is density ($p/m^2$)
Table 4: Mean Absolute Percentage Error (%)

<table>
<thead>
<tr>
<th>Model</th>
<th>MAPE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( K_i^{avg} = k_{i,1}^{inst} )</td>
<td>23.36</td>
</tr>
<tr>
<td>2. ( K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,4}^{inst} + k_{i,7}^{inst}}{3} )</td>
<td>27.36</td>
</tr>
<tr>
<td>3. ( K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,4}^{inst} + k_{i,6}^{inst}}{3} )</td>
<td>26.24</td>
</tr>
<tr>
<td>4. ( K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst}}{5} )</td>
<td>15.79</td>
</tr>
<tr>
<td>5. ( K_i^{avg} = \frac{k_{i,1}^{inst} + k_{i,2}^{inst} + k_{i,3}^{inst} + k_{i,5}^{inst} + k_{i,6}^{inst} + k_{i,7}^{inst}}{6} )</td>
<td>26.39</td>
</tr>
</tbody>
</table>

Figure 12 Plot of estimated speed and observed speed

From table 2 and 3, speed-density-travel time relationship of case 4 is selected because goodness of fitness is 0.3775 for density-speed relationship and 0.4208 for travel time-density relationship are better among other cases. Regarding section of sidewalk area, it found that multi-section models provide \( R^2 \) value better than single section model. Final section of both 2nd model and 5th model are included in model but final section was neglected effect in model.
3rd and 4th which provide better results than 2nd and 5th model. In addition, we assume that we can increase accuracy of speed-density model by increase numbers of section for speed-density estimation but 5 sub-sections provides $R^2$ better than 6 sub-sections.

Table 4 shows Mean Absolute Percentage Error (%). The selected speed-density model is evaluated, estimated and observed pedestrian speed is plotted to investigate the precision of model estimation of selected model. Model 4 is fitter well than model 1, 3, 2 and 5 respectively. Model 4 shows the well fit of MAPE 15.79 % and the others proposed models appear MAPE higher than 20 %. Figure 12 shows plot of the estimated speed and the observed speed, it found that almost estimated speed is higher than observed speed. Therefore, the author chooses the speed estimation from case 4 to determine speed-speed-travel time relationship in flow model because of the highest $R^2$ among the other cases and case 4 presents the well fit of MAPE among other cases.

6. SUMMARY

In this study, the sidewalk in Central Business District (Silom, Bangkok, Thailand) is chosen as the observation entities to study the relations of pedestrian density, speed and travel time. We have investigated the pedestrian flow in peak time by video recording. We have discussed the pedestrian flow that depends on density. The condensed area of platoon may occur in several zones in the sideway. The variety of density affects the speed and travel time of pedestrian. So, in the macroscopic point of view then the speed estimation should determine by average instant densities. We have proposed new data collection processes. We have compared the pedestrian flow in five models that depend on the number of sections for each model. It shown that separation sideway in several sub-sections can predict the speed and travel time better than single section. The 4th model is selected to simulate the pedestrian flow in the next task because the 4th model presents the highest $R^2$ among other proposed models. In addition, 4th model is validated by actual data and presents the well fit of MAPE less than the others proposed models. However, too many sub-section does not presents a well fit of speed estimation such as case 5. Case 5 has sub-section more than case 4 but it presented less $R^2$. In addition, the different terms in case 4 and 5 model is $k_i^{inst}$, so we can assume that the final sub-section of this sideway does not give a significant impact on the speed of the whole section.

7. FURTHER RESEARCH

The density boundaries can affect the speed and travel time; the nearest region of density may highly affect the speed and travel time more than the far region. So we need to analysis the parameters or ratio of density region. We will apply index fund optimization using genetic algorithm. It is one of portfolio optimization in index fund studies (Orito et al., 2009 and Orito et al., 1998). The concept is the optimization of the proportion of funds in the index fund, which consists of a small number of listed companies. We will optimize nonlinear weight of density with genetic algorithm.
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