Road Pricing Evaluation for Freight Transport with Non-cooperative Game Theory

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1. Abstract

Road pricing has been implemented in a few countries but was not well accepted generally. Most road pricing initiatives has been to control passenger car traffic and very few studies were done to evaluate the impact of road pricing on freight transport. Road pricing is considered an effective tool for the authority to mitigate congestion and fully utilise the existing road network. However, road pricing can be ineffective if pricing of road links do not consider the behaviour of the stakeholders prior to the implementation. Generally, in the freight transport environment carriers are interested in reducing its delivery cost by choosing the cheapest route to reach the customers while an authority seeks to reduce congestion on popular road links. Such conflicting objectives create a good opportunity for non-cooperative game theory. This paper attempts to evaluate the impact of road pricing on carriers' route choices using a simple non-cooperative game theoretic approach, which features a carriers' game played between 2 carriers and an authority game between a union of carriers playing against the authority. The preliminary results of the evaluation show the route choice dilemma faced by the carriers when they are playing their equilibrium choices and provide a feasible range of toll price for the authority.

2. Introduction

(1) Background

In the report published by Organisation for Economic Co-operation and Development (OECD, 2003), the Working Group recognised that the complexity of urban freight transport can be solved by involving stakeholders for policy-making in urban goods transport. As defined in City Logistics, it is "the process for totally optimising the logistics and transport activities by private companies in urban areas while considering the traffic environment, the traffic congestion and energy consumption within the framework of a market economy." (Taniguchi et al. 1999). The main stakeholders in City Logistics are the Shippers, Carriers, Residents and Administrators. It is expected that as more people migrate and live in the city, the demand for goods generated by the residents in the city will increase. Shippers will increase their daily or weekly delivery to retailers and frequency of home delivery is expected to rise. The increase in demand for deliveries will create a competitive market for carriers, who will try to improve their services while trying to gain as much profit as possible and reduce the cost of delivery. With the increase in global trading and domestic consumption, the economy of a country is likely to improve. However, freight transport creates several problems including environmental and social if no attention is paid on proper urban logistics policies. Policy measures require in depth evaluation before implementation and thorough analytical evaluation of policy measures will be an added value to convince various stakeholders on its acceptance. As mentioned by Boerkamps et. al. (2000), purely statistical models have limitations due to the dynamic changes in freight transport but behavioural models are able to predict freight transport in future situations, especially when we study the impact of City Logistics measures. There are several initiatives to solve urban logistics problems including advanced information systems, co-operative freight transport systems, urban distribution centres, load factor controls, underground freight transport systems and road pricing. The term "road pricing" has been used interchangeably with road user charging, congestion charging, congestion pricing, road tolling, variable pricing, etc (Saleh et. al. 2009). The motivation for this paper is partly influenced by an article, Game Engineering, written by Nobel Laureate, Aumann (2008). In his article, Aumann personally experienced the dilemma typically faced by drivers in a road pricing scheme; should he pay a higher price to enter the city or choose not to travel. The price Aumann has to pay for entering New York City during the 911 incident is to risk his life compared to the risk of not able to find a place to say his prayers outside the city. Similarly, carriers who face the demands of

*Keywords: City Logistics, Non-cooperative Game Theory, Freight Transport, Road Pricing

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customers' strict time window of delivery will have to decide on the best alternative route to travel in view of the congestion pricing and road link congestion. In this paper, we attempt to produce a non-cooperative game theoretic route choice model to gather some theoretical explanation of carriers' route choice in response to road pricing. A game theoretic road pricing model between the carriers and authority will also be developed.

(2) Literature Review

Road pricing systems require theoretical frameworks to assist local authorities in traffic management to meet local traffic objectives and to be politically and publicly feasible, rather than implementing some policies based on previous experience (Saleh, 2005). The theoretical background of road pricing has depended on the fundamental economic principle of marginal cost pricing where the toll is charged according to the difference between the marginal social cost and marginal private cost (Yang & Huang, 1998). Several scientific papers, books and references listed by (Tsekeris & Voß, 2009) review the vast research on road pricing but problems like social, political and institutional concerns still hinder decision makers. Freight transport is often disproportionately neglected as compared to passenger traffic when policies are considered to mitigate traffic congestion (Hensher and Puckett, 2005). Past research surveys (Link, 2008; Noordegraaf & van de Riet, 2007; Holguín-Veras, et. al., 2006) highlighted that freight transporters are less optimistic that road pricing will affect their behaviour of travel due partly to the fact that they are restricted by the delivery time window requested by customers. Game theory has been applied in several transportation issues and Hollander & Prashker (2006) covered a list of non-cooperative game theory application in transport analysis. In the paper of Joksimovic et. al. (2004), an optimal toll design problem is represented by a bi-level optimisation problem. In the paper, a simple route choice problem under the influence of road pricing is formulated as a monopoly, Stackelberg and Cournot game and the road network is classified to three route choices, namely "tolled", "untolled" and "do not travel". Levinson (2005) developed a 2-players game theoretic congestion model including road pricing followed by a 3-player game model among passenger traffic. The use of game theory approach requires the acceptance of assuming that the players in the game are rational, have common knowledge and all players know the rules of the game. In our evaluation of road pricing for freight transport, we assumed that the carriers have no choice of delivering the goods at a different time-window and are travelling simultaneously. Congestion will occur when both carriers travel on the same link and the delay time will depend on whether they are travelling on an arterial road or a street.

3. Problem formulation

In our problem, the carriers seek to minimise their delivery cost, which includes the distance-based cost for their truck, additional cost from road pricing by the authority and delay cost due to congestion on road links. The cost of the carriers can be represented by the following

$$O_i^r = \sum_{k \in K} d_k(c_i)x_k + \alpha_i t_k + p_k x_k$$

where O_i^r is the outcome of carrier *i* for choosing route *r*, d_k is the distance of link *k*, c_i is the distance-based cost for the truck, α_i is the value of time for carrier *i*, t_k is the delay time experienced by the carriers at link *k*, p_k is the road pricing by the authority and x_k is1if link *k* is used and 0 otherwise.

In contrary, the Authority is concern on the congestion of individual links and seeks to minimise the cost of congestion or maximise the congestion net benefit by pricing the road links. The congestion net benefit can be represented by the following

$$B = \sum_{c \in C, k \in K} p_k x_k^c - \sum_{c \in C, k \in K} \beta_k t_k x_k^c$$

where *B* is the congestion net benefit, β_k is the value of link congestion of the authority, x_k^c is 1 if link *k* is used by carrier *c* and 0 otherwise. In the authority's game, the carriers' payoff will be the average cost of the 2 carriers in the carriers' game. This assumption is to consider that the authority is playing a game between a group of carriers and consider the total cost incurred by their usage of links.

4. Game theory notation

The above problem is represented with a non-cooperative, non-zero sum game in the carriers' game and in the authority's game. This paper follows closely to the notations by Fudenberg & Tirole (1991). Carrier *i*'s strategy set is denoted by $s_i \in S_i$. We will change the notation from s_i to r_i where $S_i = \{r_i, \ldots\ldots r_m\}$, representing the routes, r_i available to Carrier *i*. The game between the two carriers has a strict Nash equilibrium (NE) if $O_i(r_i^*, r_{-i}^*) > O_i(r_i, r_{-i}^*)$.

5. Scenario Application

We shall use the road network as shown in Figure 1 for our application. In this network, the blue links represent arterial roads while the red links represent streets. The numbers in parenthesis represent the reverse direction of each link. There are two carriers, C1 and C2, one shipper S and R can be considered an area of receivers. It is assumed that the carriers are to visit the shipper before visiting R and heading back to their respective location. It is assumed that the carriers have only a truck each and to simplify our problem for easier evaluation, the links' distances, distance-based cost of each carrier's truck, value of time of each carrier are provided in Table 1. The authority's values of delay for links are shown in Table 2. The delay times of links are shown in Table 3 where delay time equals t_k if there is only one carrier on the arterial road, $2t_k$ if there are 2 carriers on the arterial road and one carrier on street, and 4 t_k if there are 2 carriers on the street. We will let t_k = 10mins in our example. Table 4 shows the routes available to Carriers 1 and 2.

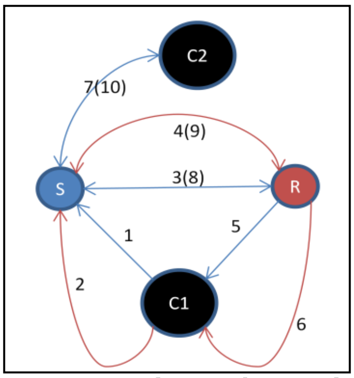

Figure 1: Road network example

6. Results and discussion

The carriers' game shown in Table 5 is without road pricing and the NE is that both carriers will choose Route 1 as their choice which cost 3400units for Carrier 1 and 4500units for Carrier 2. Both routes 1 taken by the carriers consist of links 3 and intuitively link 3 is chosen as an option to price. We have considered 1000units to price for link 3 and resulted in 3 NE as shown in Table 6. In the authority's game, we have repeated the previous step to price 1000units on each link individually and took the average cost borne between the carriers for each route choice combination as the representative value to minimise. The results are presented in Table 7. To model the authority game, we have assumed that there is only one chance for the authority to price a link at 1000units. The authority's option of not pricing is not the best response to the carriers' choices of routes 1 but to price link 3 which will increase their benefit from -1800units to 200units if the carriers continue on routes 1. If link 3 is priced in the carriers' game, both carriers will face a situation where alternating their own route will create lesser costs to their competitor. However if both carriers do not alternate their routes and continue on routes 1, the authority will benefit 200units from their link usage. The carriers will face a dilemma of whether to alternate their routes to benefit their competitor or to face with road pricing where both carriers used the same link and the authority benefits. We extended the game by increasing the link 3 pricing to 1300units as shown in the carriers' game in Table 8. A new NE of both carriers taking route 3 replacing the NE of both carriers taking route 1 has emerged. The cost of taking route 3 is now 100units cheaper than route 1. Table 9 shows the authority's game with 1300units priced on link 3 with 2 same NE as the authority's game played previously. Similarly, the alternative route for each carrier in the carriers' game will benefit their competitor but the higher price for link 3 has caused the carriers to avoid travelling on link 3 in their NE of route 3. Therefore, further increase in pricing of link 3 may not be necessary by the authority. As such, we attempted to increase the link price to 1400units and the single NE in the carriers' game is for both carriers to choose route 3 as shown in Table 10. However the NE in the authority's game shown in Table 11 remains as when link 3 was priced at 1300units. This reflected that the carriers' objective of a cheaper delivery did not meet the authority's objective of benefiting from pricing link 3. These preliminary results have provided a range of 1000units to 1300units for the authority to consider for the price on link 3 while the non-cooperative game representation of the carriers' game models the dilemma faced by the 2 carriers

Table 1: Parameters used in example problem

Link distance	Red links = 20km, Blue links = 10km
Distance-based cost of carriers	Fixed at 100units/km
Value of time for carriers	Fixed at 10units/min

Table 2: Authority's value of delay for links (unit/min)

Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8	Link 9	Link 10
20	10	40	10	20	10	20	20	10	20

Table 3: Delay time of links (in minutes)

	Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8	Link 9	Link 10
1 carrier	10	20	10	20	10	20	10	10	20	10
2 carriers	20	40	20	40	20	40	20	20	40	20

Table 4: Sets of routes available to Carriers

Routes for Carrier 1	Links
Route 1	1-3-5
Route 2	1-3-6
Route 3	1-4-5
Route 4	1-4-6
Route 5	2-3-5
Route 6	2-3-6
Route 7	2-4-5
Route 8	2-4-6

Routes for Carrier 2	Links
Route 1	7-3-8-10
Route 2	7-3-9-10
Route 3	7-4-8-10
Route 4	7-4-9-10
Route 5	7-3-5-1-10
Route 6	7-3-5-2-10
Route 7	7-3-6-1-10
Route 8	7-3-6-2-10
Route 9	7-4-5-1-10
Route 10	7-4-5-2-10
Route 11	7-4-6-1-10
Route 12	7-4-6-2-10

Table 5: Costs of Carriers if there is no road pricing (in 1000units)

0	Carrier 2																							
Carrier 1	**Route 1**		**Route 2**		**Route 3**		**Route 4**		**Route 5**		**Route 6**		**Route 7**		**Route 8**		**Route 9**		**Route 10**		**Route 11**		**Route 12**	
Route 1	3.4	4.5	3.4	5.6	3.3	5.5	3.3	6.6	3.6	5.8	3.5	6.8	3.5	6.8	3.4	7.8	3.5	6.8	3.4	7.8	3.4	7.8	3.3	8.8
Route 2	4.5	4.5	4.5	5.6	4.4	5.5	4.4	6.6	4.6	5.7	4.5	6.7	4.8	7	4.7	8	4.5	6.7	4.4	7.7	4.7	8	4.6	9
Route 3	4.4	4.4	4.4	5.5	4.6	5.7	4.6	6.8	4.6	5.7	4.5	6.7	4.5	6.7	4.4	7.7	4.8	7	4.7	8	4.7	8	4.6	9
Route 4	5.5	4.4	5.5	5.5	5.7	5.7	5.7	6.8	5.6	5.6	5.5	6.6	5.8	6.9	5.7	7.9	5.8	6.9	5.7	7.9	6	8.2	5.9	9.2
Route 5	4.5	4.5	4.5	5.6	4.4	5.5	4.4	6.6	4.6	5.7	4.8	7	4.5	6.7	4.7	8	4.5	6.7	4.7	8	4.4	7.7	4.6	9
Route 6	5.6	4.5	5.6	5.6	5.5	5.5	5.5	6.6	5.6	5.6	5.8	6.9	5.8	6.9	6	8.2	5.5	6.6	5.7	7.9	5.7	7.9	5.9	9.2
Route 7	5.5	4.4	5.5	5.5	5.7	5.7	5.7	6.8	5.6	5.6	5.8	6.9	5.5	6.6	5.7	7.9	5.8	6.9	6	8.2	5.7	7.9	5.9	9.2
Route 8	6.6	4.4	6.6	5.5	6.8	5.7	6.8	6.8	6.6	5.5	6.8	6.8	6.8	6.8	7	8.1	6.8	6.8	7	8.1	7	8.1	7.2	9.4

Table 6: Costs of Carriers if 1000units is priced on Link 3 (in 1000units)

1000	Carrier 2																							
Carrier 1	**Route 1**		**Route 2**		**Route 3**		**Route 4**		**Route 5**		**Route 6**		**Route 7**		**Route 8**		**Route 9**		**Route 10**		**Route 11**		**Route 12**	
Route 1	4.4	5.5	4.4	6.6	4.3	5.5	4.3	6.6	4.6	6.8	4.5	7.8	4.5	7.8	4.4	8.8	4.5	6.8	4.4	7.8	4.4	7.8	4.3	8.8
Route 2	5.5	5.5	5.5	6.6	5.4	5.5	5.4	6.6	5.6	6.7	5.5	7.7	5.8	8	5.7	9	5.5	6.7	5.4	7.7	5.7	8	5.6	9
Route 3	4.4	5.4	4.4	6.5	4.6	5.7	4.6	6.8	4.6	6.7	4.5	7.7	4.5	7.7	4.4	8.7	4.8	7	4.7	8	4.7	8	4.6	9
Route 4	5.5	5.4	5.5	6.5	5.7	5.7	5.7	6.8	5.6	6.6	5.5	7.6	5.8	7.9	5.7	8.9	5.8	6.9	5.7	7.9	6	8.2	5.9	9.2
Route 5	5.5	5.5	5.5	6.6	5.4	5.5	5.4	6.6	5.6	6.7	5.8	8	5.5	7.7	5.7	9	5.5	6.7	5.7	8	5.4	7.7	5.6	9
Route 6	6.6	5.5	6.6	6.6	6.5	5.5	6.5	6.6	6.6	6.6	6.8	7.9	6.8	7.9	7	9.2	6.5	6.6	6.7	7.9	6.7	7.9	6.9	9.2
Route 7	5.5	5.4	5.5	6.5	5.7	5.7	5.7	6.8	5.6	6.6	5.8	7.9	5.5	7.6	5.7	8.9	5.8	6.9	6	8.2	5.7	7.9	5.9	9.2
Route 8	6.6	5.4	6.6	6.5	6.8	5.7	6.8	6.8	6.6	6.5	6.8	7.8	6.8	7.8	7	9.1	6.8	6.8	7	8.1	7	8.1	7.2	9.4

Table 7: Game representation between Carriers and Authority for pricing 1000units (units in 1000units)

Carrier Routes (C1,C2)	Authority																					
	No pricing		Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9		Link 10	
1,1	3.95	-1.8	4.45	-0.8	3.95	-1.8	4.95	0.2	3.95	-1.8	4.45	-0.8	3.95	-1.8	4.45	-0.8	4.45	-0.8	3.95	-1.8	4.45	-0.8
2,1	4.50	-1.8	5.00	-0.8	4.50	-1.8	5.50	0.2	4.50	-1.8	4.50	-1.8	5.00	-0.8	5.00	-0.8	5.00	-0.8	4.50	-1.8	5.00	-0.8
3,1	4.40	-1.6	4.90	-0.6	4.40	-1.6	4.90	-0.6	4.90	-0.6	4.90	-0.6	4.40	-1.6	4.90	-0.6	4.90	-0.6	4.40	-1.6	4.90	-0.6
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1,3	4.40	-1.6	4.90	-0.6	4.40	-1.6	4.90	-0.6	4.90	-0.6	4.90	-0.6	4.40	-1.6	4.90	-0.6	4.90	-0.6	4.40	-1.6	4.90	-0.6
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8,12	8.30	-1.6	8.30	-1.6	9.30	0.4	8.30	-1.6	9.30	0.4	8.30	-1.6	9.30	0.4	8.80	-0.6	8.30	-1.6	8.30	-1.6	8.80	-0.6

Table 8: Costs of Carriers if 1300units is priced on Link 3 (in 1000units)

1000	Carrier 2																							
Carrier 1	**Route 1**		**Route 2**		**Route 3**		**Route 4**		**Route 5**		**Route 6**		**Route 7**		**Route 8**		**Route 9**		**Route 10**		**Route 11**		**Route 12**	
Route 1	4.7	5.8	4.7	6.9	4.6	5.5	4.6	6.6	4.9	7.1	4.8	8.1	4.8	8.1	4.7	9.1	4.8	6.8	4.7	7.8	4.7	7.8	4.6	8.8
Route 2	5.8	5.8	5.8	6.9	5.7	5.5	5.7	6.6	5.9	7	5.8	8	6.1	8.3	6	9.3	5.8	6.7	5.7	7.7	6	8	5.9	9
Route 3	4.4	5.7	4.4	6.8	4.6	5.7	4.6	6.8	4.6	7	4.5	8	4.5	8	4.4	9	4.8	7	4.7	8	4.7	8	4.6	9
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Route 8	6.6	5.7	6.6	6.8	6.8	5.7	6.8	6.8	6.6	6.8	6.8	8.1	6.8	8.1	7	9.4	6.8	6.8	7	8.1	7	8.1	7.2	9.4

Table 9: Game representation between Carriers and Authority for pricing 1300units (units in 1000units)

Carrier Routes (C1,C2)	Authority																					
	No pricing		Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9		Link 10	
1,1	3.95	-1.8	4.60	-0.5	3.95	-1.8	5.25	0.80	3.95	-1.8	4.60	-0.5	3.95	-1.8	4.60	-0.5	4.60	-0.5	3.95	-1.8	4.60	-0.50
2,1	4.50	-1.8	5.15	-0.5	4.50	-1.8	5.80	0.80	4.50	-1.8	4.50	-1.8	5.15	-0.5	5.15	-0.5	5.15	-0.5	4.50	-1.8	5.15	-0.50
3,1	4.40	-1.6	5.05	-0.3	4.40	-1.6	5.05	-0.3	5.05	-0.3	5.05	-0.3	4.40	-1.6	5.05	-0.3	5.05	-0.3	4.40	-1.6	5.05	-0.30
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1,3	4.40	-1.6	5.05	-0.3	4.40	-1.6	5.05	-0.3	5.05	-0.3	5.05	-0.3	4.40	-1.6	5.05	-0.3	5.05	-0.3	4.40	-1.60	5.05	-0.30
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Table 10: Costs of Carriers if 1400units is priced on Link 3 (in 1000units)

1400	Carrier 2																							
Carrier 1	**Route 1**		**Route 2**		**Route 3**		**Route 4**		**Route 5**		**Route 6**		**Route 7**		**Route 8**		**Route 9**		**Route 10**		**Route 11**		**Route 12**	
Route 1	4.8	5.9	4.8	7	4.7	5.5	4.7	6.6	5	7.2	4.9	8.2	4.9	8.2	4.8	9.2	4.9	6.8	4.8	7.8	4.8	7.8	4.7	8.8
Route 2	5.9	5.9	5.9	7	5.8	5.5	5.8	6.6	6	7.1	5.9	8.1	6.2	8.4	6.1	9.4	5.9	6.7	5.8	7.7	6.1	8	6	9
Route 3	4.4	5.8	4.4	6.9	4.6	5.7	4.6	6.8	4.6	7.1	4.5	8.1	4.5	8.1	4.4	9.1	4.8	7	4.7	8	4.7	8	4.6	9
...	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**	**...**

Table 11: Game representation between Carriers and Authority for pricing 1400units (units in 1000units)

Carrier Routes (C1,C2)	Authority																					
	No pricing		Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9		Link 10	
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
3,1	4.40	-1.6	5.10	-0.2	4.40	-1.6	5.10	-0.2	5.10	-0.2	5.10	-0.2	4.40	-1.6	5.10	-0.2	5.10	-0.2	4.40	-1.6	5.10	-0.2
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1,3	4.40	-1.6	5.10	-0.2	4.40	-1.6	5.10	-0.2	5.10	-0.2	5.10	-0.2	4.40	-1.6	5.10	-0.2	5.10	-0.2	4.40	-1.6	5.10	-0.2
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7. Conclusion

We have presented the behaviour of freight carriers' route choice in response to road pricing and without road pricing in the carriers' game. The authority's game represents a game played between the authority and a union of carriers represented by the average cost of the 2 carriers. The authority seeks to maximise the congestion net benefit while the carriers choose routes to minimise their delivery cost. From the evaluation of the authority's game, it is rational for the authority to implement road pricing. The non-cooperative game between the carriers shows the dilemma of the carriers when road pricing is implemented. They will need to choose between alternating their routes or to travel on the usual route. Alternating their routes when their competitor did not, will bring benefit to their competitor but without alternating their routes the authority will benefit from their link usages. The authority gathers the range of link prices to charge the carriers when it plays the authority game but may face a conflict of objectives when the link price is charged beyond an amount acceptable to the carriers. This simple game theoretic representative of the behaviour between authority's decision to price which link and carriers' route choices in response to road pricing provides a basic understanding of conflicting interactions. Future research will seek to improve the model and provide more interaction and competitive evaluation between the authority and carriers. Attempts will also include the evaluation of different road pricing schemes, for example distance-based pricing, expanding the behavioural evaluation of more stakeholders including shippers.

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