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Congestion Pricing for Multi-Modal Transportation System in Bangkok: Formulation, Calibration and Evaluation

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Abstract: In this study, a multi-modal transportation system of Bangkok Metropolitan Area (BMA) is setup and calibrated for evaluating the impact of different congestion pricing schemes. In the proposed model, auto and public transport demands will be assigned separately to the same network for finding the utilities of travel. Based on the travel utilities, captive and non-captive demands for auto and public transport are estimated by nested logit model or elastic demand functions. 8 different congestion pricing schemes are tested on the current and future networks of BMA for choosing the most beneficial scheme for the next 20 years with the consideration of demand growth and extension of railway lines. The result suggested that congestion pricing scheme with the combination of radial, inner-cordon and outer-cordon tolls gives the best performance in shifting auto users to public transport and, reducing the congestion of network.

Key Words: *Multi-modal, congestion pricing, captive demand*

1. INTRODUCTION

In Bangkok, congestion pricing has long been considered as a part of the effective transport strategy for managing car demand and congestions (TDRI, 2001; Jaensirisak *et al*., 2008). In addition, the Urban Rail Transportation Masterplan (OCMLT, 2001) also recommended the use of road pricing to support the proposed rail transit network in Bangkok. Yet, an effective and practical implementation of congestion pricing should found on the in-depth review of previous experiences and the comprehensive description of the problem. Various governments have been interested in introducing urban congestion pricing in their cities, but only few of them have actually succeeded (i.e. Singapore, UK and Sweden). Public acceptability was probably the greatest barrier to the implementation of congestion pricing (Jones, 1998). To overcome this barrier, various studies in literature have incorporate an acceptability-related indices in the design of congestion pricing (Jeansirisak *et al*., 2002; Maruyama and Sumalee, 2002; Ho and Sumalee, 2009)

Congestion pricing has been considered as an effective mean for reducing traffic congestion and raising revenue for funding transportation improvements (Odeck and Brathen, 2002; Sumalee *et al*., 2004; Ho *et al*., 2005; Hau, 2006). In early stage, researches were mainly focused on the study of first-best congestion pricing which the total benefit of the system is maximized (Beckmann, 1965; Yang and Huang, 1998). As the first-best congestion pricing could only be achieved by applying the designed tolls to each of the links within the network, it is not practical and socially acceptable for real-world implementation. Thus, recent researches have been focused on finding the optimal toll locations and levels such that only a subset of links in the network could be tolled (Hearn and Ramana, 1998; Verhoef, 2002; Shepherd and Sumalee, 2004). Such optimal toll locations and levels found are known as the second-best solution of congestion pricing. As not all the links are tolled in this second-best congestion pricing, various kinds of pricing methods are developed. In the literatures two main types of pricing methods, point-based and area-based, are consider (Jones, 1998). For the point-based charging, drivers are charged when passing through a charging point and the charge is directly dependent on the number of passing made by the vehicle. Cordon-based charging (Sumalee, 2007; Ho *et al*., 2005), which is a combination of point-based charging, is the most common type of point-based charging. For area-based charging, area licensing system (Li, 1999; Richards and Harrison, 1999) is commonly adopted. Under an area licensing system, drivers have to purchase a permit to gain the right for entering the charging zone.

Majority of the previous literatures in road pricing have been focused on using traffic equilibrium models in predicting the impact of different road pricing schemes. For this type of model, the impact of road pricing on route diversion and trip depression can be evaluated directly. Nevertheless, this type of model could not directly evaluate the impact of modal shift and induced congestion on public transport system (due to the diversion of travelers from autos to public transport). The concept of multi-modal transport model was then proposed to allow for such effects to be explicitly considered. There has been a long history of the development of an underlying transit or multi-modal network model. Boyce and Bar-Gera (2004) provided an excellent review on this topic. One of the main difficulties in modeling public transport system is the representation of travelers' strategies in choosing the service route and line which is different from the car drivers. Earlier developments have been on the representation of the static strategic route choice of transit passenger (Chiriqui and Robillard, 1975; Spiess and Florian, 1989). These models were later extended to case with a congested network where waiting time and in-vehicle costs (crowding effect) are functions with passenger flows (De Cea and Fernandez, 1993; Wu *et al*., 1994). The resulting congested transit model involves the asymmetric travel cost function and hence the equilibrium condition for the transit assignment problem is formulated as a variational inequality (VI). In relation to the congested transit network, the limitations of explicit capacity constraints in static assignment models for the transit services are well recognized in the literature (De Cea and Fernandez, 1993; Lam *et al*., 2002; Comminetti and Correa 2001). Sumalee *et al*. (2009)

recently proposed a transit model considering the seat allocation and seat capacity constraint explicitly. Extensions of the transit model to the case with multi-modal trip have also been considered for a single journey comprised of different modes, e.g., park and ride (Fernandez *et al*., 1994) and a complex fare structure, e.g., transfer fare (Lo *et al*., 2003). Uchida *et al*. (2007) utilized the multi-modal network model to study the network design problem which aims to optimize the frequency of public transport service.

The remainder of this paper is organized as follows. Section 2 defines the formulation of the proposed combined modal split and assignment model for the multi-modal transportation system in BMA. Section 3 introduces the calibration procedure for adopting the proposed model in BMA. Description of BMA, calibration results and congestion pricing schemes are given in Section 4. The results for different congestion pricing schemes are discussed in Section 5 and we conclude the paper in Section 6.

2. MODEL FORMULATION

2.1 Combined modal split and assignment model

In this paper, the multi-modal transportation system in BMA is formulated as a combined modal split and assignment model. In the proposed model, auto and public transport (transit) demand will be separately assigned to the same network for determining the corresponding travel utilities which will be used in the modal split. Due to the interdependence of the modal split and auto/transit assignment process, an iterative approach is adopted for this combined modal split and assignment model (Figure 1). The proposed iterative approach is adopted separately for the captive and non-captive demand. Captive demand refers to the travelers that are not able to change their mode choice due to their geographical location or availability of car. In contrast, non-captive demand refers to the travelers that are able to change their mode choice based on the utilities they experienced. For the non-captive demand, the iteration starts with the potential OD matrix for the non-captive demand (N_d), which is estimated from the calibration process describe in Section 3. By using a nested logit modal split model, which will be described in more details in Section 2.3, the non-captive auto demand ($Q_d^{auto-nc}$), non-captive public transport demand (Q_d^{PT-nc}) and the not-travel demand for the non-captive travelers ($Q_d^{not-travel\_nc}$) could be found. For the captive demands, the iteration will be considered separately for the auto and public transport users. The captive auto demand ($Q_d^{auto\_c}$) and captive public transport demand (Q_d^{PT-c}) could be directly estimated from their elastic demand function, which will be discussed in more details in section 2.4. Then, the captive and non-captive demand for auto (transit) will be summed for the auto (transit) assignment. . The auto and transit assignment in the proposed model will be solved by using EMME (INRO, 2008) and the results (i.e. travel times and distance of auto and public transport users) will be used to update the modal split model and the elastic demand functions. With these updates, the OD matrices will be re-estimated and the above process will be repeated until the differences of OD matrices between successive iterations are less than the predefined tolerance.

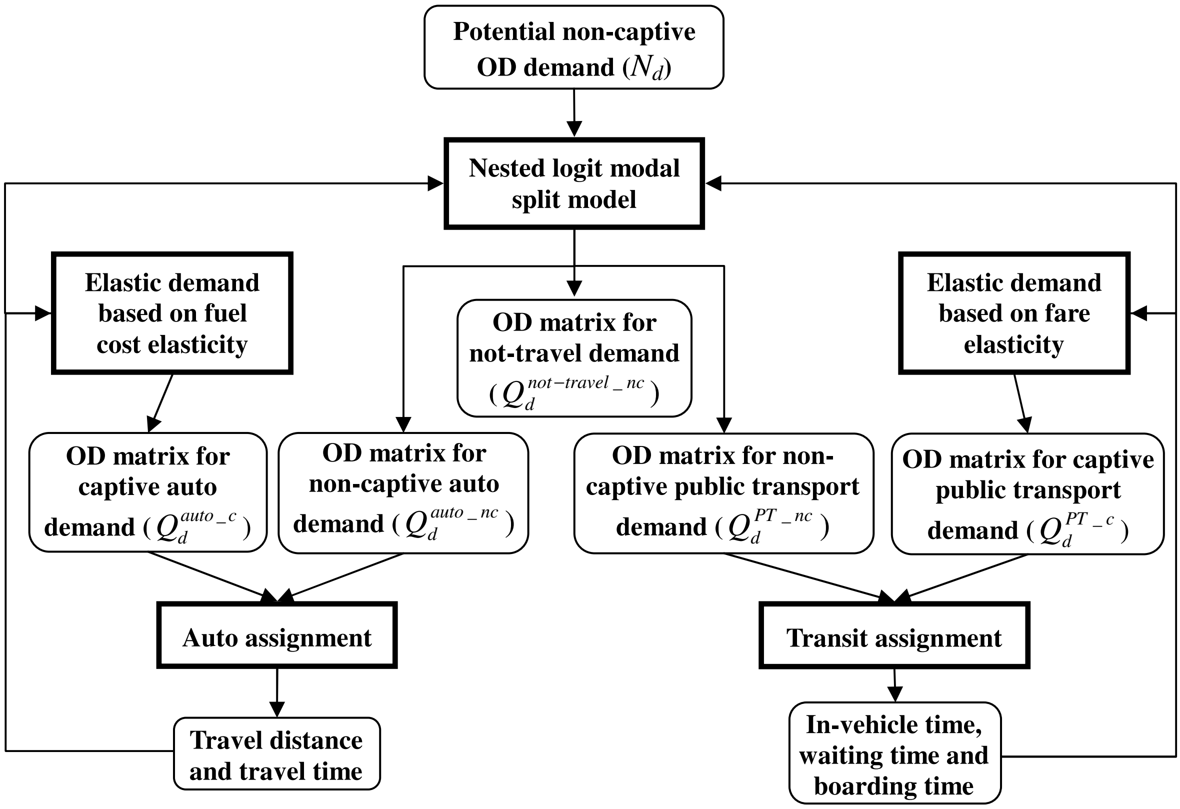

Figure 1 Combined modal split and assignment model

2.2 Link travel time functions for autos and transit vehicles

In this study, the generalized cost (in minutes) for autos to travel on link a is defined by the following generalized link cost function, c_a^{auto}:

$$c_a^{auto}\left(V_a^{auto}\right) = t_a^0\left(1 + 0.73\left(\frac{V_a^{auto}}{C_a}\right)^3\right) + \frac{\tau_a}{\gamma_{travel}} \tag{1}$$

where V_a^{auto} is the hourly volume of autos on link a; t_a^0 is the free flow travel time (in minute) of link a, which is estimated by the length of that link and its speed limit (80km/hr); C_a is the capacity of link a in veh/hr and is taken as 1000 veh/hr times the number of lanes on that link; τ_a is the toll that auto users have to pay as they used link a; γ_{travel} is the value of time for travel and is taken as 1.27 Baht/min in this study. The constants (0.73 and 3) in Equation (1) come from the link volume-delay relationship calibrated for the BMA. The first term on the RHS of Equation (1) represents the time needed for auto users to travel on link a, while the second term is the equivalent time value of toll that the auto users have to pay as they use that link. Apart from the generalized link cost function for autos, a separate travel time function is adopted to represent the time needed for the bus passengers to travel on a link within the modeled network. The travel time function for the bus passengers (in minutes) is defined as follow:

$$t_a^{bus}\left(V_a^{auto}\right) = 1.1\, t_a^0\left(1 + 0.73\left(\frac{V_a^{auto}}{C_a}\right)^3\right) \tag{2}$$

As buses share the same road space with autos, its speed (or travel time) will depend on the speed (or travel time) of autos on that link. Also, as bus is generally moving slower than autos, it is assumed that the bus travel time on any link is equal to 1.1 times of the corresponding time for autos. For railway, as it has its exclusive track, its speed (or travel time) will not be affected by the surface traffic. For segment *a'* of railway line *k'*, the travel time function (in minutes) is defined as follow:

$$t_{k'a'}^{rail} = \frac{L_{a'}}{S_{k'}^{rail}} \tag{3}$$

where $L_{a'}$ is the length of the rail segment *a'*; $S_{k'}^{rail}$ is the designed speed of trains on railway line *k'*.

2.3 Utility functions and nested logit model for non-captive demand

In this paper, a nested logit model is adopted to capture the choice behavior of the non-captive demand. In the nested logit model, the potential non-captive demand for OD pair *d* first choose between the choice of travel and not-travel based on the utility of these two choices. Then, the demand chose to travel make another choice between auto and public transport based on the utilities for these two modes. The auto and public transport demands found from this nest logit model are considered to be non-captive as they could shift between these two modes based on the utilities they experienced. For the utility of not-travel ($U_d^{not-travel}$), no specific functional form could be defined and could only be estimated from the demand elasticities, which will be discussed in Section 3.3. For the case of travel, the utility could simply defined by the logsum of the two choices (auto and public transport) in the lower nest, and it is defined as,

$$U_d^{travel} = \ln\left[\exp\left(U_d^{travel}\right) + \exp\left(U_d^{PT}\right)\right] \tag{4}$$

where U_d^{travel}, U_d^{auto} and U_d^{PT} are respectively the utility of demand for OD pair *d* making a choice of travel, auto and public transport. The utility for travelers in OD pair *d* making the choice of auto is defined as follows:

$$U_d^{auto} = -ASC_d - \gamma_{travel} \times u_d^{auto} - FC_d \tag{5}$$

where ASC_d is the alternative specific constant for OD pair *d.* This constant could be estimated from the calibrated auto and public transport OD matrices, which will be discussed in Section 3.1; u_d^{auto} is the auto travel time between OD pair *d*; *FC* is the fuel cost for OD pair *d*. For the public transport mode, the utility function between OD *d*, which is the same for both of the bus and rail mode, is defined as follow:

$$U_d^{auto} = -\gamma_{travel} \times u_d^{PT} - F_d - \gamma_{wait} \times w_d - p_d \tag{6}$$

where u_d^{PT} is the public transport travel time between OD pair *d*; F_d is the total fare paid for traveling between OD pair *d*; γ_{wait} is the value of time for waiting; w_d is the total waiting time spend in taking public transport to travel between OD pair *d*; p_d is the non-air-conditioned penalty for travelers travel between OD pair *d*. This non-air conditioned penalty is imposed only on the non-air conditioned public transport services to reflect passengers' preference of air conditioned services. With the definition of the above utility functions and the corresponding logsum, the demand of auto and public transport users for OD pair *d* are, respectively, defined by equation (7a) and (7b),

$$Q_d^{auto\_nc} = Q_d^{travel\_nc} \frac{\exp\left(U_d^{auto}\right)}{\exp\left(U_d^{auto}\right) + \exp\left(U_d^{PT}\right)} = N_d \frac{\exp\left(U_d^{auto}\right)}{\exp\left(U_d^{not-travel}\right) + \exp\left(U_d^{auto}\right) + \exp\left(U_d^{PT}\right)} \tag{7a}$$

$$Q_d^{PT\_nc} = Q_d^{travel\_nc} \frac{\exp\left(U_d^{auto}\right)}{\exp\left(U_d^{auto}\right) + \exp\left(U_d^{PT}\right)} = N_d \frac{\exp\left(U_d^{PT}\right)}{\exp\left(U_d^{not-travel}\right) + \exp\left(U_d^{auto}\right) + \exp\left(U_d^{PT}\right)} \quad (7b)$$

where the subscript d represents the variables for OD pair d; $Q_d^{travel\_nc}$ is the travel demand of the non-captive users for OD pair d; Besides the parameters that could be externally input (i.e. FC, γ_{travel}, etc), ASC_d, N_d and $U_d^{not-travel}$ are the remaining parameters in Equation (7) that need to be estimated for setting up this nested logit model. The details for estimating these parameters could be found in Section 3.

2.4 Captive auto and public transport demand

Apart from the non-captive demand, which is estimated by the nested logit model discussed in the previous section, this study also considered the captive counterparts. As the captive demand will not change their mode choice, the auto and public transport demand for this kind of travelers is defined by the following elastic demand functions:

Captive auto demand:
$$Q_d^{auto\_c} = Q_{d0}^{auto\_c}\left[1 + e_{fuel}\left(\frac{FC_d - FC_{d0}}{FC_{d0}}\right)\right] \quad (8a)$$

Captive public transport demand:
$$Q_d^{PT\_c} = Q_{d0}^{PT\_c}\left[1 + e_{fare}\left(\frac{F_d - F_{d0}}{F_{d0}}\right)\right] \quad (8b)$$

where FC_{d0} and F_{d0} are respectively the fuel cost and public transport fare for OD pair d in the base case (i.e. the 2007 network); $Q_{d0}^{auto\_c}$ and $Q_{d0}^{PT\_c}$ are respectively the captive auto and public transport demand for OD pair d in the base case; e_{fuel} and e_{fare} are respectively the elasticities of demand with respect to the fuel cost and public transport fare.

3. MODEL CALIBRATION

In order to setup the model described in the previous section, the alternative specific constant (ASC_d), potential demand (N_d), and not-travel utility ($U_d^{not-travel}$) for each of the OD pair are needed. But in reality, these information are less available and more difficult to collect as compared to traffic volumes and public transport passenger counts. Thus, this section introduces the procedure for calibrating these parameters based on: i) observed link volume/speed; ii) public transport passenger count; iii) fuel cost elasticity; iv) public transport fare elasticity. In this study, as the above information is in 2007, the base case is calibrated for the 2007 network of the Bangkok Metropolitan Area (see Section 4). The calibration will be completed in two steps: First, calibrate the total travel demand and ASC for each OD pair. Then, estimate the potential demand and not-travel utility for each OD pair.

3.1 Calibration of ASC and total travel demand

As the link volumes and public transport passenger counts used in the calibration is undistinguishable between the captive and non-captive demands, the calibrated auto ($\mathbf{Q}^{auto}$) and public transport ($\mathbf{Q}^{PT}$) OD matrix are the sum of the captive and non-captive demands. After calibration, the captive and non-captive demands for auto and public transport are estimated by applying the percentage of captive demand for each these modes in the based year (i.e. 2007). The framework for calibrating the ASCs and total travel demand ($\mathbf{Q}^{travel}$) for BMA is summarized in a flowchart (Figure 2) and the details of the calibration process is described in the following procedure:

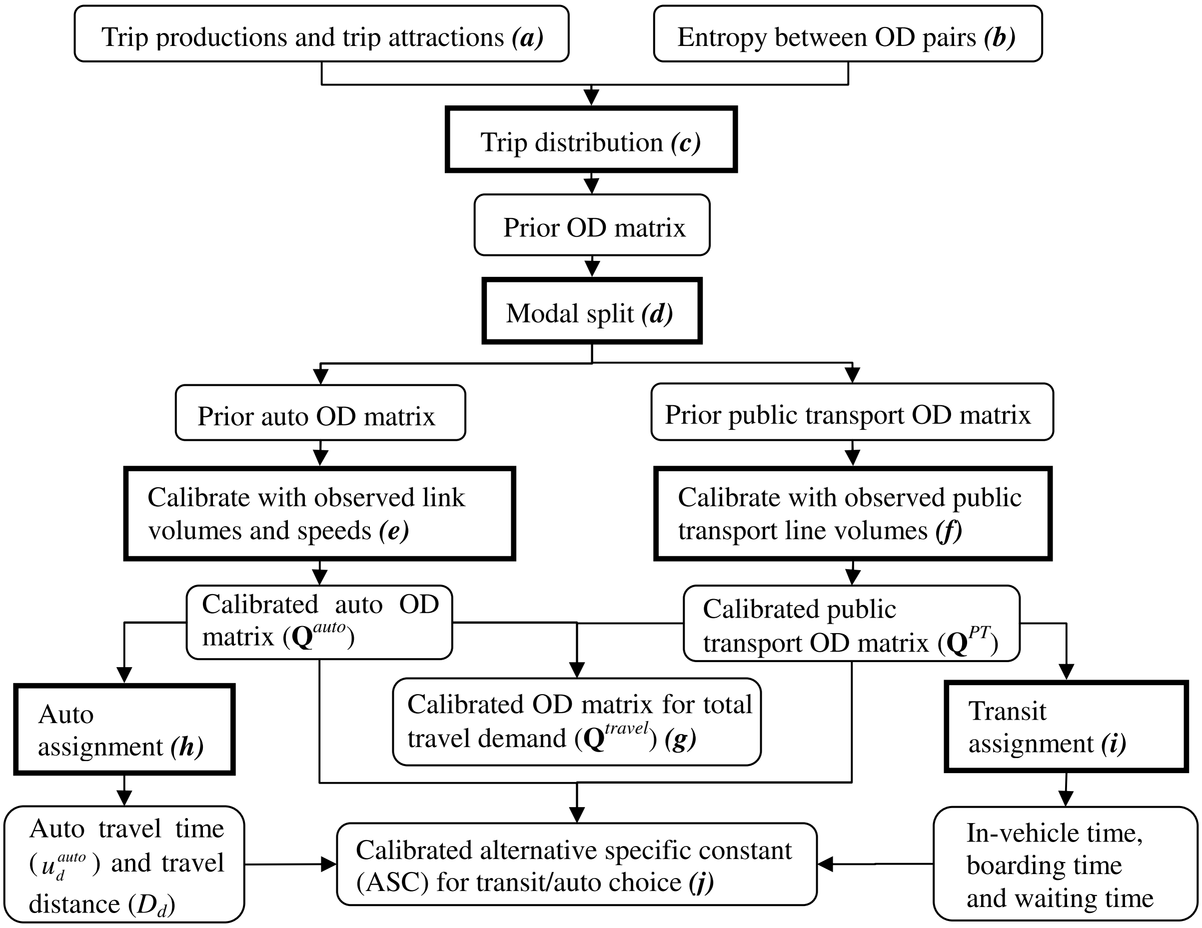

Figure 2 Calibration process

Step 1: For each of the zones defined in the model, hourly trip attraction and trip production information is extracted from the EBUM database (OTP, 2007) (a).

Step 2: Evaluate the entropy between each of the OD pairs defined in the network ***(b)***. Entropy between OD pair d, E_d, is defined as:

$$E_d = \exp\left(-\frac{u_{fd}}{\bar{u}_f}\right) \tag{9}$$

where u_{fd} is the free flow travel time between OD pair d and $\bar{u}_f$ is the mean free flow travel times for all OD pairs within the network. With this definition of entropy, OD pair with shorter free flow travel time will give a higher entropy value.

Step 3: Matrix balancing method (Furness, 1965) is adopted in this trip distribution step for finding the prior OD matrix ***(c)***. In this matrix balancing approach, trip production and attraction data from EBUM ***(a)*** will take as constraints while the entropy ***(b)*** will be the weight for distribution. Thus, more demand will be distributed to OD pairs with shorter free flow travel time. Noted that the prior OD matrix estimated in this step only gives a general pattern of the OD matrix and will serve as the initial matrix for the calibration process.

Step 4: With the prior OD matrix from the previous step, this modal split process will split the matrix into the prior OD matrices for auto and public transport ***(d)***. At this point, as there are no assignment results (e.g. travel time, fuel cost, etc), which is needed in the utility function for the logit modal split model (Equation 7), an arbitrary modal split of 0.5 is adopted.

Step 5: The prior auto OD matrix from the previous step will be calibrated based on the observed link volumes and speeds ***(e)***. In this study, 899 links (16.18% of the total number of links) with either observed link volume or speed are used in calibrating the hourly auto OD matrix. These 899 links, which are shown in black in Figure 3, are the major arterials/freeways in central Bangkok. After the calibration, R-square between the observed link flows/speeds and the EMME link flows/speeds is 0.7023.

Step 6: The prior public transport OD matrix from Step 4 will be calibrated based on the observed public transport line passenger counts ***(f)***. This matrix should be calibrated after the calibration of auto OD matrix as the auto link travel time is needed to evaluate the transit travel time. In this study, bus passenger counts of 116 bus lines and railway passenger counts of 3 railway lines are used in the calibration of the hourly public transport OD matrix. All these 119 public transport lines are serving in the central Bangkok area, which is the same area for the observed link volumes and speeds (Figure 3). After calibrating the public transport OD matrix, R-square between the observed line volumes and the line volumes from EMME is found to be 0.8641.

Step 7: By summing up the calibrated auto OD matrix ($\mathbf{Q}^{auto}$) from Step 5 and the calibrated public transport OD matrix ($\mathbf{Q}^{PT}$) from Step 6, the calibrated OD matrix for total travel demand ($\mathbf{Q}^{travel}$) could be found ***(g)***.

Step 8: With the calibrated auto OD matrix ($\mathbf{Q}^{auto}$), auto assignment in EMME is completed to find the auto travel time (u_d^{auto}) and travel distance (D_d) between each of the OD pair ***(h)***.

Step 9: With the calibrated public transport OD matrix ($\mathbf{Q}^{PT}$), transit assignment in EMME is completed to find the public transport travel time (u_d^{PT}), fare (F_d), waiting time (w_d) and non-air-conditioned penalty (p_d) for each of the OD pair ***(i)***.

Step 10: With the information from Step 8 and 9, and the calibrated auto and public transport OD matrix, ASC for each of the OD pair could be found by using Equation (5), (6) and (7) ***(j)***.

3.2 Estimation of potential demand and not-travel utility

The potential demand (N_d) and not-travel utility ($U_d^{not-travel}$) could be estimated by considering the following definition of fuel cost and public transport fare elasticities,

Fuel cost elasticity:
$$e_{fuel} = \frac{\partial Q_d^{auto\_nc}}{\partial FC_d}\frac{FC_d}{Q_d^{auto\_nc}} \quad (10a)$$

Fare elasticity:
$$e_{fare} = \frac{\partial Q_d^{PT\_nc}}{\partial F_d}\frac{F_d}{Q_d^{PT\_nc}} \quad (10b)$$

By Equation (5)~(7), Equation (10) is solved simultaneously for the potential demand (N_d) and the not-travel utility ($U_d^{not-travel}$) of each OD pairs,

Potential demand:
$$N_d = Q_d^{auto\_nc}\left(\frac{e_{fuel}}{FC_d}+1\right)^{-1} \quad (11a)$$

Not-travel utility:
$$U_d^{not-travel} = \ln\left[\exp\left(U_d^{auto}\right)\left(\frac{e_{fuel}}{FC_d}+1\right)^{-1} - \exp\left(U_d^{auto}\right) - \exp\left(U_d^{PT}\right)\right] \quad (11b)$$

Based on: i) the calibration and assignment results from section 3.1, and ii) the fuel cost and fare elasticities from survey, the potential demand and not-travel utility of OD pair *d* could be directly estimated by Equation (11).

4. BANGKOK METROPOLITAN AREA

In this study, the EMME models for road and public transport network is setup for the BMA in 2007, 2010, 2019 and 2029. The base model in 2007 will be calibrated based on the process describe in Section 3 and tested for different congestion pricing schemes. This section will give the descriptions of the modeling area, traffic conditions of the base year (2007) and the proposed congestion pricing schemes.

4.1 Description of the modeling area

The BMA includes Bangkok and five surrounding provinces, i.e. Nonthaburi, Samut Prakan, Pathum Thani, Samut Sakhon and Nakhon Pathom. It covers an area of 7,762 km^2 and has an approximate population of 9,014,470 as of December 31, 2008 (DOPA, 2009). The road network, including the national highways and major arterial roads within BMA, is shown in Figure 3. The BMA network consists of 243 zones, 58,806 OD pairs and 4,598 road links, which are represented by green/black lines in Figure 3.

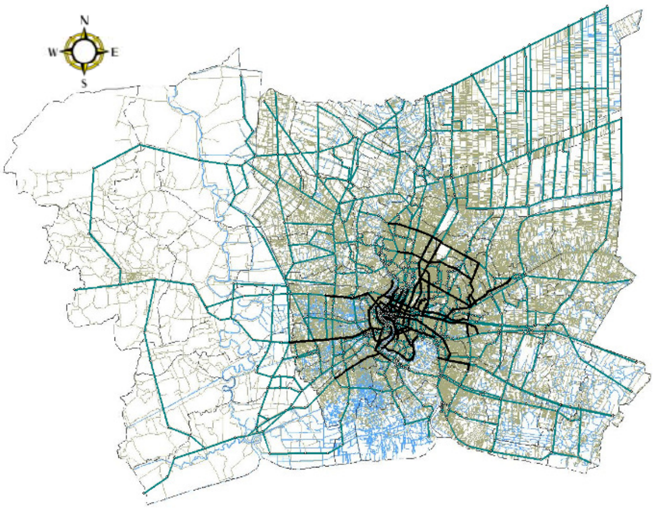

Figure 3 Bangkok metropolitan area network

For public transport, the 2007 network, which included a total of 261 public transport services serving within the BMA, is taken as the base network. Among these 261 services, 3 of which are railway services (MRT Chaloem Ratchamongkhon Line, BTS Sukhumvit Line, and BTS Silom Line) while the others are bus services. For the bus services, the fare is ranging from 6.5 Baht to 11 Baht while the fare for railway services is 15 Baht. Among the modeled public transport services, 64 lines are air conditioned that charged an extra distance-based fare of 0.25 Baht/km for bus and 1.25 Baht/km for rail.

Apart from the base network in 2007, this study also considers the current network in 2010 and two future networks in 2019 and 2029. The 2019 and 2029 networks are considered as the first and second stage of MRT extension will be completed in these two years. This study aims at finding the impact of the implementation road pricing and public transport services on traveler's choice and network conditions in 2010, 2019 and 2029. The road and public transport network is the same in 2007 and 2010. For these future networks, the road networks and bus services are considered to be the same as in 2007 and 2010, while the railway services are improved by extending the original services or introducing new services. Table 1 below shows the change of railway services (BTS and MRT) among these four networks (2007, 2010, 2019 and 2029). For the future 20 years, there will be a substantial extension in the railway network: number of lines will increase from 3 to 16, number of station will increase from 43 to 312 and, total length of rail will increase from 46 km to 508 km.

Table 1 Summary of railway services in 2007, 2010, 2019 and 2029

Year	2007	2010	2019	2029
Number of railway lines	3	3	11	16
Number of stations	43	43	237	312
Total length of railway (km)	45.7	45.7	384.8	507.7

4.2 Results of the base case in 2007

Based on the calibrated auto and public transport OD matrices for 2007 (Section3), auto and transit assignment is completed by using EMME and the following results on flows and travel times are obtained. Figure 4 and 5 respectively shows the spatial distribution of link volumes and the corresponding speeds of the BMA network. Generally, these figures give the results as expected: high link volumes (and low link speeds) around the downtown area of Bangkok and a low link volumes (and higher link speeds) in the surrounding areas. For the links on the western part of the network, the link volumes are relatively high (the link speeds are relatively low) despite their locations at the suburban area. It is because all the demand in the western part of BMA is only served by those few links. On the other hand, the links located at the north-east part of BMA seems to be less congested than it is expected. This is mainly due to the aggregated definitions of zones and centroid connectors in those areas.

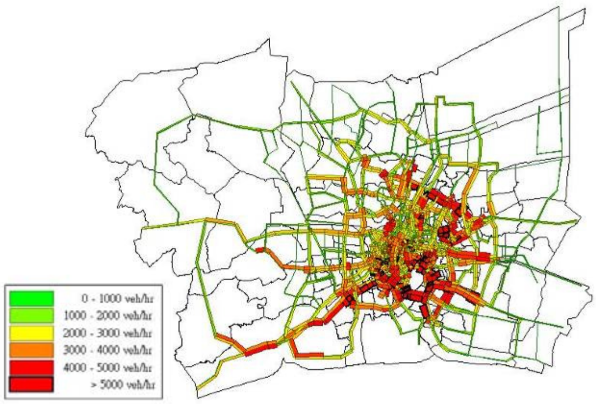

Figure 4 Spatial distribution of link volume

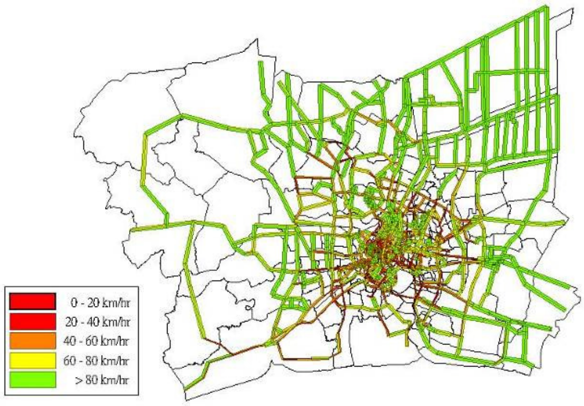

Figure 5 Spatial distribution of link speed

Figure 6 and 7 respectively show the distribution of auto trip length and public transport in-vehicle time from the assignments of the calibrated auto and public transport OD matrices. For this based case, the mean auto trip length is 16 minutes while the mean public transport in-vehicle time is 24 minutes. The maximum trip length for auto and public transport trips are 106 minutes and 99 minutes respectively.

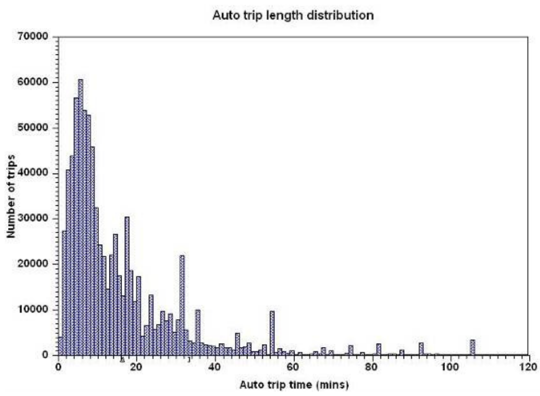

Figure 6 Distribution of auto trip length (min)

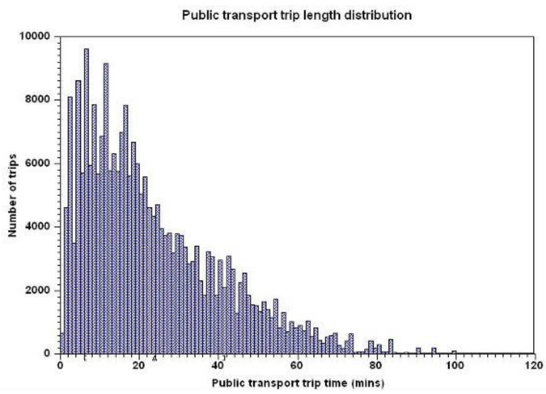

Figure 7 Distribution of transit trip length (min)

4.3 Charging locations and congestion pricing schemes

By adopting the ASCs, potential demands and not-travel utilities calibrated for the base case in 2007, the do-nothing scenario, which no congestion pricing is implemented, of 2010 network is solved by assuming a 2% annual growth in demands. Three basic charging schemes (location and charging method), are proposed based on the spatial distribution of link volume and volume-to-capacity ratio of the do-nothing scenario in 2010. The three basic charging schemes are: 1) Radial toll scheme, which will adopt a distance-based charging method, will setup for the major radial roads (Wipha Wadi Rangsit road, Phetchaburi road, Rama I road, etc) stretching out from the central Bangkok (red lines in Figure 8). The aim of having this radial toll scheme is to shift the auto users in the highly congested trunk road to the less congested parallel routes; 2) Inner cordon toll scheme, which covers most of the Pathum Wan district (green dotted-line in Figure 8), will adopt an area-based charging method, and; 3) Outer cordon toll scheme, which located in the central of Bangkok Province (blue doted-line in Figure 8), will also adopt an area-based charging method. Inner and outer cordon tolls are adopted to reduce the number of autos entering the congested area by shifting them to public transport or to different time. Compare to the area toll schemes, the radial toll scheme is less effective in shifting the auto demand to public transport. It is because under the radial toll scheme, auto users could be easily diverted to other non-tolled parallel routes for traveling to their destinations. In this paper, the combinations of these three basic charging schemes with different toll levels are tested for their performance in the current and future networks (with the assumption of 2% annual growth in demands). Table 2 shows the 8 charging schemes that will be tested in this paper.

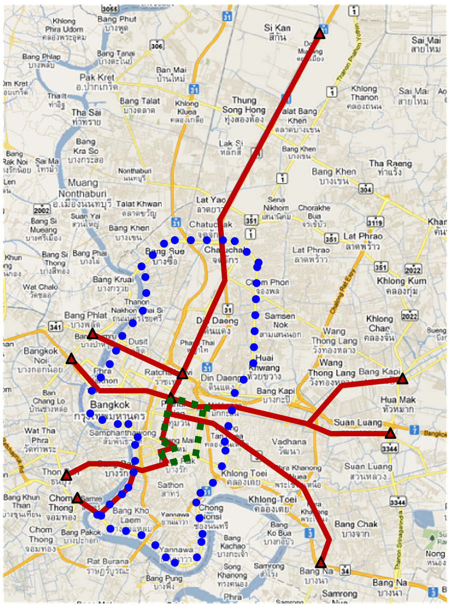

Figure 8 Charging locations

Table 2 Congestion pricing schemes

Scheme	R1	R2	RI1	RI2
Radial toll	2 baht / km	4 baht / km	2 baht / km	2 baht / km
Inner cordon toll	-----	-----	30 baht	50 baht
Outer cordon toll	-----	-----	-----	-----

Scheme	RI3	RI4	OU	RIO
Radial toll	4 baht / km	4 baht / km	-----	2 baht / km
Inner cordon toll	30 baht	50 baht	-----	30 baht
Outer cordon toll	-----	-----	50 baht	50 baht

5. RESULTS AND DISCUSSION

After setting up and solving the 27 scenarios (8 different congestion pricing schemes and the do-nothing scenario in 2010, 2019 and 2029), the change of auto trips (Figure 9), public transport trips (Figure 10) and average speed (Figure 11) are plotted and compared among these scenarios. Considering the number of auto for the do-nothing scenario, it could be seen that the number of auto trips increases from 2010 through 2019 to 2029 regardless of the extensions of MRT line in 2019 and 2029. Such increases could be explained by the fact that the shifting of auto demand to public transport (percentage of public transport trips increases from 24% in 2010 to 30% in 2029) could not compensate the substantial growth of auto demand in the future years. This result indicates that the current plan of railway network extension could not effectively shift the demand from auto to public transport (especially for the high demand growth scenario). This shed light on the necessary of congestion pricing which provides additional incentive to the auto users to switch their mode choice.

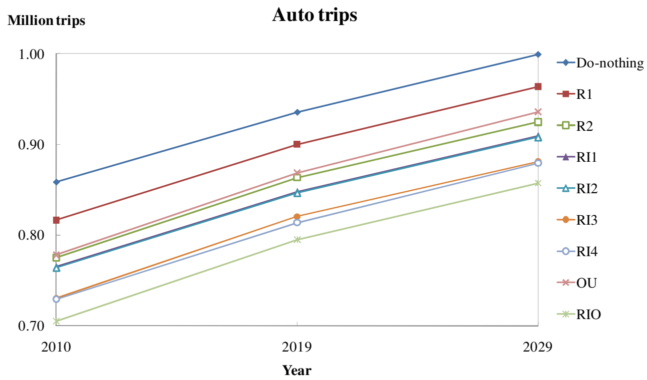

Figure 9 Number of auto trips in BMA

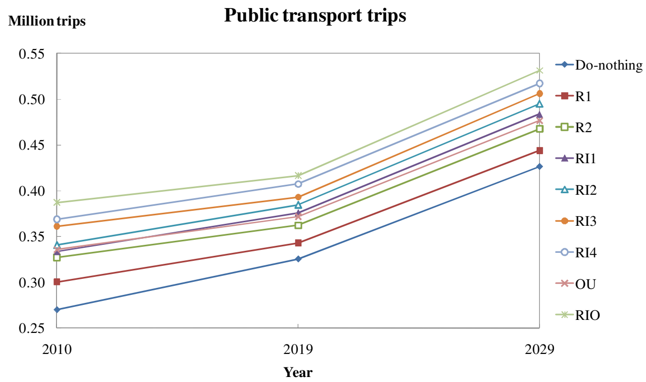

Figure 10 Number of public transport trips in BMA

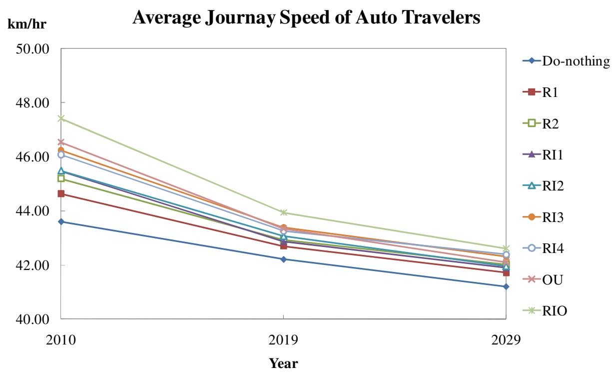

Figure 11 Average journey speeds

In Figure 9, it could be seen that the auto trips for all the tested congestion pricing schemes are less than that of the do-nothing scenario (5% to 18% reduction in 2010, 4% to 15% reduction in 2019, and 4% to 14% reduction in 2029). Such decrease is come from the shifting of demand to public transport and not-travel choice (or travel in different time) after the implementation of the schemes. Among the tested schemes, RIO and RI4 give the largest decreases in auto trips for all years. RIO scheme gives a 14% reduction (while a 12% reduction for RI4 scheme) of auto trips in 2029 as compare to the do-nothing scenario. Such large reduction is mainly due to the implementation of inner and/or outer cordon toll schemes to ensure the charging of auto users as they enter the most congested area. R1, R2 and OU are the three schemes that give the least reduction of auto demand over in the three tested years. Compare to the area toll schemes, the radial toll scheme (R1 and R2) is less effective in shifting the auto demand to public transport or not travel choice. It is because under the radial toll scheme, auto users could be easily diverted to other non-tolled parallel routes for traveling to their destinations. As a result, the implementation of radial toll scheme will mainly shift the route choice, but not the mode choice. As an area based charging scheme, OU, which only consists of the outer area toll scheme, is not effective in reducing the auto volume than it is expected. It is because the reduction of auto demand from outside will be offset by the induced demand within that large charging area.

In general, the number of public transport trip for different congestion pricing schemes and the do-nothing scenario is increased in 2019 (by 8% to 20%) and 2029 (by 37% to 58%) as compare to 2010 (Figure 10). Such increases are resulted from the extensions of MRT lines, which increase the attractiveness of the MRT system, and the increase in network congestion resulted from the demand growth. Comparing within year, the implementation of congestion pricing schemes generally increase the public transport demand. Owning to the similar explanation for the decreases in auto trips, RIO and RI4 gives the largest increase in the public transport demand. Owning to the similar explanations for the changes in auto trips, RIO and RI4 give the largest increase in the public transport demand, while R1 and R2 give the smallest increase.

As the average journey time is highly influenced by the network structure and the OD demands, average journey speed (Figure 11) is adopted as the measure of different congestion pricing schemes in reducing network congestion. For 2010, 2019 and 2029, all tested road pricing schemes increases the average journey speed: 2.3%~8.7% in 2010; 1.2%~4.1% in 2019; 1.2%~3.4% in 2029 as compared to the do-nothing scenario. As the travel demand increases (Figure 9 and 10), the effect congestion pricing reduces. It is because with the higher travel costs, which are resulted from the more congested environment, the same toll levels could not provide similar effect in shifting the auto demand as in the less congested case. Similarly, the RIO scheme gives the largest increase in average journey speed in 2029, while R1 and R2 gives the least increase in the average journey speed as compare to the do-nothing scenario.

Figure 12 and 13 are respectively the changes of auto volume after R1 and RIO is implemented in 2029. The red bands in these figures indicate a decrease in the auto volume, while a green band indicates an increase. Figure 12 and 13 are plotted in the same scale and the thickness of the bands is directly proportion the increase/decrease of auto volumes. In figure 12, it could be seen that the reduction in auto volume (red bands) occurs mainly on the corridor that the radial toll is implemented. Also, the reduced demand on the charging corridor is shifted to the nearby network and causing an increase in the auto volumes (green bands). Compare to R1 (Figure 12), the RIO scheme (Figure 13) is more effective, in terms of magnitude and extend, in reducing the congestion in the charging area. Due to the charging characteristics, radial toll schemes (R1 and R2) are more capable to divert traffic to the parallel routes. After the implementation of R1 (Figure 12), there is an average decrease of auto volume (1,550 veh/hr) along corridor 1, while an average increase of auto volume (352 veh/hr) is recorded on corridor 2. This change of auto volumes suggests a diversion of traffic from the tolled road (Corridor 1) to the parallel and not tolled road (Corridor 2).

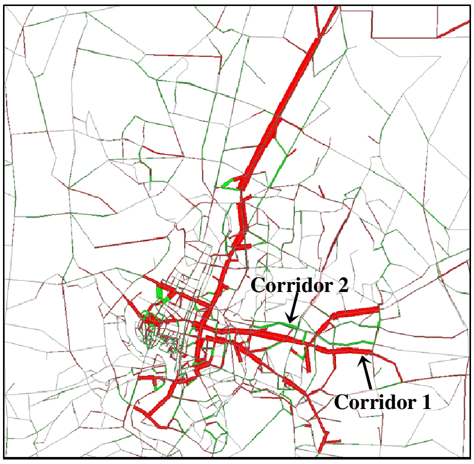

Figure 12 Change of auto volume: R1 minus do-nothing

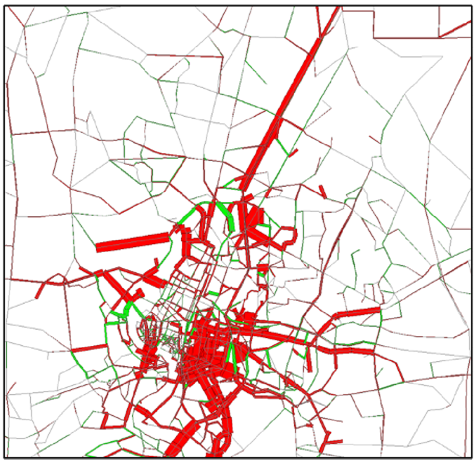

Figure 13 Change of auto volume: RIO minus do-nothing

To further compare the effect of different congestion-pricing schemes, three different indexes are considered. The three indexes are: *Travel time saving*, *Toll collected from road pricing* and *Increase in public transport revenue*. *Travel time saving* refers to the decrease of total travel time under the road pricing scheme as compare to the do-nothing scenario. This value is transformed to the monetary value by multiplying the value of time. *Toll collected from road pricing* refers to the total toll collected from the distance-based or area-based charging methods. *Increase in public transport revenue* refers to the increase in total fare collected from bus, MRT and BTS under the road pricing scheme as compared to the do-nothing scenario. Table 3 listed out the travel demand and the above three indexes for the do-nothing scenario and the 8 tested road pricing schemes. The demands show in Table 3 is the sum of the corresponding hourly demand for each year over the study period (2010 ~ 2029). The three indexes are the sums of present (year 2010) values, which are calculated based on a 9% interest rate, of the corresponding hourly value of the indexes in the period 2010 ~ 2029.

Table 3 Comparison of different road pricing scheme[1,2] (per hour)

Scheme	Auto demand ('000)	Public transport demand ('000)	Travel time saving ('000 Baht) (a)	Toll collected from road pricing ('000 Baht) (b)	Increase in public transport revenue ('000 Baht) (c)	Total ('000 Baht) (a) + (b) + (c)
Do-nothing	18,671	6,791	0	0	0	0
R1	17,934	7,205	7,120	3,664	4,610	15,393
R2	17,165	7,649	12,902	3,576	8,221	24,700
RI1	16,886	7,902	11,432	4,326	10,594	26,352
RI2	16,856	8,079	11,539	4,529	13,131	29,198
RI3	16,294	8,327	16,997	4,556	14,121	35,674
RI4	16,217	8,559	16,147	4,841	17,527	38,515
OU	17,294	7,833	12,188	249	13,942	26,379
RIO	15,794	8,818	18,619	3,559	23,331	45,509

[1] The numbers in this table is the total for the corresponding values in the period 2010 ~ 2029.
[2] Future values are discounted back to year 2010 by using the an interest rate of 9%

Comparing the auto and public transport demand of the 8 tested congestion pricing schemes with the do-nothing scenario, it could be seen the while the reduction of auto demand is up to 15.4%, the reduction of total travel demand, which is the sum of auto and public transport demand, is only between 1.3% to 3.3%. These figures suggested that, with the provision of public transport as an alternative choice, congestion-pricing could effectively reducing the congestions (auto demand) without excessively sacrifice the travel needs of travelers (total demand). Considering the *Travel time saving* column, the RIO scheme gives the largest saving in travel time as it provide the least congested network (i.e. the largest reduction in auto demand, see the column of *Auto demand*) after the implementation of scheme. Comparing the travel time savings of R1 to R2 (also RI1 and RI2 to RI3 and RI4) it could be seen that by charging 2 Baht more per kilometer in the distance-based toll, the travel time saving will be increased by 81% (40% ~ 49%). For the *Toll collected from road pricing* column, RI4, instead of RIO, gives the largest amount of toll collected from road pricing. Although the RIO scheme includes all of the three basic charging schemes introduced in Section 4.3, the toll revenue generated by this scheme is only better than OU. It is because the RIO has excessively shifted the auto users to other choices (see the column of *Auto demand* and *Public transport demand*). With the smaller number of auto travelers, the amount of toll collected from this RIO scheme will be constrained. Considering the column for *Increase in public transport revenue*, RIO gives the largest increase as it is the most effective congestion-pricing scheme to shift the auto travelers to use public transport. Considering the three indexes, it is difficult to determine whether RIO (2 first ranks and 1 seventh rank) or RI4 (1 first rank, second rank and third rank) is more beneficial for the implementation in BMA. For the current study, as there is no preference to any of these indexes, they are summed up to give the final rank of the schemes (last column in Table 3). Based on this sum, RIO is considered to be the most beneficial road pricing scheme for implementing in BMA.

6. CONCLUSIONS

In this study, the multi-modal transportation system of Bangkok Metropolitan Area (BMA) is setup as a combined modal split and assignment model for evaluating the impact of different congestion pricing schemes. This model is calibrated by using the link volumes/speeds and public transport line volumes in 2007. In the proposed model, auto and public transport demands will be assigned separately by using EMME software package on the same network for finding the utilities of travel. Both captive and non-captive demands are considered in this study. For captive demands, elastic demand functions are adopted for estimating the demand for auto and public transport. A nested logit model is adopted for the non-captive demand for estimating the mode choice and the choice of not-travel. 8 different congestion pricing schemes are tested on current and future networks of BMA. Among the tested schemes, the scheme with 2 baht/km radial toll, 30 baht inner cordon toll and 50 baht outer cordon toll produces the best performance in shifting the auto users to public transport and, reducing the congestion of network.

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