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Impacts of urban transit system development on modal shift and greenhouse gas (GHG) emission reduction: A Khon Kaen, Thailand case study

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Abstract

The objectives of this study are: (1) to apply an Urban Transport Planning Model (UTPM) to predict the current and future travel demand characteristics in Khon Kaen City (KKC), and to determine the potential GHG emission reductions as a result of implementing a complete mass transit system consisting of five lines, and (2) to evaluate the proposed scenarios along with some recommendations in terms of policy implications. Four-step UTPMs were developed and applied to predict the travel demands. Consequently, a bottom-up 2 approach was adopted to project the GHG emissions resulting from each established scenario in the years 2016 through 2046. The proposed five-line mass transit system was compared with the baseline (no-project). The results showed that the proposed project would likely cause a shift from private modes of transportation (motorcycles (MC) and passenger cars (PC)) to public transport (PT) over the projected time period (30 years). It could also improve the traffic and transport conditions in the study area by reducing the Vehicle Kilometers of travels (VKT), Vehicle Hours of travels (VHT), Volume-to-Capacity (V/C) ratio values, increase the average travel speed and reduce CO_2 emissions. However, the impact of PT transport development is still limited.

Keywords: Greenhouse gas (GHG), CO_2 emission, Bottom-Up 2 approach, Mass transit system

1. Introduction

Climate change is one of the most critical environmental issues facing the world today. The transport sector accounts for 64.5% of global oil consumption [1] and 25% of global CO_2 emissions [2]. The energy consumption in the transport sector is predicted to double by 2050 [3]. The international community has committed to deliver a legally binding and universal agreement on efforts to mitigate climate change with the hope of limiting the increase in the average global temperature to below 2°C compared to pre-industrial levels [4]. To achieve this global target, the transport sector must play a significant role [2, 5]. At the same time, automobile ownership worldwide is predicted to triple (to over two billion) by 2050 [2]. Therefore, it is important to identify potential transport strategies for all cities to reduce GHG emissions from the transport sector.

A number of transport strategies to reduce private vehicle trips and energy related carbon emissions have been developed over the years. Kei et al. [6] indicated that early railway development could reduce the growth of car ownership by 5% to 30%. GTZ [7] and Nakamura and Hayashi [5] suggested three potential sustainable transport strategies to reduce GHG emissions by the transport sector. These are to avoid (reducing unnecessary travel), shift (shifting travel to lower-carbon modes) and improve (improving intensity of transport-oriented emissions). Each strategy relates four individual instruments, i.e., technology, regulation, information, and the economy. Banister [8] suggested various transport and land use strategies supporting the compact city concept that can reduce private vehicle trips and their associated travel distances.

Along with the British GHG emission reduction target of 80% by 2050, Hickman et al. [9] assessed various transport strategies to determine how the level of CO_2 emissions could be considerably reduced in London. They found that it would be difficult to achieve the GHG emission reduction from transport sector using the individual transport policies such as speed restrictions, alternative fuels, public transport, emission taxes, and pricing regimes. Crozet and Lopez-Ruiz [10] conducted a scenario exercise for France using a TILT (Transport Issues in the Long Term) model. They found that a reduction of 80% of CO_2 emissions can be realized by 2050, of which more than 50% would be attributed to technological advances and the rest to behavioral changes.

Ratanavaraha and Jomnonkwao [11] indicated that the amount of CO_2 emissions from Thailand road transport will increase by 10 tons annually. The S6-5 Group [12] applied a leap-frog/back-casting approach together with avoid, shift, and improve strategies to the KKC transport network with various scenarios. The result showed that the combination of avoid (50% of Transit-Oriented Development (TOD)), shift

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(five lines using ethanol Bus Rapid Transit (BRT)), and improve (50% of electric and hybrid vehicles) strategies (optimum case) could reduce the total CO_2 emissions by 47.6% from the baseline by 2030. Chindaprasirt et al. [13] applied a four-step UTPM with a bottom-up approach to estimate the reduction of GHG emissions under the blue line (BTS transit system) extension project, and the feasibility study on clean development mechanisms (CDM) project for the transport sector in Bangkok. Klungboonkrong et al. [14] proposed different transport and land use scenarios for Khon Kaen University (KKU). They found that technological change in vehicle engines was the most effective scenario in reducing CO_2 emissions, followed by land use measures, restriction of private vehicle use and public transport improvement measures. They also concluded that the integrated scenario generally had higher impact than the individual ones. Satiennam et al. [15], based on the stated preference survey, found that 25% and 30% of car and motorcycle users in KKC would likely shift to BRT.

Along with the rapid growth of the economy, urbanization, commercialization and industrialization in Thailand, the transport sector has become the second largest energy consuming sector (35.3%) [16] and for GHG emissions (23%) [17]. The key objectives of this study are: (1) to apply UTPM to determine the current travel and future demand characteristics in KKC and determine the potential GHG emission reduction as a result of implementing a complete five line of mass transit system, and (2) to evaluate the proposed scenarios along with some recommendations in terms of policy implications.

2. Methodology

The research methodology is illustrated in Figure 1 and briefly described as follows.

2.1 Study area specification

KKC, covering approximately 228 km^2 with a population of 323,409 in 2015, was selected as a case study. This is discussed further in Section 3.

2.2 Data collection

To identify the traffic and transport problems and other related issues in the study area, both primary and secondary data were collected using various techniques. The details of data collection are described in Section 4.

2.3 Identification of traffic and transport related problematic issues

Based on the traffic and transport survey, some related transport problematic issues arose. The level of service (LOS) of existing public transport, the share of private vehicles, road LOS and other transport related issues were identified. The details of traffic and transport related problems are described in Section 5.

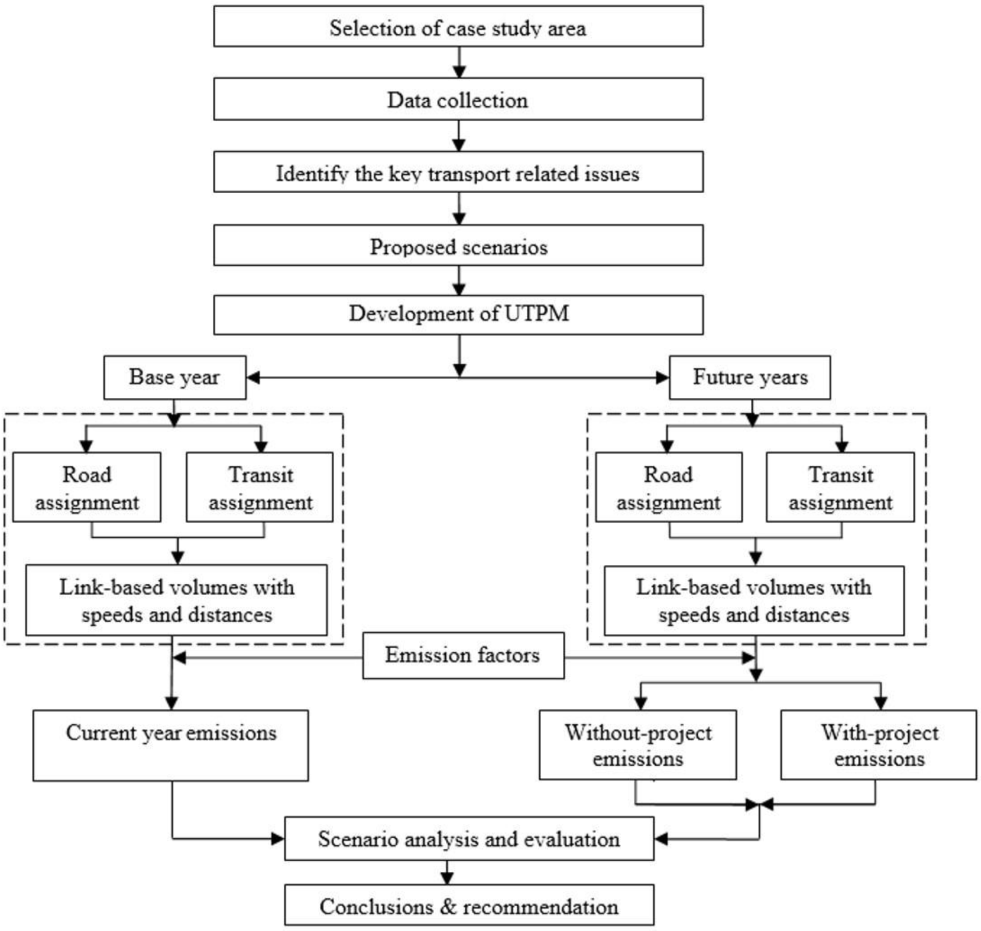


Figure 1 Research methodology flowchart adapted from Klungboonkrong et al. [14]

2.4 Identification of potential scenarios

Based on SIRDC [18], Nakamura and Hayashi [5] and GTZ [7], a mass transit system development scenario was selected. At the same time, Scenario 0 (with no project) was analyzed as the base case to compare it with the proposed scenario (with project). The details of each scenario are discussed in Section 8.

2.5 Urban transport planning models (UTPMs)

The four-step UTPMs [18], including trip generation, trip distribution, modal split, and trip assignment models were applied to predict travel demands in the case study. CUBE software [19] was used to develop the UTPMs. Trip purposes were classified into four categories including home-based work (HBW), home-based education (HBE), home-based other (HBO) and non-home-based (NHB). More details of UTPMs development are presented in Section 6.

2.6 GHG emission estimations

The bottom-up 2 approach [20] was applied to estimate the GHG emissions for each proposed scenario in 2016, 2026, 2036 and 2046. The amount of GHG emissions were estimated from each combination of vehicle class and engine type on all the road links. The emission factors adopted in this study were motorcycle (MC), passenger car (PC), pick-up truck (PuT), bus (B), and heavy truck (T). GHG emission calculations are given in Section 7.

2.7 Analysis and evaluation of each scenario

Scenario comparisons and evaluation were based on the traffic and environmental indicators that differed between the baseline (without-project) and with-project scenarios. The details of this comparison and evaluation are discussed in Sections 9 and 10.

3. The basic information of the case study area

KKC, covering approximately 228 km^2 with a population of 323,409 in 2015 [18], was selected as a case study. It is a strategic city in which numerous studies have been conducted in various transport related aspects, including a master plan for a mass transit system [21], a study of a BRT prototype system in the region for sustainable traffic safety [22], a detailed design of a BRT system [23] and a design of a transport sector for a low-carbon city [12]. More importantly, KKC: (1) is expected to be a transport and logistic hub because of its location, (2) is an academic hub since KKU, the largest university in the northeastern region of Thailand, is located in KKC, (3) is a medical hub since Srinakarin, the largest hospital in the northern region of Thailand is in KKC and (4) was selected as a smart city under the JICA project. Future social and economic development as well as significant changes in KKC can potentially contribute to the global warming and climate change crisis.

4. Data collection

Based on its size, location and transport network characteristics, the study area was divided into 82 internal zones and five external zones as shown in Figure 2.

4.1 Primary data collection

The present origin and destination (O-D) matrices of person trips were obtained from a Household Interview Survey (HIS). Approximately 3,500 households (2.2% of the total households) were interviewed. Additionally, external vehicle trips (i.e., internal-external, external-internal, or external-external (through traffic) trips) crossing the cordon line of the study area were derived from a Roadside Interview Survey (RIS) at six locations with a sample size of 5600 interviews. The traffic volumes by vehicle type at 44 road mid-block locations were observed. Average delays, queue lengths and turning count traffic volumes at 43

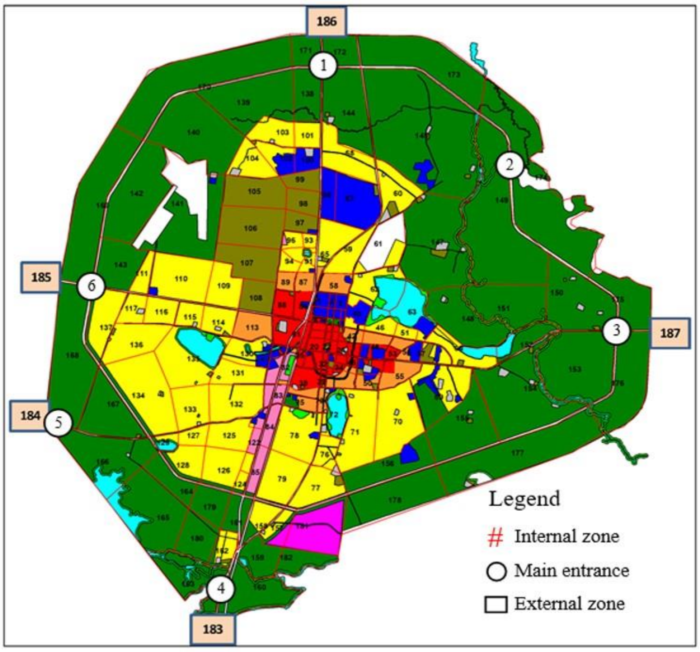


Figure 2 The KKC traffic analysis zones (TAZs) [18]

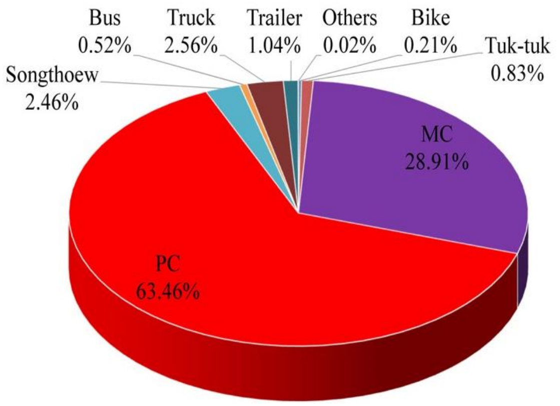


Figure 3 The current traffic composition in the study area [18]

intersections were also collected. The average speeds for different road classes were surveyed along 35 road segments. This traffic data was collected during three specific time periods, i.e., morning peak (07:00-10:00), off-peak (11:00-14:00), and evening peak hours (15:00-18:00). The average traffic composition for these time periods is shown in Figure 3.

4.2 Secondary data collection and sources

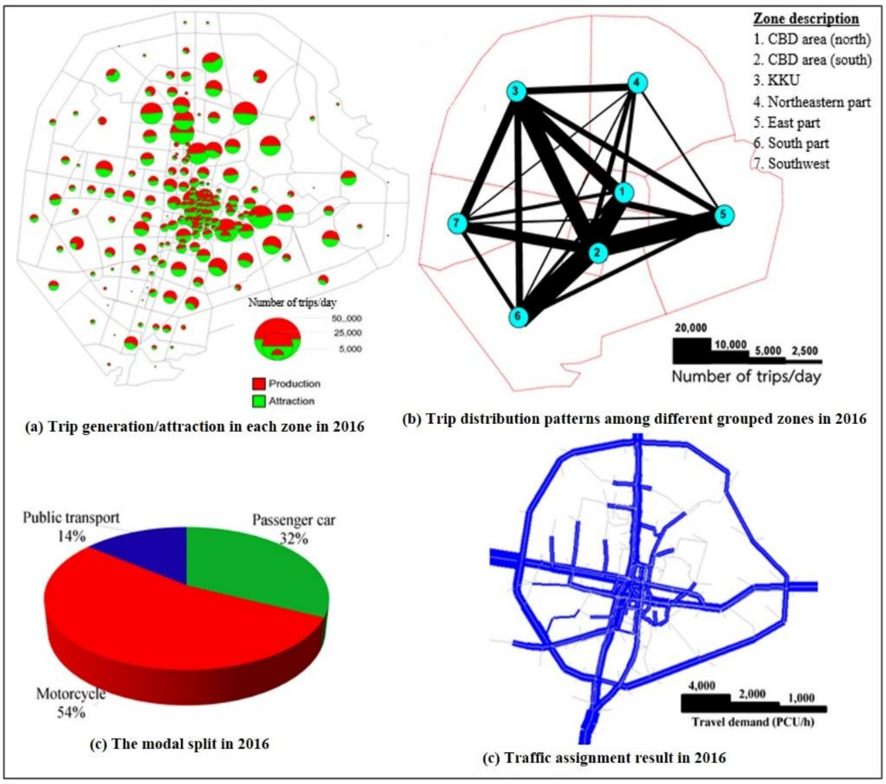
Secondary data were collected from different sources. The projected future socioeconomic characteristics (including population, number of students and employment), road physical network and land use characteristics were adopted from SIRDC [18]. The numbers of registered vehicles were obtained from the Department of Land Transport (DLT) [24]. Additionally, the emission factors were adopted from SIRDC [20] and OTP [25].

5. The current traffic and transport related problematic issues

Based on the traffic and transport surveys, the main traffic and transport problematic issues in the study area were the low LOS of existing public transport (e.g., low safety standards, lack of timetables and designated bus stops, excessive delays and unreliability), the high rates of private vehicle trips and traffic congestion.

6. Urban transport planning model (UTPM) development

Many studies such as Satiennam et al. [26], SIRDC [21], S6-5 Group [12], Klungboonkrong et al. [14], and OTP [25, 27] used a four-step UTPM to estimate the travel demands on the transport network. The current study also applied a four-step UTPM to predict the travel demands on the KKC transport network in 2016, 2026, 2036 and 2046. CUBE software [19] was used to develop the UTPM. The details of each step are as follows. In the trip generation step, the cross-classification trip rates per person per day categorized according to car ownership levels [18] were used to estimate total trips. Linear regression analysis was applied to establish the trip attraction equations. The total trip generation in 2016 was estimated to be 656,500 trips per day. Of these, 59%, 24%, 10% and 7% were attributed to HBW, HBE, HBO and NHB, respectively. The total number of trips produced in and assigned to each zone is presented in Figure 4a. In the trip distribution step, a gravity model was applied to estimate the interchange trips between zones of the O-D matrices [18].



(a) Trip generation/attraction in each zone in 2016

(b) Trip distribution patterns among different grouped zones in 2016

(c) The modal split in 2016

(c) Traffic assignment result in 2016

Figure 4 The results of four-step UTPMs in 2016 [18]

Table 1 Selected CO_2 emission factors, adapted from SIRDC [20] and OTP [25]

Vehicle types	Fuel types	Manufacturers	Emission factors	R^2
Motorcycle (MC)	Gasoline	Honda	$Y = 0.0169X^2 – 1.3909X + 57.674$	0.80
Passenger car (PC)	Gasoline	Toyota	$Y = 0.0686X^2 – 7.7792X + 340.01$	0.92
Pick-up truck (PuT)	Diesel	Isuzu	$Y = 0.0695X^2 – 8.0605x + 373.14$	0.94
Bus* (B)	Diesel	Hino	$Y = 0.1955 X^2 – 21.345X + 836.12$	0.90
Heavy truck* (T)	Diesel	N/A	$Y = 0.2889X^2 – 33.506X + 1493.7$	0.93

*Only one tested vehicle available, X=average speed (km/h), and Y=CO_2 emissions (g/km)

This model was commonly used in case studies such as Klungboonkrong et al. [14], the S6-5 Group [12] and Satiennam et al. [26]. The trip distribution in 2016 is shown in Figure 4b [18]. In the modal split step, the Binary Logit model developed for KKC [18] was used to split the distributed trips for each O-D pair into either transit or private modes. This method was also adopted for the Extended Bangkok Urban Model (eBUM) study [27-29]. The current modal split for each transport mode was predicted and is shown in Figure 4c [18]. In the trip assignment step, capacity restraints were applied to assign the derived O-D trips on KKC roads and transit networks. The traffic assignment results in 2016 are shown in Figure 4d [18]. Finally, the assigned trips were validated against the observed trips along six selected screen lines with a total of 16 validation points [18]. The results of validation revealed that the assigned trips were reasonably well-matched with observed trips with an average Root Mean Square (RMS) of 5.5% [18]. This means that the developed models can potentially be used to predict the travel demands in the future.

7. The GHG emission estimation approach

A bottom-up 2 approach was adopted for this study. This method predicts the amount of GHG emissions based on the link-based traffic volumes by the combined vehicle and engine types, their associated travel speeds and distances in the years under consideration. The derived link-based volumes with average speeds and distances of each road link calculated by the 4-step UTPM are highly important for GHG emission estimations. The total GHG emission calculation by the bottom-up 2 approach is shown in equation 1 [12, 14, 20]:

$$TE = \sum_{e} \sum_{i} \sum_{j} \left(Ef_{ij} \times D_e \times 1000 \times V_{ije} \right) \tag{1}$$

where:

TE: Total emission from all vehicles of type i and engines type j for all links (e) in a road network (g)
Ef_{ij}: Emission factor of vehicle type i and engine type j (g/km)
D_e: Road distances of the link (e) (km)
V_{ije}: Traffic volume of vehicle type i and engine type j on all links (e) (number of vehicles/day)

The baseline GHG emissions were calculated from the no-project scenario in each year of interest and the with-project GHG emissions as derived from each proposed scenario. Assuming that leakage of emissions is zero [14], the potential GHG emission reduction will consequently be the difference between the no-project (baseline) and the with-project GHG emissions as presented in equation 2 [20, 25, 30]. In this study, only CO_2 emission was selected as the key indicator for scenario comparisons and evaluation since it normally is the largest constituent among other types of GHG emissions [20, 25, 30].

$$ER_y = BE_y - PE_y - LE_y \tag{2}$$

where:

ER_y: CO_2 emission reductions in year “y” (tons/year)
BE_y: Baseline CO_2 emissions in year “y” (tons/year)
PE_y: Project emissions in year “y” (tons/year)
LE_y: Leakage emissions in year “y” (tons/year)

In the CO_2 emission calculations, the emission factors for each type of vehicles were adopted from SIRDC [20] and OTP [25]. Acknowledging the possibility that the in-use vehicles in Bangkok and KKC might be different in terms of vehicle composition, driving cycles, road physical characteristics and network, among other factors, we assumed they were similar. This assumption was also adopted elsewhere [14]. The transport modes in KKC were classified into five types including MC, PC, PuT, B and T. The selected emission factors by vehicle type and engine for each type of vehicle are shown in Table 1 with the R^2 ranging from 0.8 to 0.94. The relationship between the CO_2 emission rates and vehicle speeds for each adopted vehicle presented in Table 1 is depicted as Figure 5.

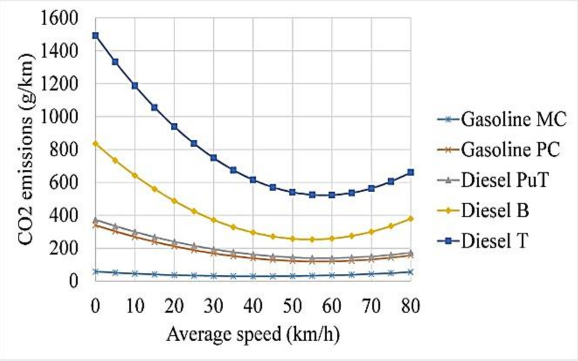


Figure 5 The CO_2 emission factors related to speed for each vehicle type

8. Design scenarios

The scenario adopted in this study was based on Avoid (A), Shift (S), and Improve (I) strategies and their associated instruments (i.e., Technology (T), Regulation (R), Information (I) and Economy (E)) as suggested by Nakamura and Hayashi [5] and GTZ [7].

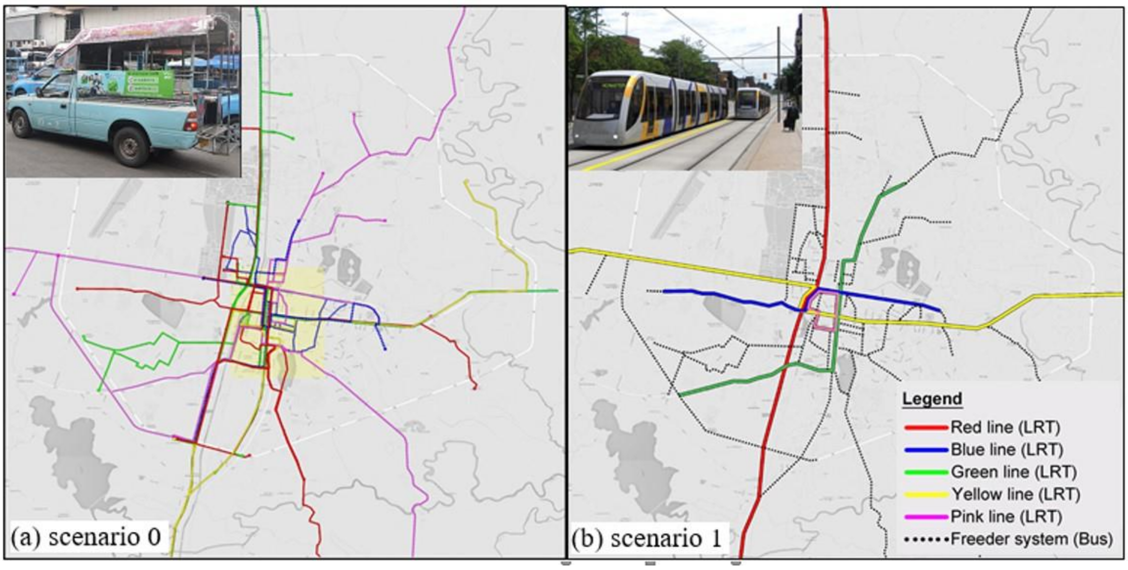


Figure 6 The existing paratransit network (a) and the proposed 5 lines of LRT network (b) [18]

Table 2 The total trip generation (trips/day) [18]

2016	2026	2036	2046
656,500	860,670	1,145,990	1,518,130
-	(+31.17%)	(+74.62%)	(+131.25%)

The proposed scenario to be evaluated was the development of a Light Rail Transit (LRT) system in KKC [18]. The details of the proposed project along with the baseline (without project) scenario are described as follows.

Scenario 0 (no-project or baseline): This scenario assumed the status of road network and transport systems remained unchanged from 2016 to 2046 as shown in Figure 6a, while the future socioeconomic characteristics in the specific years (e.g., population, number of students and employment) could be extrapolated based on historical trends. Based on SIRDC [18], the annual growth rates of the populations and employment in the study area from 2016 to 2046 were assumed to be 2.75% and 3.25%, respectively; while those of students were assumed to be decreased by 1.8% from 2016 to 2026 and constant from 2026 to 2046.

Scenario 1 (Public Transport Measure): This scenario assumed a complete five service line LRT system with designated Park and Ride (P&R) facilities, q proposed feeder system and ITS fully be implemented in 2026 through 2046 [18] as shown in Figure 6b. The existing paratransit systems (i.e. Songthoew, public vans and shuttle buses) would be rerouted and serve as a feeder systems. The socio-economic characteristics were assumed to be identical to those presented in Scenario 0. It should be noted that the major source of GHG emissions would be from electricity generation [30], since the LRT would require electricity. However, the GHG emissions generated from electricity generation were not considered in this study.

9. Results and discussion

Based on the developed UTPMs and the projected future population, numbers of students and employment, the total daily trips generated in 2016, 2026, 2036 and 2046 were estimated to be 656,500, 860,670, 1,145,990, and 1,518,130, respectively. The growth rates of the estimated trips in 2026, 2036 and 2046 compared with those in 2016 (base year) were 31.17%, 74.62% and 131.25%, respectively, as presented in Table 2 [18].

As a result of the proposed project, the modal shares of both MC and PC are forecast to decrease over the years from the baseline (no-project), while those of PT will increase as shown in Table 3. The modal share of MC decreased with time at higher rates than that of PC. This will occur if the generalized costs for MC transport are relatively more sensitive to the generalized costs of travel than for PCs.

As the result of the modal shift, the values of VKT, VHT, and V/C would be reduced over the years from the baseline. Average speeds can increase as shown in Table 4.

Eventually, CO_2 emissions could be reduced by 4.83%, 10.07% and 15.06% in 2026, 2036 and 2046, respectively, from the baseline as shown in Table 5.

The annual CO_2 emissions estimated in this study were marginally different from those of S6-5 Group study [12] conducted in the same study area (KKC), i.e., 226,410 (2016) (this study) vs 229,100 (2012) [12] tons/year. This can be due to the differences of the number of TAZs, the selected emission factors, the data availability, and scenario assumptions, among other factors. Conversely, the results of the current study are consistent with previous studies [6, 15, 23] in terms of modal shift and GHG emission reductions, even through the impact magnitudes are different.

10. Conclusions

The developed four-step UTPMs were applied to predict the current and future travel demand characteristics in KKC. Additionally, a bottom-up 2 approach was adopted to estimate the CO_2 emissions. The impacts of the proposed five LRT lines in KKC were determined against the baseline (no project). It was found the proposed development of five LRT lines could potentially cause a modal shift from private modes (MC and PC) to public modes (LRT and Songthoew) over the time period (30 years) of interest. MC riders would be more likely to shift to PT than those of PC. As the result of the modal shift, the traffic and transport conditions in the study area could potentially be improved by reducing the

Table 3 Shares for each mode [18]

Modes	Base case 2016	Baseline 2026	Scenario 1 2026	Baseline 2036	Scenario 1 2036	Baseline 2046	Scenario 1 2046
MC	351,720	454,690	413,370	594,440	515,430	777,340	633,890
%	53.58	52.83	48.03	51.87	44.98	51.2	41.75
Δ%	-	-	-4.8	-	-6.89	-	-9.45
PC	211,040	272,420	253,020	357,040	323,610	468,270	412,750
%	32.15	31.65	29.4	31.16	28.24	30.85	27.19
Δ%	-	-	-2.25	-	-2.92	-	-3.66
PT	93,740	133,560	194,280	194,510	306,950	272,520	471,490
%	14.28	15.52	22.57	16.97	26.78	17.95	31.06
Δ%	-	-	+7.05	-	+9.81	-	+13.11
Total	**656,500**	**860,670**	**860,670**	**1,145,990**	**1,145,990**	**1,518,130**	**1,518,130**

Note: Δ%=percentage difference between the baseline and Scenario 1

Table 4 The baselines and the potential reduction in traffic indicators

Indicators	Base case 2016	Baseline 2026	Scenario 1 2026	Baseline 2036	Scenario 1 2036	Baseline 2046	Scenario 1 2046
VKT (veh-km/h)	447,544	536,352	518,363	665,578	623,444	790,864	719,618
Δ%	-	-	-3.35	-	-6.33	-	-9.01
VHT(veh-hr/h)	14,447	20,477	18,662	36,989	28,416	82,115	53,678
Δ%	-	-	-8.87	-	-23.18	-	-34.63
Ave.speed (km/h)	30.98	26.19	27.78	17.99	21.94	9.63	13.41
Δ%	-	-	6.05	-	21.93	-	39.20
V/C ratio	0.51	0.615	0.561	0.762	0.659	0.936	0.795
Δ%	-	-	-8.78	-	-13.52	-	-15.06

Note: Δ% = percentage difference between baseline and Scenario 1

Table 5 The baseline and the projected CO_2 emissions (tons/year)

Indicator	Base case 2016	Baseline 2026	Scenario 1 2026	Baseline 2036	Scenario 1 2036	Baseline 2046	Scenario 1 2046
CO_2	226,410	289,997	275,984	399,210	359,004	538,456	457,355
Δ%	-	-	-4.83	-	-10.07	-	-15.06

VKT, VHT and V/C values and increasing the average travel speeds. These changes consequently could lead to a reduction of CO_2 emissions. Although, the impacts of the proposed LRT project are limited, it clearly shows that the existing public transport system (modified pick-up truck-Songthoew) could not be an alternative transport mode to the private (MC and PC) modes due to its poor service such lack of timetables, lack of designated bus stops, low safety standards, excessive delays and unreliability. However, this study has the following practical and policy implications:

(1) the KKC transport network should develop mass transit systems to deal with the growth of private vehicle trips and their associated CO_2 emission in the city. However, PT improvement and development alone cannot produce significant impacts. To meet the city's sustainable transport target, PT measures must be combined with other policies that have not been considered in the current study, such as road pricing policies, parking restrictions, TOD, low-emissions vehicles and active transport modes (walking and cycling). Based on this study framework, each of these individual policies can feasibly be selected and developed as a set of integrated measures.

(2) In practice, mass transit planning and implementation is difficult due to the existence of various barriers. However, the most critical ones are institutional, financial, legal and political issues [31]. For example, a single line of BRT operated in Bangkok failed due to the weak and discontinuous political leadership and the failure to manage competitive transportation modes [32]. Therefore, strong commitment and leadership of the local government, financial support for transport infrastructure development, and public participation and acceptance are key factors leading to success.

(3) It should be noted that the CO_2 emission reduction is only one dimension of the key objectives for policy-making. Efforts should be made to improve the quality of human life with sustainable development in the social, economic, and environmental dimensions. Therefore, consideration of policy options against multiple objectives and inclusion of economic, financial and social analyses should be considered for further research.

11. Acknowledgements

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