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Energy Saving and CO_2 Reduction Potential from Partial Bus Routes Reduction Model in Bangkok Urban Fringe

Chinnawat Hoonsiri [1], Vasin Kiattikomol [2] and Siriluk Chiarakorn [3,*]

[1] Division of Energy Management Technology, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; chinnawat_h@dede.go.th
[2] Division of Transportation Engineering, Department of Civil Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; vasin.kia@kmutt.ac.th
[3] Environmental Technology Program, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand
* Correspondence: siriluk.chi@kmutt.ac.th; Tel.: +66-2470-8654

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Abstract: Bus networks in many capital cities are long distances and partially overlapping with each other. As a result, waiting time is high and energy consumption efficiency is poor. Bus operators in many countries tried to reform their bus routes to reduce waiting time and fuel costs by reducing overlapping bus routes. However, most of the reformed bus routes were complicated, which caused discomfort to passengers to use the bus service. To overcome this problem, this study proposed a new bus reformed model called the Partial Bus Routes Reduction in Urban Fringe Model (PBRU) which was a simple and passenger-friendly route operation. It resulted in 14% of total inbound and 16% of total outbound passengers receiving the benefit of waiting time reduction. Most passengers wait twice at the resident bus-stop and transfer point. As a result, the overall waiting time increased by 0.72–3.75 min. The reduction of fuel consumption was consistent with increasing load factors and dependent on the time period. The bus reform operations during the off-peak hours had more benefits in terms of waiting time reduction, energy-saving potential, and CO_2 reduction than during the rush hours.

Keywords: bus line overlapping reduction; load factor; Bangkok; bus reform; the Partial Bus Routes Reduction in Urban Fringe Model (PBRU)

1. Introduction

Nowadays, the quantity of energy consumption is at a high level despite a global concern on adverse environmental issues. The transportation sector is one of the major contributors to a high proportion of energy consumption that also produces a significant amount of particulate matter (P.M.10 and P.M. 2.5) and greenhouse gas (GHG) [1,2]. Government agencies around the world attempt to reduce GHG emissions by promoting public transportation that can decrease the number of private vehicles on the road and the air pollution problem. A popular type of public transportation that many people choose to travel in urban cities is bus transit. In general, a structure of bus routes in many capital cities is a long-distance route and passengers can travel to their destinations without any transfer [3,4]. Some bus routes are circuitous and overlapping with other bus lines as they compete for passengers [5,6]. Bus operators have tried to improve the bus network to overcome the overlapping bus routes problem. Normally, the bus route reform can be divided into two types. The first reform type is the bus route reorganization with a dedicated lane for buses which can be found in Brazil, China, Turkey, and Columbia [7–10]. This measure can reduce the total travel time of passengers, the number of bus lines, and excessive buses in the bus network. It was reported that after the bus route reform in Istanbul, this new approach reduced 116,261 vehicle-km intermediate forms (minibus and taxi) and 95,554 vehicle-km buses. Total energy consumption of intermediate transport forms and buses reduced from 310 L/1000 passengers to 160 L/1000 passengers. However, the dedicated bus lane caused an increase in traffic congestion in the other lanes. As a result, the energy consumption of private-vehicles after dedicating a lane to buses was higher than before [11].

The second reform type was the bus route reorganization without a dedicated lane for buses which can be found in Santiago (the capital city of Chile) and Barcelona (Spain). The entire bus network was reformed by increasing the number of transfer points to reduce overlapping bus routes while still maintaining the same destination. This strategy helped reduce the number of buses on the road, energy consumption, and average waiting time. The bus network reform in Barcelona resulted in the decrease of total bus routes from 63 to 48 routes, the decrease of average waiting time from 12.30 min to 6.18 min, and the number of buses decreased from 761 to 573. [12,13]. Additionally, most of the passengers preferred to travel by bus regardless of the new bus routes operating on the network due to more transfer points [14,15]. At the transfer point, bus operators would have to maintain service conditions of shelter and other infrastructure to provide a safe and comfortable environment for passengers [16]. However, the main problem after the bus network reform was that many passengers were confused about the complicated bus routes and felt uncomfortable to use the new service. The origin and the destination of some reformed bus routes were changed and the traveling distance of some reformed bus routes was also different from the regular routes.

In this research study, the Partial Bus Routes Reduction in Urban Fringe Model (PBRU) was proposed to reform the bus network in the urban fringe area. The advantage of the PBRU is that the origin and destination of the bus routes after reform are not changed. Only the overlapping bus route section in the urban fringe area is partially reduced to a single line and the transfer points are added at the end of the overlapping section. The PBRU model was applied to the bus network Rama 2 Road, the urban fringe area of Bangkok, Thailand which has 14 overlapping bus routes along a 12.9-km section. To improve the efficiency of the bus transportation on this road, the 14 overlapping bus lines were reduced to a single line on Rama 2 Road without a dedicated lane for buses. All passengers would have to make a transfer at the end of the overlapping section to continue their trips to the desired destinations. Furthermore, this study focused on the potential of energy saving during different periods such as a.m. peak time (06.00–09.00 a.m.), off-peak time (9.00 a.m.–5.00 p.m.), and p.m. peak time (5.00–8.00 p.m.). The expected changes in waiting time, bus frequency, energy-saving, and CO_2 emission which were considered as performance indicators for the bus network improvement in the urban fringe area were investigated.

2. Public Transportation Background on Rama 2 Road

Rama 2 Road is located in western Bangkok. It serves as a major route in the urban fringe area in the Chomthong and Bangkhunthian districts. In 2016, the population density of Chomthong and Bangkhunthian districts was 1490 and 5851 people/km^2, respectively [17]. Typically, the number of passengers/km for general bus routes in the central business district (CBD) is higher than the urban fringe and the earning income in the urban fringe is lower than the CBD zone [18].

Most of the bus routes in Bangkok are long-distance routes that allow passengers to travel to their destinations without any transfer. Currently, the bus network in the urban fringe area consists of many overlapping bus lines on each major road. The overlapping bus lines lead to high waiting times and high competition for passengers that cause low revenue for each bus line [19,20]. The study research on bus reform indicated that the result benefited the urban fringe more than CBD because the transport disadvantages were higher there [21]. Motivated by these problems, this study proposed the bus network improvements by reducing the overlapping bus lines on Rama 2 Road. The study boundary covered 12.9 km from Samaedam terminal to Rama 2 T-junction as shown in Figure 1.

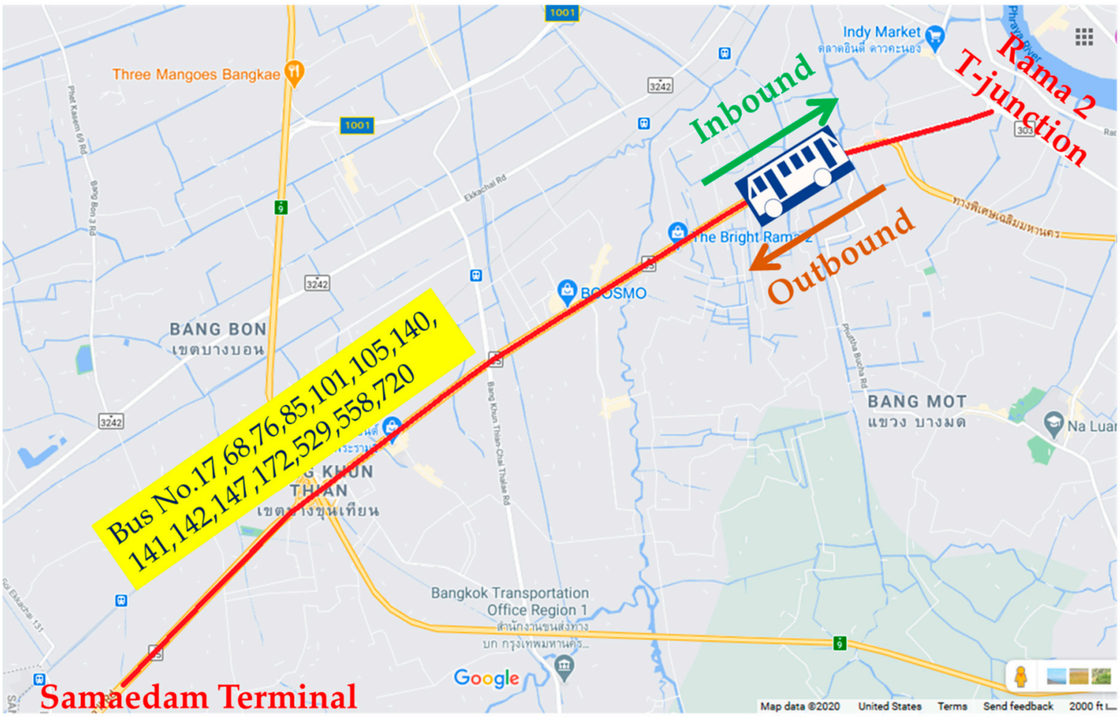

Figure 1. Bus Network before Reform (Adapted from Google Map).

Public transportation in this study consisted of 72% bus transit services provided by Bangkok Mass Transit Authority (BMTA) and 28% from a private bus company (from survey data from 14 August 2018 to 11 September 2018). Rama 2 Road has 14 overlapping bus lines including buses No. 17, 68, 76, 85, 101, 105, 140, 141, 142, 147, 172, 529, 558, and 720 [22]. At present, all inbound buses start from Samaedam terminal to Rama 2 T-junction and continue to different destinations. In the opposite direction, all outbound buses conjoin at Rama 2 T-junction before heading to Samaedam terminal as shown in Figure 1.

3. Study Methodology

This study illustrated the Partial Bus Routes Reform in Urban Fringe Model (PBRU) by introducing a single bus line along the overlapping corridor (Rama 2 Road). Bus No. A was assigned to run on Rama 2 Road from Samaedam terminal to Rama 2 T-junction. At Rama 2 T-junction, all passengers transferred back to the regular bus lines to continue their trips. The bus route structure after reform is shown in Figure 2. The analysis methodology and calculation framework for this study are shown in Sections 3.1–3.4 and Figure 3, respectively.

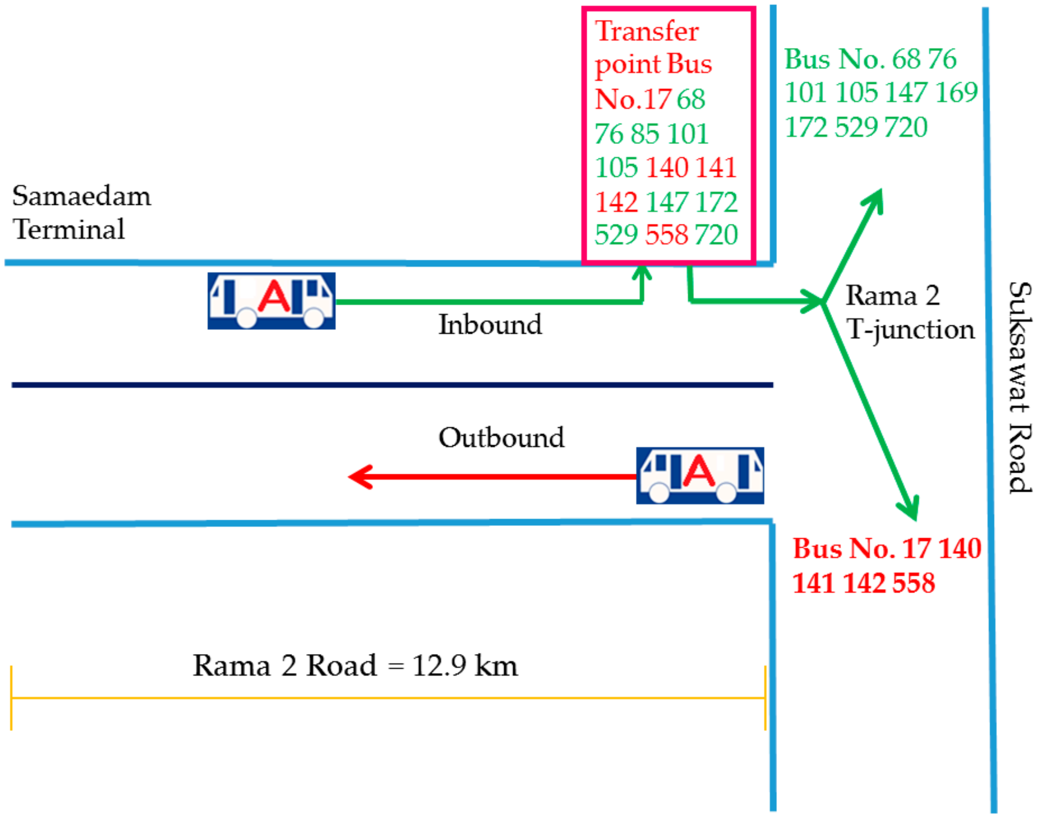

Figure 2. Bus Reform Using a Single Bus Line along the Overlapping Corridor (Rama 2 Road).

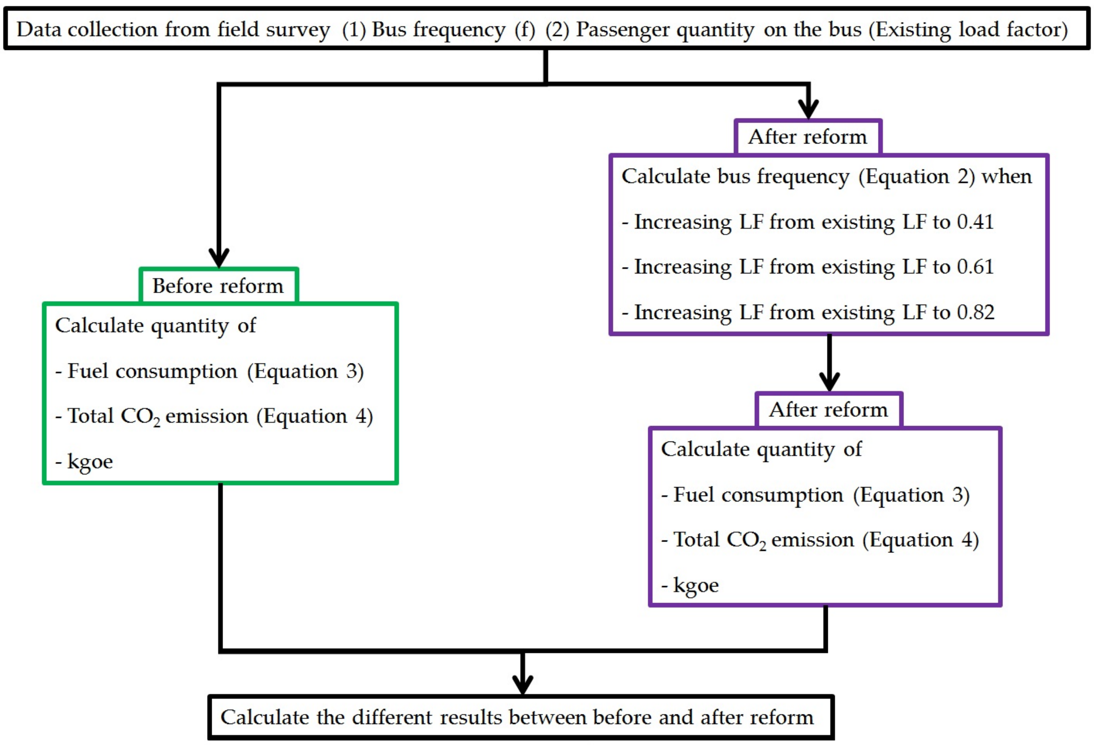

Figure 3. Calculation Framework of energy saving by using the Partial Bus Routes Reduction in Urban Fringe Model (PBRU) and CO_2 emission reduction along the Rama 2 Road after bus route reform.

3.1. Analysis of the Passenger Load Profile for Inbound and Outbound Directions

In this study, average passenger numbers of 27 bus samples (sample size determined by Yamane's formula with the confidential level as 80%) that operated on the overlapping section on Rama 2 Road were collected from 23 January 2018 to 13 February 2018. The number of passengers getting on and getting off all buses along Rama 2 Road was recorded from random individual buses to analyze the passenger load profile for both inbound (Samaedam terminal to Rama 2 T-junction) and outbound directions (Rama 2 T-junction to Samaedam terminal). The relationship between the total passengers on the bus, the number of passengers getting on and getting off is illustrated in Equation (1).

$$T_{passenger} = T_0 + \sum_{i=1}^{n} [T_{i\ (get\ on)} - T_{i\ (get\ off)}];\ i = 1, 2, 3, \ldots, n \quad (1)$$

T_0 = The number of passengers at the bus-terminal (Inbound) or transfer point at Rama 2 T-junction (outbound)
$T_{passenger}$ = The total passengers on the bus.
$T_{i\ (get\ on)}$ = The number of passengers getting on at the bus-stop $i = 1, 2, \ldots, n$
$T_{i\ (get\ off)}$ = The number of passengers getting off at the bus-stop $i = 1, 2, \ldots, n$

3.2. Finding the Number of Passenger Throughput on Rama 2 Road

The number of passengers/bus on Rama 2 Road and the number of buses from the field survey was collected from 24 August 2018 to 27 September 2018 to analyze the number of passenger throughput on Rama 2 Road. The number of passengers/bus in this study during the a.m. peak, off-peak, and p.m. peak was 62, 69, and 62 samples for inbound buses and 63, 70, 61 samples for outbound buses, respectively. The number of existing passengers from the field survey (passengers/hour) can be determined by multiplying the load factor (passengers/bus) with the number of buses (buses/hour).

3.3. Bus Frequency after Increasing the Load Factor

If the bus operators increased the load factor of the bus from the existing value to 0.41, 0.61, and 0.82, bus frequency on Rama 2 Road can be calculated by the number of passengers (from Section 3.2) and load factor characteristics (full/not full vehicle capacity). The relationship between each variable is illustrated in Equation (2) [23].

$$f = m/pb_{max} \quad (2)$$

where f is the bus frequency (buses/period), m is the number of passengers (passengers/period), b_{max} is the ratio between the number of passengers and the vehicle capacity (load factor), and p is the vehicle capacity (passengers/bus). In general, the vehicle capacity is 98 passengers/bus. In this research, the number of passengers did not exceed 80 passengers/bus to support the bus delay from traffic fluctuation that causes the overcrowding of passengers at the bus-stop. The relationship between the number of passengers on the bus and the load factor is illustrated in Table 1.

Table 1. The Relationship between the Load Factor and Total Passengers on the Bus.

Load Factor (b_{max})	Total Passengers on the Bus	Load Factor Characteristics
0.41	40	Full seated & a few passengers stand
0.61	60	Full seated & some passengers stand
0.82	80	Full seated & many passengers stand

3.4. Kilogram of Oil Equivalent and CO_2 Reduction Potential

3.4.1. Quantity of Fuel Consumption

The buses on Rama 2 Road are equipped with diesel and NGV engines. The buses operated by the private company are 100% NGV engines. The BMTA buses are 17% NGV engines and 83% diesel engine [24] The life cycle analysis (LCA) and life cycle cost (LCC) of diesel and NGV engines found that they were slightly different [25]. The quantity of fuel consumption in transportation can be calculated from a multiplication of the number of buses, travel distance, and fuel consumption rates as shown in Equation (3).

$$A = ND/F \tag{3}$$

A = quantity of fuel consumption (liter or kg/period time)
N = the number of buses on Rama 2 Road (buses/period time)
D = travel distance (km/bus). In this study, the distance from Samaedam terminal to Rama 2 T-junction is 12.9 km or 25.8 km for a round trip.
F = fuel consumption rate. (Diesel = 2.55 km/L, NGV = 1.60 km/kgNGV) [24].

3.4.2. Total CO_2 Emission from Fuel Consumption

The total CO_2 emission depends on the quantity of fuel consumption and emission factors. The relationship between each factor is shown in Equation (4) [26].

$$E = A \times EF \tag{4}$$

E = total CO_2 emission (kg CO_2/period time)
A = quantity of fuel consumption (liter or kg per period time)
EF = emission factor (kg CO_2/weight or volume) that can be calculated using emission factor per heating value of fuel proportion (kg CO_2/TJ) and energy content value (MJ/liter or kg). The emission factor of diesel and NGV engines are 2.70 kg CO_2/liter of diesel and 2.528 kg CO_2/kgNGV, respectively [27–29]. The calculation details of emission factors of diesel and NGV are illustrated in Appendix A.

3.4.3. Kilogram of Oil Equivalent (kgoe) Conversion

A kilogram of oil equivalent (kgoe) can be calculated using a multiplication of the quantity of fuel consumption and energy content of fuel (kgoe = $A \times EC$). Where A is the quantity of fuel consumption (kgNGV or liter/time period) and EC is energy content of fuel. Energy content of diesel is 36.42 MJ/liter or 0.86 kgoe/liter (1 toe = 42.244 GJ) [27]. Energy content of NGV is 42,710 Btu/kgNGV [28] or 1.07 kgoe/kgNGV (1 toe = 40.047×10^6 Btu) [27].

3.5. Waiting Time

The waiting time has a relationship to the number of overlapping routes and bus frequency. The waiting time can be estimated by the equation $t_{wait} = 60R/f$. From this equation, t_{wait} is the waiting time of passengers (minutes), R is the number of overlapping routes. In the case of Rama 2 Road, R = 14 and f = the bus frequency (buses/hour).

4. Results

4.1. Passenger Load Profile for Inbound and Outbound Directions

The profile of total passengers on the bus each day was collected from 27 bus samples in the urban fringe area (Rama 2 Road) between 23 January 2018 to 13 February 2018. The passenger load profiles for the inbound and the outbound directions were different. The inbound buses gained more passengers as they traveled closer to Rama 2 T-junction, which caused increasing in-vehicle passengers in this direction. Therefore, Rama 2 T-junction had the highest number of passengers on Rama 2 Road as shown in Figure 4. The average number of passengers getting off and getting on the bus on Rama 2 Road was 6 and 35 passengers, respectively, which is also considered as 14% and 86% of total passengers, respectively. On the contrary, the buses traveling in the outbound direction to the urban fringe area (from Rama 2 T-junction to Samaedam terminal) tended to have passengers get off rather than get on the bus, as shown in Figure 5. The average number of passengers getting on and getting off the bus was 6 and 32 passengers, respectively, which is also considered as 16 and 84% of total passengers, respectively.

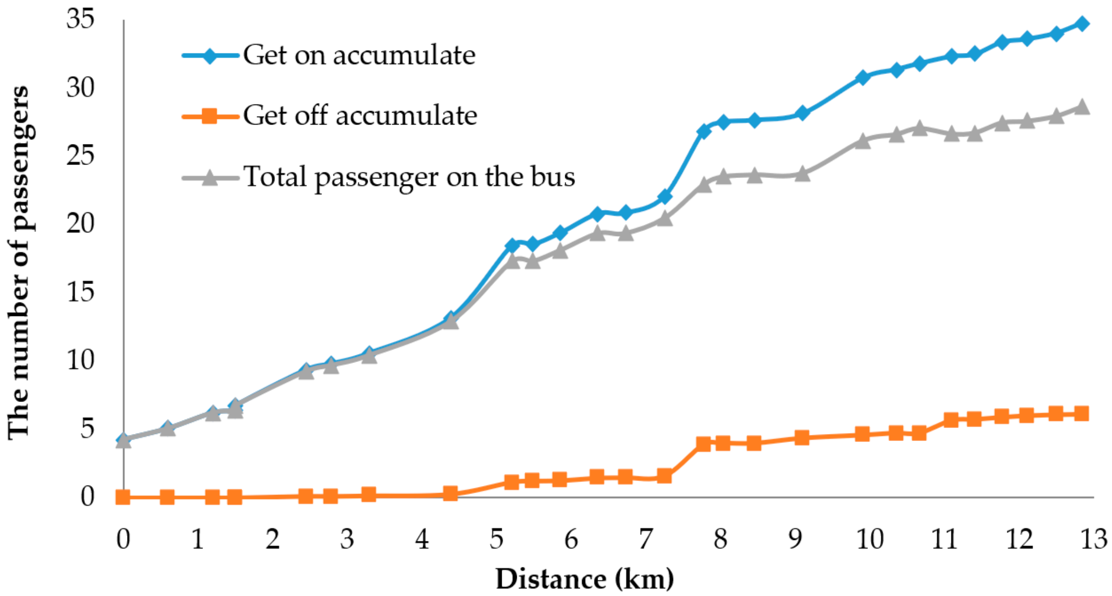

Figure 4. Inbound Passenger Load Profile from Samaedam Terminal (distance = 0 km) to Rama 2 T-junction.

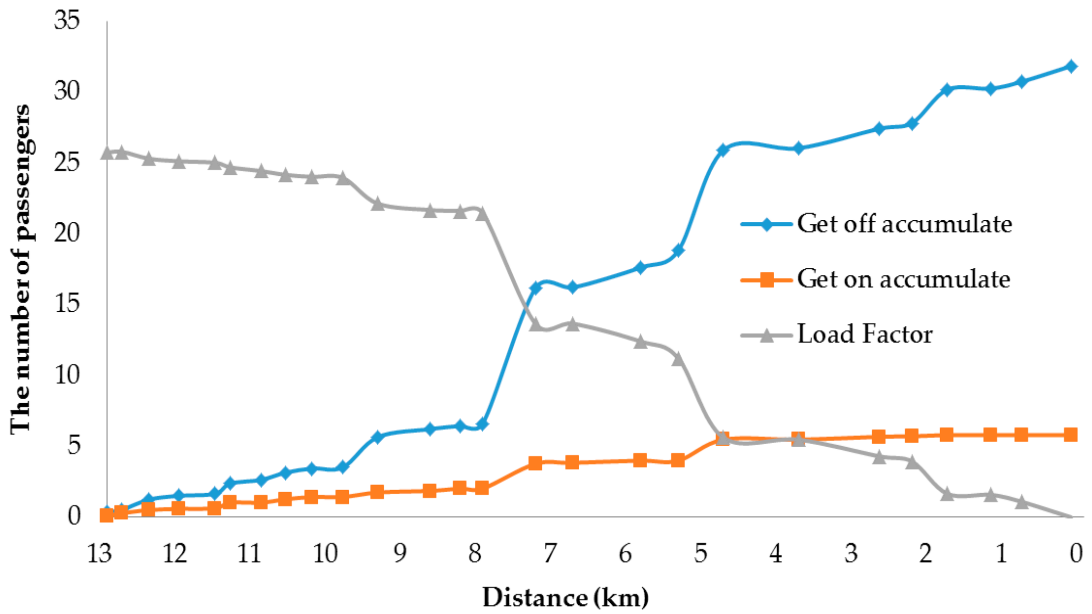

Figure 5. Outbound Passenger Load Profile from Rama 2 T-junction to Samaedam Terminal.

4.2. Travel Demand Analysis

From this study, the number of passengers on the bus samples along Rama 2 road (Rama 2 T-junction) was collected from 24 August 2018 to 27 September 2018. In this analysis, 62, 69, and 62 samples of the inbound buses and 63, 70, and 61 samples of the outbound buses were collected during the a.m. peak, off-peak, and p.m. peak times, respectively. The field survey results are illustrated in Table 2. It is found that the maximum travel demands of all time periods do not exceed the vehicle capacity (98 passengers). The long-range of the standard deviation of the load factor (the number of passengers on the bus) might result from uncontrollable reasons, such as (1) the fluctuated traffic on Rama 2 Road, (2) the competition of each bus driver to find more passengers by trying to reach the bus stop before others, and (3) the difference of driving speeds and driving behaviors.

Table 2. The Field Survey Results of Travel Demand with Different Time Periods.

Data Results	Inbound			Outbound		
	A.M. Peak	**Off-Peak**	**P.M. Peak**	**A.M. Peak**	**Off-Peak**	**P.M. Peak**
Samples (n)	62	69	62	63	70	61
Passengers/bus (Average)	44 ± 16.9	16 ± 9.2	29 ± 13.1	27 ± 17.3	20 ± 11.4	44 ± 14.5
Passengers/bus (Maximum)	83	46	60	75	47	75
Load Factor (Average)	0.45 ± 0.17244	0.16 ± 0.09388	0.30 ± 0.13367	0.28 ± 0.17653	0.20 ± 0.11633	0.45 ± 0.14796
Amount of Buses/hour	83	68	57	64	64	71
Passengers/hour	3652	1088	1653	1728	1280	3124
Passengers/hour-km	283.1	84.3	128.1	134.0	99.2	242.2
Waiting Time Average (Minutes)	10.12	12.35	14.74	13.13	13.13	11.83

The average passenger demand per hour is a product between the average number of passengers on the bus (passengers/bus) and the average number of buses on Rama 2 Road (buses/hour). The inbound passenger demand during the a.m. peak, off-peak, and p.m. peak times were 3652, 1088, and 1653 passengers/hour, respectively. The outbound passenger demand during the a.m. peak, off-peak, and p.m. peak times were 1728, 1280, and 3124 passengers/hour, respectively. The inbound passenger demand during the a.m. peak time was higher than the outbound one, therefore, the inbound direction was selected for the bus frequency analysis during this period. On the other hand, the outbound direction was selected for the bus frequency analysis during off-peak and p.m. peak times due to a higher demand than the inbound one.

4.3. Bus Reform Results

4.3.1. The Relationship between the Average Bus Frequency and Load Factor with Different Time Periods

The bus frequency varied by different load factors as shown in Figure 6. During the a.m. peak time, the average bus frequency was 83 buses/hour with an average load factor of 0.45. If the bus operator increased the load factor from 0.45 to 0.61 and 0.82 by using the PBRU on Rama 2 Road, the bus frequency would reduce to 61 and 46 buses/hour, respectively. During the off-peak time, the average number of buses at normal operation was 64 buses/hour with an average load factor of 0.20. If the bus operator increased the load factor from 0.20 to 0.41, 0.61, and 0.82 by using the PBRU on Rama 2 Road, the average number of buses on Rama 2 Road would reduce to 32, 21, and 16 buses/hour, respectively. During the p.m peak time, the average number of buses at normal operation was 71 buses/hour with an average load factor of 0.45. If the bus operator increased the load factor from 0.45 to 0.61 and 0.82 by using the PBRU on Rama 2 Road, the average number of buses on Rama 2 Road would reduce to 52 and 39 buses/hour, respectively.

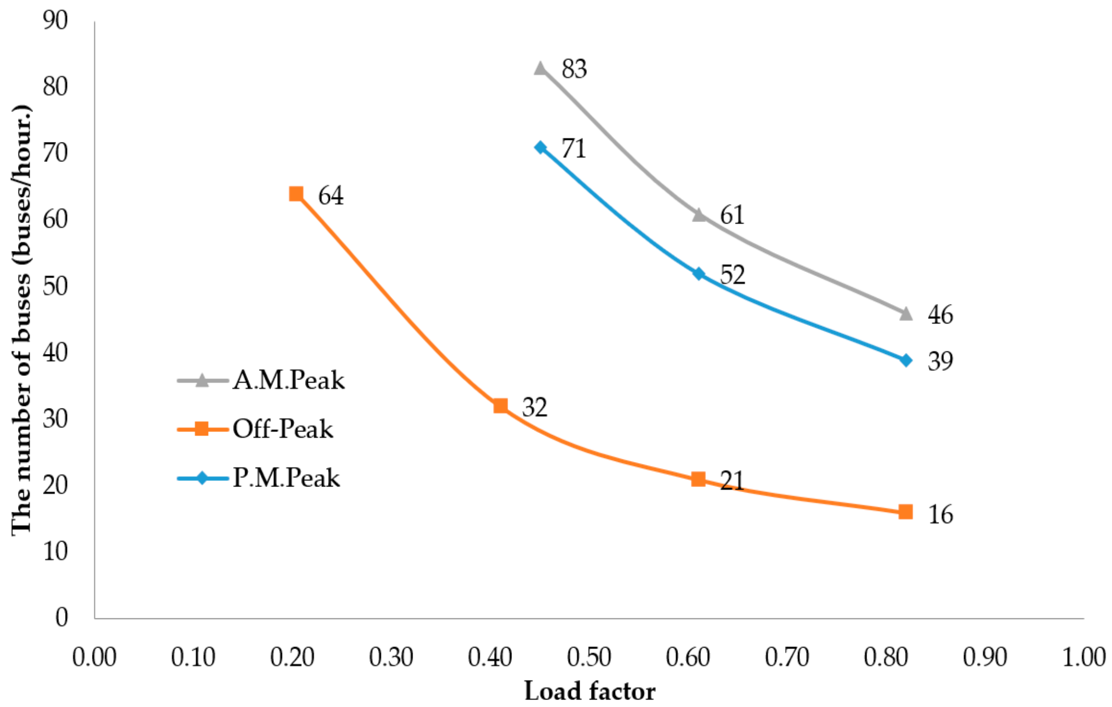

Figure 6. The Relationship between the Bus Frequency and Load Factor (LF) by Time Period for the Higher Demand Direction.

4.3.2. The Relationship between a Kilogram of Oil Equivalent Reduction and Load Factor with Different Time Periods

The analysis results of a kilogram of oil equivalent reduction for each time period are shown in Figure 7. During the a.m. peak time, a kilogram of oil equivalent reduction when the bus operators increased the load factor from existing (LF = 0.45) to 0.61 and 0.82 would be 10.31 and 17.35 kgoe/km-hour, respectively. During the off-peak time, a kilogram of oil equivalent reduction when the bus operators increased the load factor from existing (LF = 0.20) to 0.41, 0.61, and 0.82 would be 15.00, 20.16, and 22.50 kgoe/km-hour, respectively. During the p.m. peak time, a kilogram of oil equivalent reduction when the bus operators increased the load factor from existing (LF = 0.45) to 0.61 and 0.82 would be 8.91 and 15.00 kgoe/km-hour, respectively. The PBRU on Rama 2 Road during the off-peak period had more energy-saving potential than the others due to its low load factor. The load factor during the off-peak period could be increased from 0.20 to 0.82 to save energy. On the other hand, the range of increasing load factor at the a.m. peak and p.m. peak times was limited from 0.45 to 0.82.

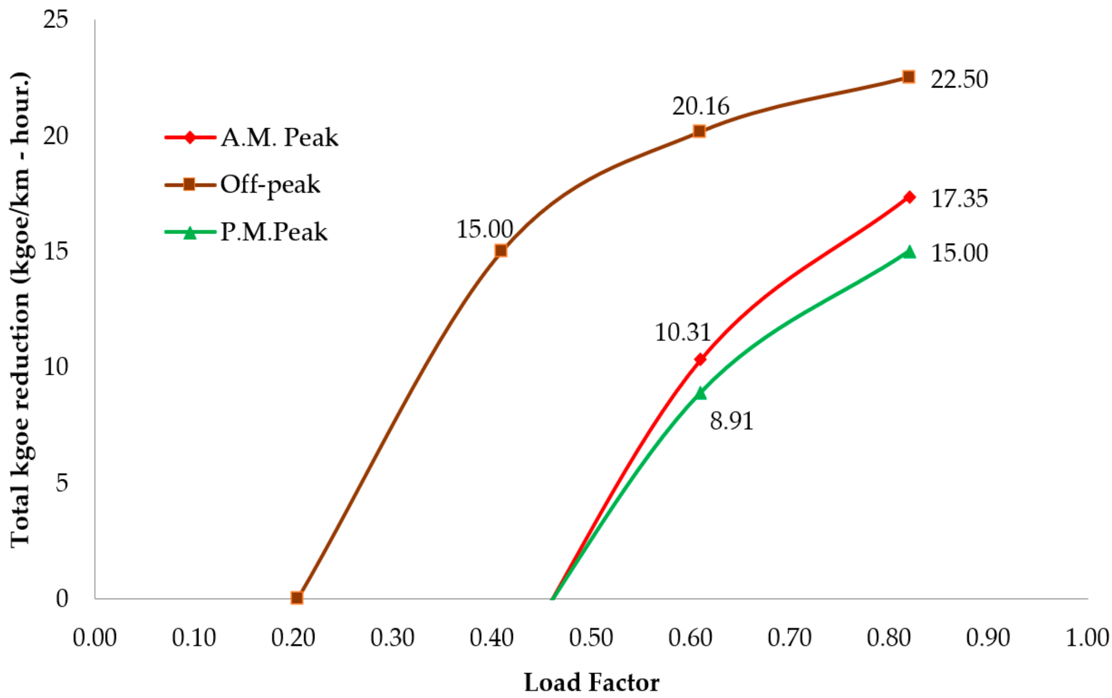

Figure 7. The Relationship between a Kilogram of Oil Equivalent Reduction (kgoe/km-hour) and Load Factor (LF) by Time Period.

4.3.3. The Relationship between the Total Emission Reduction and Load Factor with Different Time Periods

Table 3 illustrates the total emissions before and after the reform of the bus network by using the PBRU on Rama 2 Road. It was found that the bus network after reform has a lower total emission than the bus network before reform. The analysis results of the air pollution reduction for each time period are shown in Figure 8. During the a.m. peak time, the total emission reduction from the existing load factor (LF = 0.45) to 0.61 and 0.82 would be 27.86 and 46.85 kgCO_2/hour-km, respectively. During the off-peak time, the total emission reduction from the existing load factor (LF = 0.20) to 0.41, 0.61, and 0.82 would be 40.52, 54.44, and 60.77 kg CO_2/hour-km, respectively. During the p.m. peak time, the total emission reduction from the existing load factor (LF = 0.45) to 0.61 and 0.82 would be 24.06 and 40.52 kg CO_2/hour-km, respectively.

Table 3. Total CO_2 Emissions Before and After Reform of the Bus Network.

Period of Time	Total Emission (kg CO_2/hour-km)					
	Load Factor = 0.41		Load Factor = 0.61		Load Factor = 0.82	
	Before	After	Before	After	Before	After
A.M. Peak	N.A.	N.A.	105.09	77.23	105.09	58.24
Off-peak	81.03	40.52	81.03	26.59	81.03	20.26
P.M. peak	N.A.	N.A.	89.90	65.84	89.90	49.38

N.A. = Not applicable.

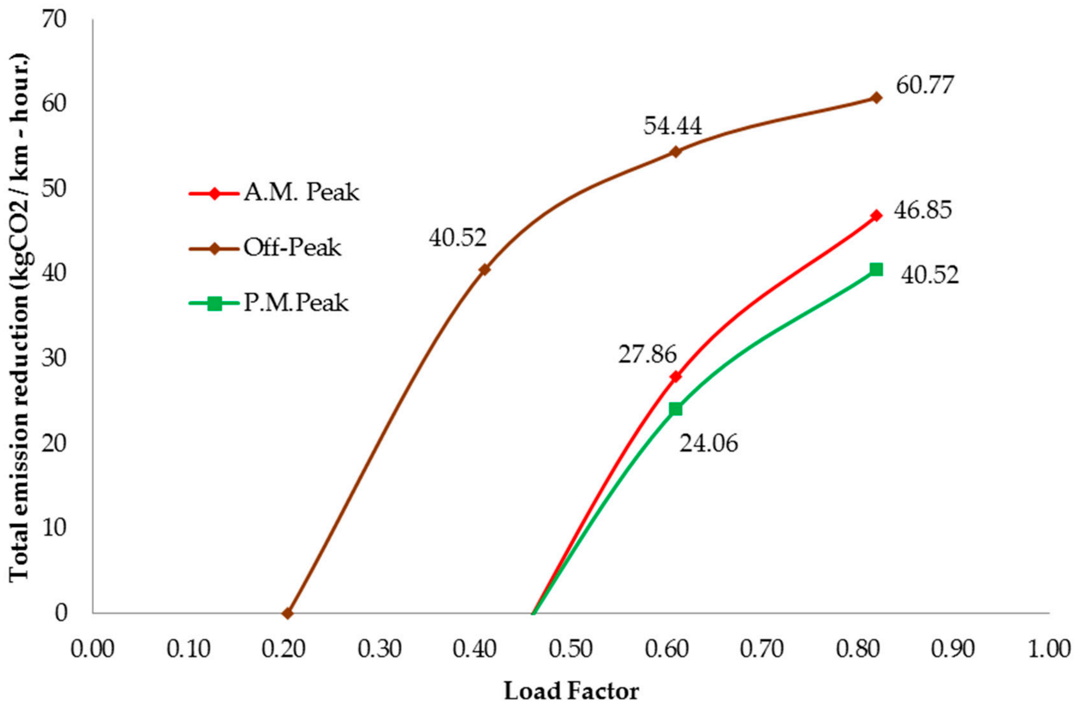

Figure 8. The Relationship between Total Emission Reduction (kg CO_2/km-hour) and Load Factor (LF) with Different Time Periods.

Figure 9 illustrates the percentage of energy or CO_2 reduction potential for a different time of a day. The relationship between the percent of daily energy or kgCO_2 reduction after the applied PBRU (y-axis) and load factor (x-axis) from the existing load factor to the maximum load factor is shown in the least polynomial degree at SSR/SSE or $R^2 > 0.99$. The relationship between the percentage of energy or CO_2 reduction and load factor during the a.m. peak and the p.m. peak time was $Y_{A.M./P.M.} = -214.6\,X^2 + 394.16\,X - 133.92$ for the load factor ranging between 0.45 to 0.82. The potential of energy or CO_2 reduction when the bus operators increased the load factor from the existing (LF = 0.45) to 0.61 and 0.82 would be 27% and 45%, respectively. The percentage of energy or kg CO_2 reduction during the a.m. peak and the p.m peak time was similar due to their identical load factors as shown in Table 2. The relationship between the percentage of energy or CO_2 reduction and load factor during the off-peak time was $Y_{Off\text{-}peak} = 464.27\,X^3 - 960.8\,X^2 + 696.45\,X - 106.03$ for the load factor ranging between 0.20 to 0.82. The potential of energy or CO_2 reduction during the off-peak time when the bus operators increased the load factor from existing (LF = 0.20) to 0.41, 0.61, and 0.82 would be 50%, 67%, and 75%, respectively.

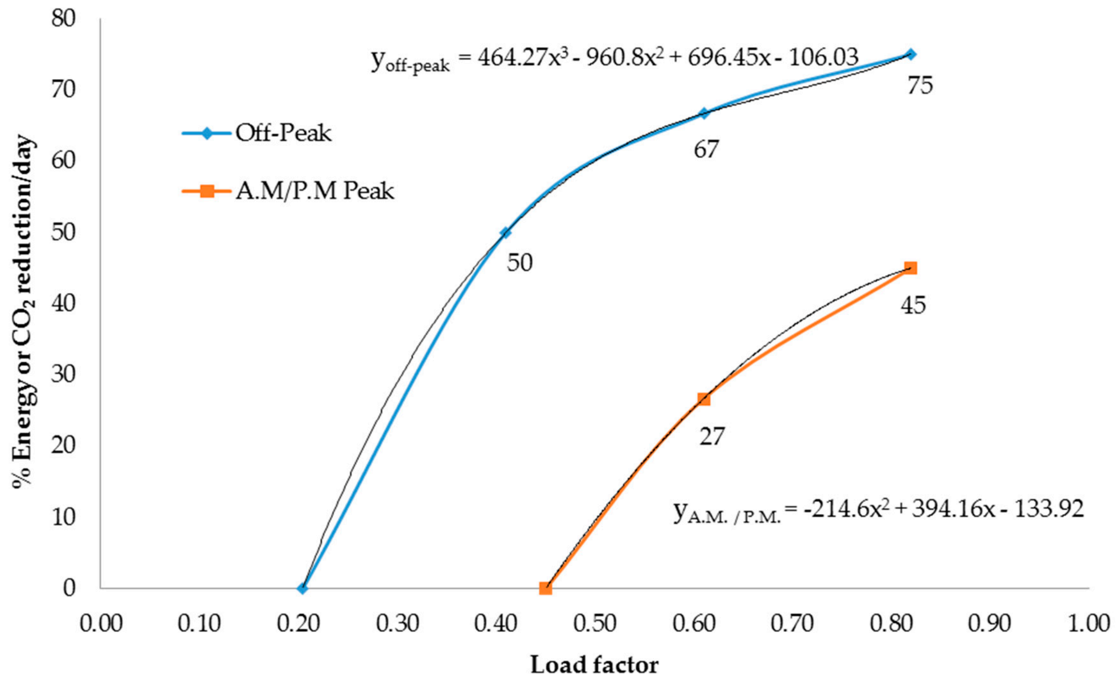

Figure 9. The Relationship between the Percentage of Energy or $kgCO_2$ Reduction after Applied PBRU and Load Factor during the a.m. peak ($Y_{A.M.}$), Off-peak ($Y_{off\text{-}peak}$), and p.m. Peak Times ($Y_{P.M.}$).

4.3.4. The Relationship between Waiting Time Reduction and Load Factor by Time Period

Table 4 illustrates the waiting time before and after combining the bus lines on the overlapping section of Rama 2 Road. The PBRU model could cut down the waiting time by 93% or 14 times if the load factor between before and after reform was identical. During the a.m. peak time, the waiting time of the existing load factor (LF = 0.45) was 10.12 min. If the bus operators increased the passenger load factor to 0.61 and 0.82, the waiting time after reform would be 0.98, and 1.30 min, respectively. The waiting time before and after reform during off-peak and p.m. peak times is illustrated in Table 4.

Table 4. Waiting Time (min) before and after the Bus Reform for each Load Factor.

Period of Time	Existing Waiting Time (min)	Existing Load Factor	Waiting Time of PBRU		
			LF = 0.41	LF = 0.61	LF = 0.82
A.M peak	10.12	0.45	N.A.	0.98	1.30
Off-peak	13.13	0.20	1.88	2.86	3.75
P.M. peak	11.83	0.45	N.A.	1.15	1.54

N.A. = Waiting time at a lower existing load factor can not be estimated.

4.3.5. Economic Benefits of the Bus Reform Using the PBRU in the Bangkok Urban Fringe

A.M. Peak Time

The analysis results for the a.m. peak time are illustrated in Table 5. The annual fuel-saving potential when the bus operators increased the load factor from existing (LF = 0.45) to 0.61 and 0.82 would be 136,942 (27%) and 230,312 USD (45%), respectively (based on the market price of diesel and NGV on 5 May 2019, 28.09 THB/liter for diesel and 16.01 THB/kg for NGV) [30]. In general, the cost of the fuel was 30.22% of the total operating cost, which consists of the drivers' and employees' remuneration, fuel cost, maintenance, depreciation, and other expenses [31]. The total annual operating cost-saving potential if the bus operator increased the load factor from existing to 0.61 and 0.82 would be 14,469,104 THB (453,151 USD) and 24,334,402 THB (762,117 USD), respectively. (1 USD = 31.93 baht) [32].

Table 5. Annual Energy Saving Potential after Applied PBRU on Rama 2 Road during the a.m. Peak Period.

Analysis Data	Annual Energy Saving Potential (242 Workdays/Year)			
	LF = 0.45 to 0.61	**%Saving**	**LF = 0.45 to 0.82**	**%Saving**
Bus Trip Reduction (bus trips/year)	15,972	27%	26,862	45%
Diesel Reduction (liters/year)	97,202	27%	163,476	45%
NGV Reduction (kg/year)	102,571	27%	172,505	45%
Fuel Saving (USD/year)	136,942	27%	230,312	45%
Fuel Saving/km. (USD/km-year.)	5308	27%	8927	45%
Operating Cost Saving (USD/year)	453,151	27%	762,117	45%
Operating Cost Saving/km. (USD/km-year.)	17,564	27%	29,539	45%

Off-Peak Time

From analysis results in Table 6, the annual fuel-saving when the bus operator increased the load factor from existing (LF = 0.20) to 0.41, 0.61, and 0.82 would be 531,170, 713,759, and 796,754 USD, respectively. This leads to the total annual operating cost-saving potential of 1,757,676, 2,361,877 and 2,636,513 USD, respectively.

Table 6. Annual Energy Saving Potential after Applied PBRU on Rama 2 Road during the Off-peak Period.

Analysis Data	Annual Energy Saving Potential (242 Workdays/Year)					
	LF = 0.20 to 0.41	**%Saving**	**LF = 0.20 to 0.61**	**%Saving**	**LF = 0.20 to 0.82**	**%Saving**
Bus Trip Reduction (bus trips/year)	61,952	50%	83,248	67%	92,928	75%
Diesel Reduction (liters/year)	377,026	50%	506,629	67%	565,539	75%
NGV Reduction (kg/year)	397,850	50%	534,611	67%	596,775	75%
Fuel Saving (USD/year)	531,170	50%	713,759	67%	796,754	75%
Fuel Saving/km. (USD/km-year.)	20,588	50%	27,665	67%	30,882	75%
Operating Cost Saving (USD/year)	1,757,676	50%	2,361,877	67%	2,636,513	75%
Operating Cost Saving/km. (USD/km-year.)	68,127	50%	91,546	67%	102,190	75%

P.M. Peak Time

The analysis results during p.m. peak time are illustrated in Table 7. The annual fuel-saving potential when the bus operator increased the load factor from existing (LF = 0.45) to 0.61, 0.82 would be 118,268 (27%) and 199,189 USD (45%), respectively. The annual total operating cost-saving potential if the bus operator increased the load factor to 0.61 and 0.82 would be 391,357 and 659,128 USD, respectively.

Table 7. Annual Energy Saving Potential after Applied PBRU on Rama 2 Road during the p.m. Peak Period.

Analysis Data	Annual Energy Saving Potential (242 Workdays/Year)			
	LF = 0.45 to 0.61	**%Saving**	**LF = 0.45 to 0.82**	**%Saving**
Bus Trip Reduction (bus trips/year)	13,794	27%	23,232	45%
Diesel Reduction (liters/year)	83,947	27%	141,385	45%
NGV Reduction (kg/year)	88,584	27%	149,194	45%
Fuel Saving (USD/year)	118,268	27%	199,189	45%
Fuel Saving/km. (USD/km-year.)	4584	27%	7720	45%
Operating Cost Saving (USD/year)	391,357	27%	659,128	45%
Operating Cost Saving/km. (USD/km-year.)	15,169	27%	25,548	45%

When comparing the saving benefits between different peak times, it was found that the off-peak time could provide the highest potential for fuel reduction than other peak times. This was because the existing load factor during the off-peak was lower than during rush hours as shown in Table 2. This provided more opportunity for the bus operators to increase the load factor to the desired level.

Moreover, the off-peak time accounted for 8 h of operations while each peak time accounted for only 3 h, e.g., 6.00–9.00 a.m. or 5.00–8.00 p.m.

5. Discussion

5.1. Direct and Indirect Benefits of the Bus Route Reform by the PBRU

5.1.1. Waiting Time Reduction

Bus routes after the reform in this study reduced the waiting time for passengers who traveled within Rama 2 Road. From Table 4, the range of waiting times for buses on Rama 2 Road after the reform of the routes throughout the day was 0.72–3.75 min, which is similar to the hub and spoke model in Bangalore city [15] and much lower than the bus network after the reform in Barcelona (waiting time = 6.18 min) and Santiago (waiting time = 8.20 min) [12–14]. However, only 14% of total inbound passengers and 16% of total outbound passengers received the benefit after the reform of the routes (see Figures 4 and 5). The majority of passengers lost the benefit because they waited at the bus-stop twice (comprised of the bus-stop near the residence and the transfer point). At the peak time, most passengers would slightly lose the benefit from waiting twice. From the results in Table 4, the maximum waiting time increases did not exceed 1.30 min at the a.m. peak and 1.54 min at the p.m. peak times. At the off-peak time, most passengers have a waiting time increase of 1.88–3.75 min. The bus operator can reduce the waiting time by increasing the load factor from the existing to 0.41 which will cause the overall waiting time to increase by only 1.88 min.

However, an advantage of the PBRM, is that passengers do not necessarily walk for the transfer. It is different from the bus reform in Barcelona that reduced overlapping routes to increase bus frequency, but the passengers must walk for the transfer. The general loss time of a bus-to-bus transfer was 5–50 min and the average was 22 min [33].

5.1.2. Energy Saving Potential and CO_2 Emission Reduction

Many literature reviews illustrate the energy-saving potential and CO_2 emission reduction after bus route reform over one day. In actuality, the energy-saving potential and CO_2 emission reduction depend on the time of the day.

From the current bus operations data in Table 2, the a.m. and the p.m. peak time already had a relatively higher load factor than the off-peak hours. Therefore, the benefits of the bus reform on the energy-saving potential and CO_2 emission reduction during peak hours would be little and could expect some limitations. If the bus operators choose to increase the load factor during rush hours, the level of service (LOS) for passengers would be lower. Consequently, the passengers would be likely to be dissatisfied with the bus service.

During the off-peak hours, although the bus operators attempted to reduce the number of fleets due to low travel demand, the average load factor was still low (existing load factor = 0.20). The bus operators had a high potential to increase the load factor from the existing value (LF = 0.20) to the maximum value (LF = 0.82). Therefore, the energy-saving potential and CO_2 emission reduction during the off-peak hours were likely to be higher than the rush hours.

Apart from the direct benefits, the bus route reform by the PBRU also had indirect benefits. The reformed bus network also had a lower risk of service disruption. When the connecting bus lines experienced any delay from traffic or accidents, services on the bus line on Rama 2 Road would not be affected. Therefore, the reformed bus routes structure would be more reliable than the overlapping bus routes structure.

5.2. Strategy of the Transfer Point Management

The PBRU can reduce the overlapping bus routes in an urban fringe area. As a trade-off, all passengers have to connect to other bus lines at the transfer point to go to their desired destinations.

In this case, the designated transfer point (Rama 2 T-junction) is expected to be overcrowded with transit passengers. Therefore, the bus operators should re-design the transfer point to accommodate all passengers in the waiting area. If the bus operators are not able to build a large bus-stop at the transfer point, one strategy could be to arrange the bus-stop into multiple sections with a designated group of bus lines to spread out the demand as shown in Figure 10.

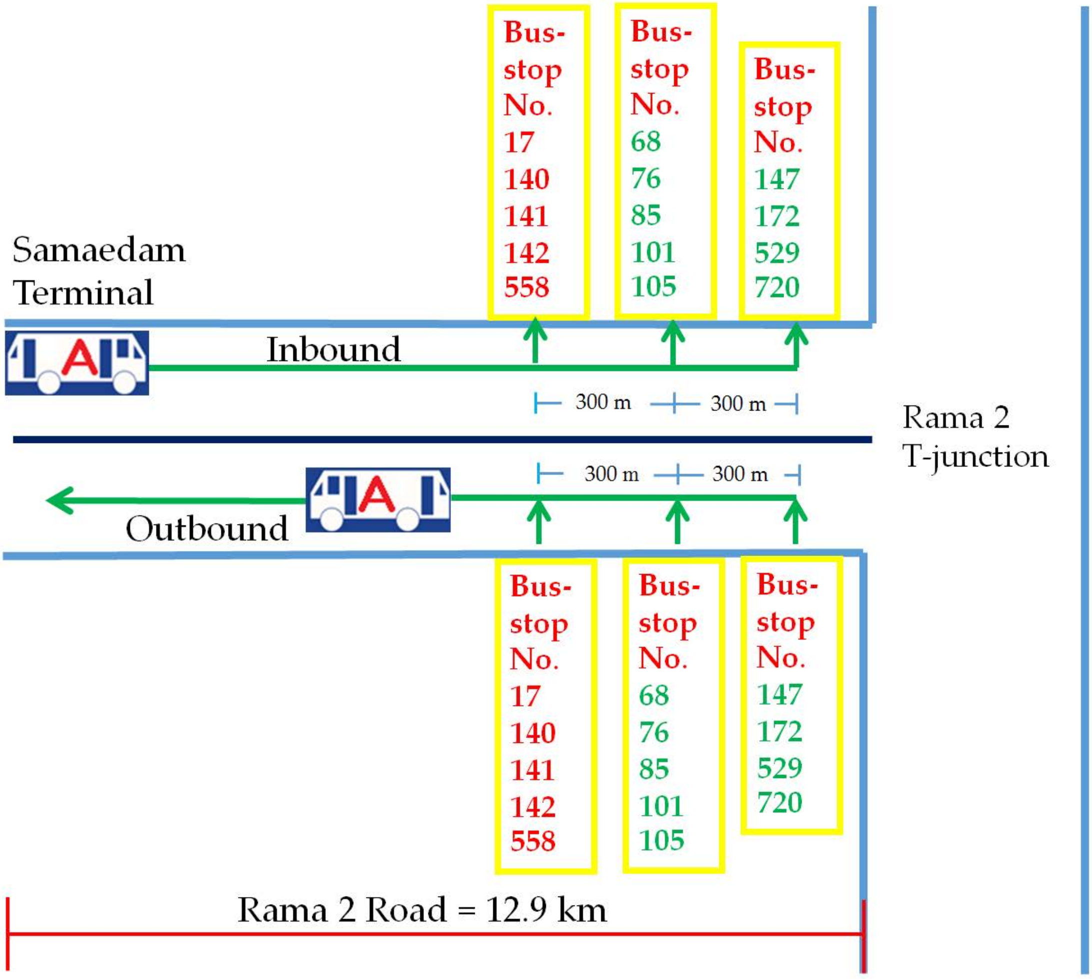

Figure 10. The Proposed Bus Reform with the Multiple Transfer Points at Rama 2 T-junction.

The other possible problem at the transfer point is the uncertainty in the bus headway from traffic congestion that causes overcrowding of passengers at the transfer point. The suggestion for prevention of this problem is sparing a small area for the bus terminal at the transfer point to serve the passengers when the transfer point has overcrowding passengers.

5.3. Application of the PBRU for Other Bus Networks

In general, the pattern of the bus network in the capital city can be divided into three types. The first group is traveling from the urban fringe to another urban fringe area. The second group is traveling from the urban fringe to the central business district area (CBD) and the third group is traveling between the CBD area. The bus routes in Bangkok have 207 routes. Over 75.36% of total bus routes operate from urban fringe to urban fringe and urban fringe to the CBD area. Approximately 50.72% of total bus routes operate in the urban fringe zone and overlap with other bus routes. For example, there are 16 overlapping bus routes in Phetkasem Road, 15 overlapping bus routes in Sukhumvit Road, 10 bus routes in Bangna-Trad, and Phahonyothin Road, etc. [22,34]. Therefore, the bus route reform by the PBRU can be applied in many roads in Bangkok that would cause a high potential for energy-saving in the public transportation system and a significant reduction of air pollution in the city.

5.4. Suggestion for Further Research

The PBRM can reduce energy and CO_2 in the bus network. However, the benefit of the waiting time reduction effect is only 14% of the total inbound passengers and 16% of the total outbound passenger, as shown in Figures 4 and 5. The methodology to increase the passenger benefit is expanding the transfer point 1 km by (1) combining 9 bus routes that turn left at Rama 2 T-junction, (2) combining 5 bus routes that turn right at Rama 2 T-junction. The result of increasing the benefits for the passenger is (1) a lot of passengers on Rama 2 Road can exchange with the other bus routes on Suksawat Road, such as buses No. 20, 21, 35, 37, 75, 82, and 195, and (2) expanding the transfer point can increase the possibility of passenger destinations. The waiting time, energy, and CO_2 reductions of further research should investigate the precise results to explore the optimal bus routes structure in the urban fringe area.

6. Conclusions

This research illustrates the bus reform strategy by the Partial Bus Routes Reduction in Urban Fringe Model (PBRU) along the overlapping section on Rama 2 Road. The advantages of the PBRU bus routes are the decrease in fuel consumption and CO_2 emissions when compared with the regular bus route. However, most passengers' waiting time slightly increased from regular routes (0.72–3.75 min), but the PBRU is better than other bus route reform in that some passengers always get confused with the new network and suffer from transferring from bus-to-bus (5–50 min). The PBRU can be applied for other overlapping bus routes from the urban fringe areas to the central business district area. The results from this study would be useful information for any bus operators (public and private buses) wanting to restructure their bus operations.

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Appendix A

Emission Factor for Diesel and NGV

The details of the source emission factors of diesel and NGV are shown below.

1. The source of emission factors for diesel.

Energy content = 36.42 MJ/liter or 0.86 kgoe/liter [27].
Emission factor of diesel = 74,100 kg CO_2/TJ [29].
Therefore, the emission factor for diesel = (74,100 kg CO_2/TJ) (36.42 MJ/liter) = 2.70 kg CO_2/liter.

2. The source of emission factors for NGV.

Energy content = 42,710 BTU/kgNGV or 1.07 kgoe/kgNGV [27,28].
Emission factor of NGV = 56,100 kg CO_2/TJ [29].
Therefore, the emission factor for NGV = (56,100 kg CO_2/TJ) × (42,710 BTU/kgNGV × 1054.94 × 10^{-12} TJ/BTU = 2.528 kg CO_2/kgNGV.

References

1. Kim, M.J. The effects of transboundary air pollution from China on ambient air quality in South Korea. *Heliyon* **2019**, *5*, e02953. [CrossRef] [PubMed]
2. Targino, A.C.; Krecl, P.; Cipoli, Y.A.; Oukawa, G.Y.; Monroy, D.A. Bus commuter exposure and the impact of switching from diesel to biodiesel for routes of complex urban geometry. *Environ. Pollut.* **2020**, *263*, 114601. [CrossRef]
3. Sun, Y.; Mburu, L.; Wang, S. Analysis of community properties and node properties to understand the structure of the bus transport network. *Phys. A Stat. Mech. Appl.* **2016**, *450*, 523–530. [CrossRef]
4. Pavón-Domínguez, P.; Ariza-Villaverde, A.B.; Rincón-Casado, A.; Gutiérrez de Ravé, E.; Jiménez-Hornero, F.J. Fractal and multifractal characterization of the scaling geometry of an urban bus-transport network. *Comput. Environ. Urban Syst.* **2017**, *64*, 229–238. [CrossRef]
5. Pucher, J.; Park, H.; Kim, H. Public Transport Reforms in Seoul Public Transport Reforms in Seoul: Innovations Motivated by Funding Crisis. *J. Public Transp.* **2005**, *8*, 3.
6. Clifton, G.T.; Mulley, C. A historical overview of enhanced bus services in Australian cities: What has been tried, what has worked? *Res. Transp. Econ.* **2016**, *59*, 11–25. [CrossRef]
7. Alpkokin, P.; Ergun, M. Istanbul Metrobüs: First intercontinental bus rapid transit. *J. Transp. Geogr.* **2012**, *24*, 58–66. [CrossRef]
8. De Aragão, J.J.G.; Yamashita, Y.; Orrico Filho, R.D. BRT in Brazil: Designing services in function of given infrastructure projects or designing infrastructure in function of established service quality patterns? *Res. Transp. Econ.* **2016**, *59*, 304–312. [CrossRef]
9. Hidalgo, D.; Pereira, L.; Estupiñán, N.; Jiménez, P.L. TransMilenio BRT system in Bogota, high performance and positive impact—Main results of an ex-post evaluation. *Res. Transp. Econ.* **2013**, *39*, 133–138. [CrossRef]
10. Deng, T.; Nelson, J.D. Bus Rapid Transit implementation in Beijing: An evaluation of performance and impacts. *Res. Transp. Econ.* **2013**, *39*, 108–113. [CrossRef]
11. Wu, I.; Pojani, D. Obstacles to the creation of successful bus rapid transit systems: The case of Bangkok. *Res. Transp. Econ.* **2016**, *60*, 44–53. [CrossRef]
12. Badia, H.; Argote-Cabanero, J.; Daganzo, C.F. How network structure can boost and shape the demand for bus transit. *Transp. Res. Part A Policy Pract.* **2017**, *103*, 83–94. [CrossRef]
13. Muñoz, J.C.; Batarce, M.; Hidalgo, D. Transantiago, five years after its launch. *Res. Transp. Econ.* **2014**, *48*, 184–193. [CrossRef]
14. Allen, J.; Muñoz, J.C.; Rosell, J. Effect of a major network reform on bus transit satisfaction. *Transp. Res. Part A Policy Pract.* **2019**, *124*, 310–333. [CrossRef]
15. Verma, A.; Kumari, A.; Tahlyan, D.; Hosapujari, A.B. Development of hub and spoke model for improving operational efficiency of bus transit network of Bangalore city. *Case Stud. Transp. Policy* **2017**, *5*, 71–79. [CrossRef]
16. Traut, E.J.; Steinfeld, A. Identifying commonly used and potentially unsafe transit transfers with crowdsourcing. *Transp. Res. Part A Policy Pract.* **2019**, *122*, 99–111. [CrossRef]
17. The Bangkok Metropolitan Administration. Statistical Profile of Bangkok Metropolitan Administration 2016. Available online: http://203.155.220.230/m.info/bkkstat/stat_2559_eng.pdf (accessed on 26 September 2019).
18. Mulley, C.; Ho, C. Evaluating the impact of bus network planning changes in Sydney, Australia. *Transp. Policy* **2013**, *30*, 13–25. [CrossRef]
19. Khemapech, I.; Kidbunjong, L. Analysis of Excessive Cost of Overlapped Bus Route System in Bangkok. *Case Res. J.* **2015**, *7*, 120–149.
20. Bangkok Mass Transit Authority. Annual Report 2015. Available online: http://www.bmta.co.th/sites/default/files/files/download/annual-report-bmta-2558.pdf (accessed on 5 March 2019).
21. Pemberton, S. Optimising Melbourne's bus routes for real-life travel patterns. *Case Stud. Transp. Policy* **2020**, *8*, 1038–1052. [CrossRef]
22. Bangkok Mass Transit Authority. Bus Lines. Available online: http://www.bmta.co.th/th/lines (accessed on 11 May 2019).
23. Pujinda, P. *Basic of Public Transportation*; Chula Press: Bangkok, Thailand, 2012; pp. 67–71, 99–104.
24. Bangkok Mass Transit Authority. Annual Report 2016. Available online: http://www.bmta.co.th/sites/default/files/files/download/annaual-report-2559.pdf (accessed on 13 April 2019).

25. Cicconi, P.; Germani, M.; Landi, D.; Mengarelli, M. Life cycle cost from consumer side: A comparison between traditional and ecological vehicles. In Proceedings of the 2014 IEEE International Energy Conference (ENERGYCON), Cavtat, Croatia, 13–16 May 2014; pp. 1440–1445.
26. Friedrich, R.; Reis, S. *Emissions of Air Pollutants*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 279–281.
27. Energy Policy and Planning Office. Energy Statistics of Thailand 2018. Available online: https://drive.google.com/file/d/1WcNsEWr93CmhqQpMJMVbdHRNaQVwr_d4/view (accessed on 14 September 2019).
28. PTT Public Company Limited. Average Heating Value of Fuel. Available online: https://web1.pttplc.com/th/Media-Center/Energy-Knowledge/Documents/MD25%20knowledge02/nc_en_ee-01_01.pdf (accessed on 10 June 2020).
29. Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for National Greenhouse Gas. Inventories. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf (accessed on 15 October 2018).
30. Bangchak Corporation Public Company Limited. Historical Retail Oil Prices. Available online: https://www.bangchak.co.th/th/OilPrice/ (accessed on 8 May 2019).
31. Bangkok Mass Transit Authority. Annual Report 2017. Available online: http://www.bmta.co.th/sites/default/files/files/download/annualreport2560-compressed.pdf (accessed on 13 April 2019).
32. Exchange Rates Organization. US Dollars (USD) to Thai Baht (THB) Exchange Rate for May 5, 2019. Available online: https://www.exchange-rates.org/Rate/USD/THB/5-5-2019 (accessed on 29 May 2020).
33. Currie, G. The Demand Performance of Bus Rapid Transit. *J. Public Transp.* **2005**, *8*, 41–55. [CrossRef]
34. Bangkok Guide Technology (1986) Co., Ltd. *Bus Guide Bangkok-Travel*; Bangkok Guide Press: Bangkok, Thailand, 2010; pp. 1–40.

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