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A Preliminary Study of Traffic Impacts Due to Operational Improvement of Bus Rapid Transit in Bangkok Using Microscopic Traffic Simulation

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Abstract: Bus Rapid Transit (BRT) has been widely used in small to mega cities due to its flexible operation, reliable service, and cost effectiveness. It has been presented as a practical solution for upgrading transit performances and systems effectiveness for some countries. However, Bangkok is one of the big cities which could not operate the system effectively. In regards to operational improvement, a microscopic traffic simulation is applied to evaluate the impacts prior to the real implementation. The objective of this study is to propose and evaluate four alternative solutions to improve Bangkok BRT by using AIMSUN software. It was found that the travel time of BRT could be reduced from 8.27% to 10.33% while scarifying the increased of travel time of car users by 3.38% to 3.92% in the rush hours. The findings from this study can be underlying information for decision making in improving BRT operation in Bangkok.

Keywords: Microscopic traffic simulation, AIMSUN, Bus Rapid Transit (BRT), Bangkok, traffic congestion

1. INTRODUCTION

Public transportation or public transit is a general term used to describe all kinds of transit service modes (Mass transit, Paratransit, and Ridesharing) available to urban and suburb inhabitants. Therefore, it does not consist of merely one single mode but it has a diversity of traditional and innovative services, which should work and support each other in order to provide system-wide mobility to any and all commuters. Principle advantages of public transportation such as high-capacity (safe, rapid, comfortable, and convenient), economical and sustainable use in term of energy-efficient movement are considered as dominant points in densely traveled corridors. According to its advantages, public transportation has become an important element and a fundamental of the total transportation services that provided in different scales metropolitan areas (Garber and Hoel, 2002).

Presently, a number of population as well as a number of motorization especially in urban areas increased rapidly, it has caused the traffic congestion meaning that traffic gets into congestion condition when the demand of commuters surpasses the transportation system capacity. Literally, the urban sprawl in Asian developing countries especially in Bangkok, a capital city of Thailand known as the “Los Angeles of the East” (Kenworthy, 1995) owing to being as one of the highest congested countries in the globe (11th-world ranking) (Cookson and Pishue, 2017), has been growing fast and uncontrollably. Nevertheless, Bangkok Metropolitan Administration (BMA) is seeking ways to solve the jam-packed problems by

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setting the policies of expanding and improving mass transit system in accordance with providing new alternatives of travelling as a cheap, convenient and fast transport option. Hence, to place this into perspective, Bus Rapid Transit (BRT) has been presented as a practical example in order for upgrading transit performances and systems effectiveness in term of cost of construction and operation. It provides the high capacity of service in the areas of transit service by its efficient performance (Eichler, 2005). Additionally, BRT is known as a bus-based mass transit system that well integrates the rail-based transit (i.e. an exclusive right-of-way lanes, timeless boarding and alighting, enclosed station with safety and comfortableness, applying an Intelligent Transportation System) along with relatively inexpensive construction and operation cost (Tao et al., 2014).

Obviously, Bangkok BRT has not been operated efficiently. According to several observations, there are three main causes adversely affecting the operational efficiency. Firstly, BRT's lane is not entirely segregated from other vehicles and hence does not have absolute rights of way, in other words, the buses have to share their lanes with other vehicles at some sections, for example, on all 4 flyovers along Rama III Road where there are 2 lanes per direction and the dedicated lanes are not implemented. In addition to its failure to provide fully dedicated right of way, the second cause is that there is a considerably large number of drivers who get into the dedicated lanes illegally; and when they manage to get into the lanes, most of the time, they cannot return to mixed-traffic lanes easily. Lastly, the buses are not given special priority, such as early green or green light extension, at the at-grade intersections, meaning that they also have to be stuck in traffic with other vehicles. These three main causes have significantly reduced the system's efficiency by increasing travelling time of the buses while decreasing their time reliability. Bus Rapid Transit ought to be a mode of public transport that is efficient; both in terms of implementation costs and operation, and these factors leading to the operational inefficiency need to be addressed as soon as possible. On one hand, there is more than one possible solution to solve the problems, but on the other hand, there are both cost and time constraints. Engineers and planners can come up with many solutions, however, testing each of them in real world may cost too much money and time.

Overcoming the aforementioned challenges, traffic simulation models play a virtual key to visualize how the impacts after applying any alternative ways to the model will be prior to the real implementation. Several studies stated that these days the number of traffic simulation application software is extensively used transport planning projects especially adopting the micro-simulation model (Boxill and Yu, 2000; Figueiredo et al., 2014; Vilarinho et al., 2014). These models were developed to represent the reality regarding the physicals of network (infrastructures), traffic volume, drivers' behaviors and so forth. Additionally, Papageorgiou et al. (2012) addressed that the traffic simulation models are the best means to evaluate the possibility of the impacts before any implementations but not always be able to represent the true traffic conditions. The objective of this study is to propose and evaluate the alternative solutions in order for improving the operation of Bus Rapid Transit in Bangkok by adopting an Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN) software. There are four alternative scenarios applying in this study according to the need of Bangkok Metropolitan Administration (BMA) to enhance the operational capacity of Bangkok BRT.

The structures of this article are organized as follows: section 2 reviews the literature, section 3 describes the study area and data collection, section 4 describes development of microscopic traffic simulation model and case studies. Section 5 presents the results and discussions of this study. Section 6 concludes the paper to contribute to the further work of BRT operation improvement in Bangkok.

2. LITERATURE REVIEW

BRT is known as a bus-based mass transit system that well integrates the rail-based transit (i.e. an exclusive right-of-way lanes, timeless boarding and alighting, enclosed station with safety and comfortableness, applying an Intelligent Transportation System) along with relatively inexpensive construction and operation cost (Tao et al., 2014). Whilst the terms of BRT may be defined heterogeneously from country to country based on the basic of understandings. Therefore, to grasp the fundamental premise of BRT is that offering a high quality, consumer based needs by yielding fast, comfortable, convenient, safety and low cost consumption for moving from place to place (Sharma et al., 2012; Wright, 2004). After launching BRT in over 167 cities all around the world (Brtdata, 2018), BRT system is now turning into a very famous transportation system among the developing cities. Besides, the impartial road space allocation of BRT systems is being brought out in the efficient way that the traffic condition can be decreased obviously as well as the air pollution and other health problems. So, there is an instantaneous need to improve the transportation systems in urban cities (Raj G et al., 2013).

On the other hand, there are several BRT projects facing the obstacles for operating the system (Gunawan, 2014) or in another word is that those projects are having barriers to lead them operate successfully such as BRT in Brisbane (Australia), Lima (Peru), Bangkok (Thailand) and so forth. The reasons of failing in operation are owing to specific reasons based on different regions including weak political leadership, poor cooperation among the internal mass transit operations, poor public participation, low perceptions of people, unable to provide the well quality of service to commuters etc (Lindau et al., 2014; Mallqui and Pojani, 2017).

Regarding the unsuccessful BRT managements, Fierek and Zak (2012) proposed a planning procedure as an Integrated Urban Transportation System for operating the BRT system appropriately and internationally. In addition, previous studies reveal that applying Intelligent Transportation Systems (ITS) in the traffic simulation model can literally enhance the BRT performance such as the Traffic Signal Priority (TSP), Automatic Vehicle Location (AVL), Advanced Scheduling Dispatch System (ASDS), and Advanced Communication System (ACS) (Deng and Nelson, 2013; Liao and Davis, 2007; Papageorgiou et al., 2012). Transit Signal Priority (TSP) is a highly regarded application among transport planners and authorities. The system receives and sends the signal through the GPS devices installed on buses with the traffic management center. This way, the buses are prioritized when coming to intersection. The empirical studies reveal in the similar direction that applying TSP is able to ostensibly decrease bus travel times specifically in the peak times (Liao and Davis, 2007; Liu et al., 2006; Miller, 2015).

While the traffic simulation will never be able to represent the local condition without the calibration process. As the default values given by the simulation software are not able to apply in the study because the default was set to be a general value for a specific case. Therefore, in the calibration process there are two main categories to be calibrated including global parameters which involves driver reaction time, reaction time at traffic, reaction time at stop, queue up speed, queue leaving speed etc, and local parameters which involves vehicular types, vehicle speed limits, and section gradients (Dowling et al., 2004; Rajasakran, 2008).

Previously, a study of Bangkok BRT assessment was conducted by Jongudomkarn (2009). The effectiveness of various transit signal methods affecting to Bangkok Bus Rapid Transit operation was analyzed and evaluated through simulations using AIMSUN. The result of the study showed that using Transit Signal Priority decreased the delay of BRT at intersections by regarding the active priority method with the huge reduction of delay time.

Whilst, another study conducted by Roaj-assawachi (2013) considered the Level of Service of BRT in terms of bus frequency and travel time, respectively. Additionally, Bangkok BRT spends much longer time than cars in traffic for most of the time due to the operational constraints (Sisoutham and Piantanakulchai, 2018). Our study, nonetheless, differs from the previous studies by focusing more on case studies on improving the BRT's operation by using the simulation model.

3. STUDY AREA AND DATA COLLECTION

3.1 Study Area

This research study area was selected to study on the Bus Paid Transit (BRT) corridor in Bangkok as shown in Figure 1. Bangkok Bus Rapid Transit, operating from Naradhiwat Road to Ratchapruek Road with a total travel distance of 15.9 km long, was selected for this research study. Bangkok Bus Rapid Transit in common known is called Sathon-Ratchapruek corridor. The corridor is located in the south-west of Bangkok which is surrounded by the offices, people houses, department stores, etc. there are 12 stations in total – start from Sathon station to Ratchaphruek station, and there are total 13 intersections; 4 intersections with traffic signal control; 4 intersections with no overfly connected; and 9 overflies at intersection.

Figure 1. Study Area: Bangkok BRT Sathorn – Ratchaphruek route map

Bangkok BRT has 6 elements of the standard principle elements of being a Bus Rapid Transit including (1) pre-board fare collection, (2) enhanced station, (3) advanced vehicle, (4) waiting are for passenger, (5) exclusive lane, and (6) road barriers as shown in Figure 2.

Figure 2. Bangkok BRT elements

3.2 Data Collection

Data collection process is the crucial part that needs to collect at almost first part before any other steps and also has a strong impact to result if there are some errors appeared through the collected data. The data used in this study was collected along the BRT corridor (15.9 km) all together 13 intersections.

3.2.1 Physical surroundings along the corridor

To obtain the physical surroundings along the Bangkok BRT Sathorn-Ratchaphruek corridor, two methods were adopted. First, the surroundings were preliminary identified and recorded using Google's online mapping services such as Google Earth and Google Street View. Second, details information of physical surrounding were collected by conducting on-site visual surveys. Data collected included road configurations, type of lanes (mixed-traffic and BRT-only), number of lanes per direction, lanes' width, and turning permissions at intersections.

3.2.2 Traffic data

Traffic data collected by Bangkok traffic and transportation department was mainly used. It contained data such as daily traffic-flow rates in passenger cars per hour (from 7:00 AM to 7:00 PM) and turning movement ratios at intersections. However, some data, such as traffic signal durations and queue lengths, that had not been collected by the department was instead collected by conducting roadside surveys and using video cameras.

Field measurements for maximum queue lengths (MQL) were carried out at three intersections during a morning period: Rama III-Yannawa (12 veh in east bound), Narathiwat-Ratchadaphisek (15 veh in east bound), and Narathiwat-Sathorn Intersections (77 veh in north bound). The measurements were conducted by manual counts at all the intersections. These maximum queue lengths were to be used later in the model calibration for system performance. Furthermore, the signal phasing data was also collected at every intersection on the Sathorn – Ratchapruek BRT corridor. The collected data of signal phasing is tabulated below in Table 1 including number of phasing and cycle lengths.

Table 1. Signal Phasing and Cycle Lengths at 13 intersections along Bangkok BRT corridor

Intersection Name	Number of Phases	Cycle Length (s)
Sathorn Road Vs Naradhiwat Road	6	340
Chan Road Vs Naradhiwat Road	4	225
Ratchadaphisek Road Vs Naradhiwat Road	6	240
Naradhiwat Road Vs Rama III Road	3	115
Rama III Road Vs Industrial Ring Road	5	270
Rama III Road Vs Yan Nawa Road	3	95
Rama III Road Vs Sathupradit Road	4	105
Rama III Road Vs Ratchadaphisek Road	3	145
Rama III Road Vs Charoenrat Road	3	135
Rama III Road Vs Charoen Krung Road	5	215
Rama III Road Vs Charoen Nakhon Road	5	315
Mahai Sawan Road Vs Somdet Prachao Taksin Road	4	160
Ratchadaphisek Road Vs Ratchapruek Road	4	225

4. DEVELOPMENT OF MICROSCOPIC TRAFFIC SIMULATION MODEL AND CASE STUDIES

4.1 Development of Microscopic Simulation Model

In the traffic simulation phase, there were 3 main parts. The first part was base model development, the second part was model calibration and validation, and the last part was scenario preparation and simulation. A main purpose of the first two parts was to create a base traffic model that accurately represented the current traffic conditions of the roads along the BRT corridor. In the last part, each established solution was to be developed and tested.

4.1.1 Base model development

To deliver this research, a single road network was constructed in AIMSUN with detailed roadway configurations and geometries as shown in Figure 3. The network started from Ratchadaphisek-Ratchaphruek Intersection, continued along Ratchadaphisek Rd., crossed Rama III Bridge, and followed the BRT corridor until it stretched to Narathiwat-Sathorn Intersection. Based on the constructed network, two sets of traffic demand and control plans were created to represent traffic conditions during morning (7am-9am) and evening (4pm-6pm) periods. Traffic-flow rates and turning movements were used in creating the two two-hourly traffic states, while traffic signal durations were used in creating the control plans.

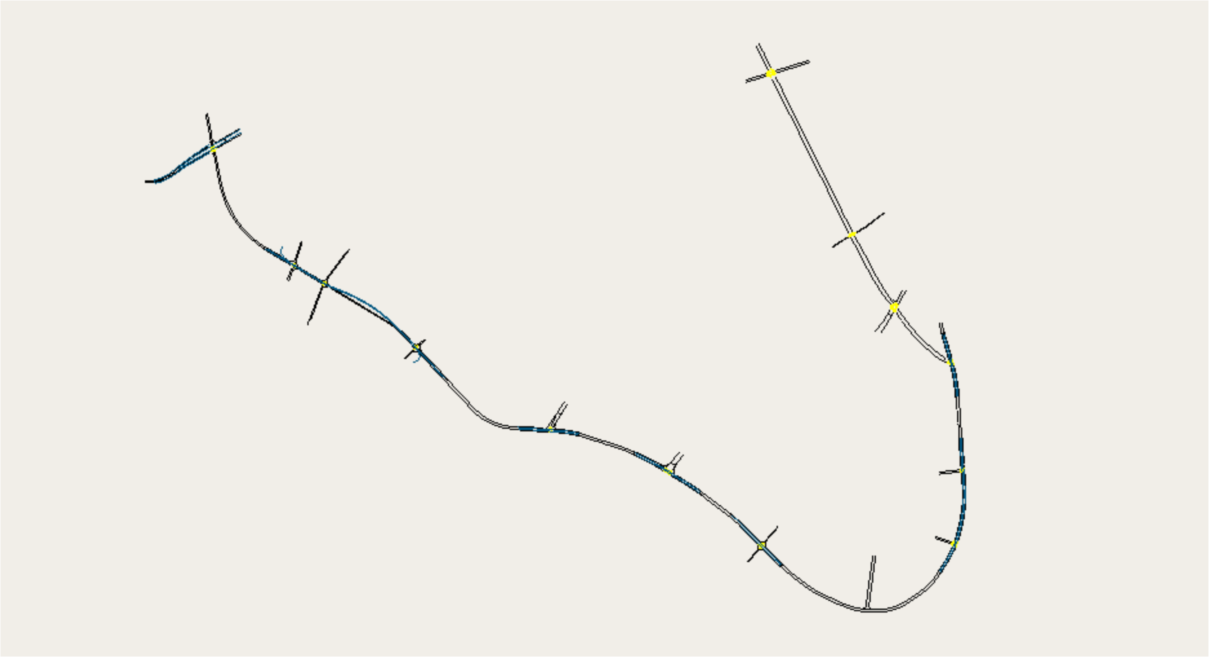

Figure 3. The road network constructed from Ratchadaphisek-Ratchaphruek Intersection (far left) to Narathiwat-Sathorn Intersection (far right)

4.1.2 Model calibration and validation

The process of model calibration and validation in this research consulted closely with Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software (Dowling et al., 2004). Two calibration steps were performed, calibration for capacity was performed first, followed by calibration for system performance. Calibration parameters were adjusted repetitively under certain limits to minimize an error. Finally, the GEH statistic was used as the calibration target in model validation.

For calibration for capacity, the simple two-parameter search algorithm was performed to minimize the total squared error of modelled traffic-flow rates using global drivers' reaction time (in sec) and reaction time at stop (in sec) as the calibration parameters. For calibration for system performance, global queue exit speed (in m/s) was selected as the calibration parameter and was repetitively adjusted until the minimum total root mean squared error of modelled maximum queue lengths was found. The total squared error of modelled traffic-flow rates was checked at a total of 55 locations, while the total root mean squared error of the modelled maximum queue lengths was checked at 3 locations. The default value in AIMSUN and the adjustment limit of each parameter are described below in Table 2.

Table 2. Default value and adjustment limit of calibration parameters

Parameters	Default value	Minimum limit	Maximum limit
Drivers' reaction time (in sec)	0.80	0.40	0.80
Drivers' reaction time at stop (in sec)	1.20	1.00	1.40
Queue exit speed (in m/s)	4.00	1.00	7.00

Calibration parameters in term of flow adjustment in this study include drivers' reaction time (rT) and drivers' reaction time at stop (rt@Stop) are measured by applying squared errors equation as below:

$$\sum_i SE = \sum_i \left(M_{ip} - C_i \right)^2 \tag{1}$$

where,

SE	Squared error
M_{ip}	Modelled flow rate at location i using parameter set p (in veh/hr)
C_i	Input flow rate at location i (in veh/hr)

Calibration parameters system performance is measured by applying root mean squared errors equation as below:

$$\sum_i RMSE = \sum_t \sqrt{\frac{1}{R} \sum_r \left(Q_{ipr} - V_i \right)^2} \tag{2}$$

where,

RMSE	Root mean squared error
R	Number of repetitive model runs
Q_{ipr}	Modelled maximum queue length at location i using parameter p for repetition r (in veh)
V_i	Observed maximum queue length at location i (in veh/hr)

In model validation, the GEH statistic was used to determine if the developed model was a good representative of the traffic situations. The GEH statistic was computed as followed:

$$GEH = \sqrt{\frac{\left(M_i - C_i \right)^2}{\left(M_i + C_i \right) / 2}} \tag{3}$$

where,

M_i	Modelled flow rate (in veh/hr) at location i
C_i	Input flow rate (in veh/hr) at location i

A criterion of using the GEH statistic suggests that for 85% of the cases, the GEH statistic must be less than 5. The model was validated using 55 flows, hence 47 flows must satisfy the GEH statistic of less than 5. The calibrated model with parameters rT = 0.40 sec, rT@Stop = 1.00 sec, and QXSpeed = 5.00 m/s proved a satisfying result where 49 flows (approximately 89%) gave the below-5 GEH statistic as shown in Figure 4.

Several iterative calibration repetitions were performed. The flow calibration yielded the optimal value of total squared error of modelled flow rates of 8.52×106 when reaction time and reaction time at stop were 0.40 sec and 1.00 sec, respectively. The calibration for system performance yielded the optimal value of total root mean squared error of modelled maximum queue lengths equaled 21.93 when queue exit speed (QXSpeed) was 5.00 m/s. The results of both calibration steps is shown in Figure 5.

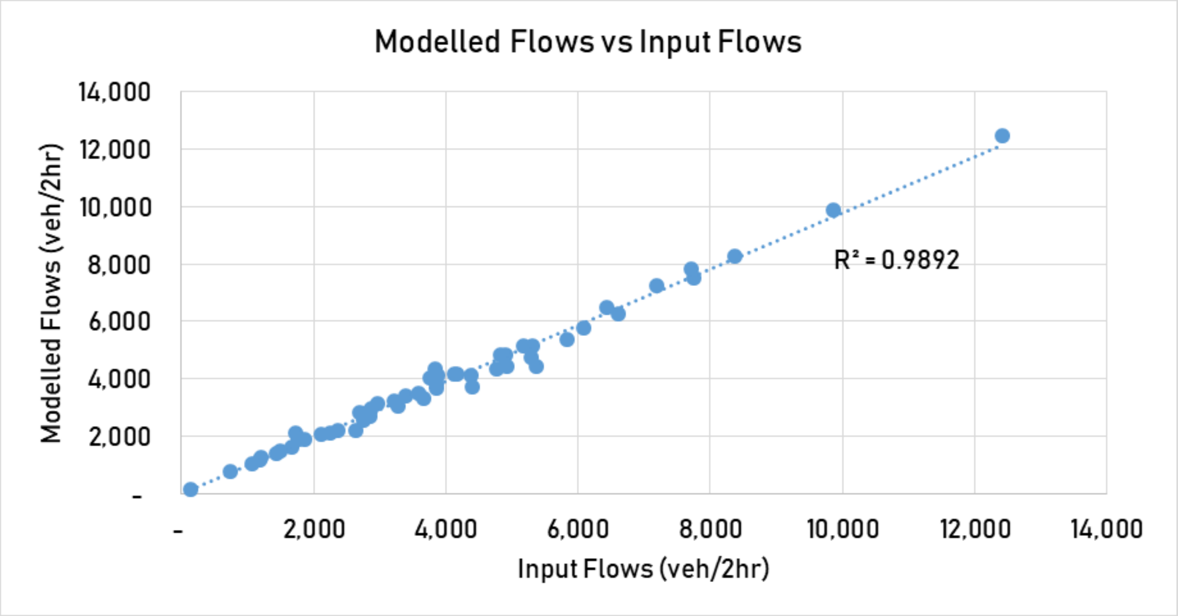

Figure 4. Plot of modelled traffic-flow rates versus input traffic flow-rates

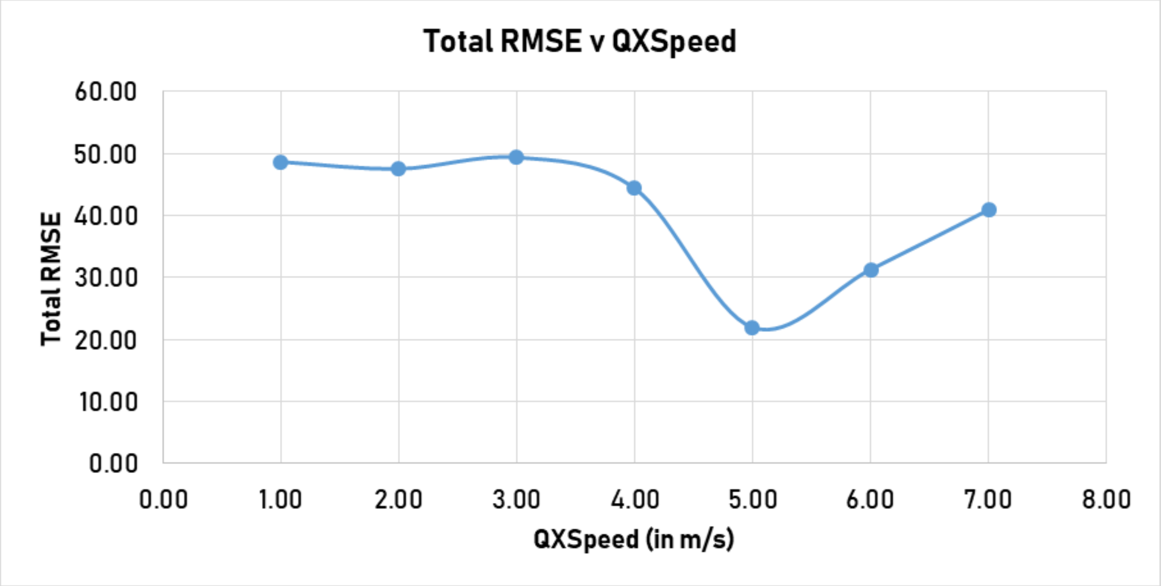

Figure 5. System performance calibration results (Total root mean squared error of maximum queue lengths versus queue exit speed (in m/s))

4.2 Case Studies

Based on several reviewed literatures, four solutions had been established. Each of the solution was prepared as a scenario and tested in the simulation. To increase reliability of the results, each scenario was tested for 10 times (seeds), and the average traffic statistical data was used in the evaluation phase.

In this study, the base case (Base) was considered to be as the current operation of BRT in Bangkok. The current BRT is operated with discontinued right of way, no any traffic priority given, and having an aggressive to its lane by other vehicles. Therefore, four alternative scenarios were purposed and compared impacts to the base case.

First, providing an additional dedicated BRT lane in the reverse direction on the flyovers according to the traffic conditions (AL). This solution benefited a fact that traffic congestion normally occurred in either of the travelling direction, in other words, outbound lanes would be less congested in the morning comparing to inbound lanes, and thus an outbound lane could be reversed to specially accommodate inbound buses.

Second, enforcing fully-segregated BRT lanes throughout the corridor (FS). The current Bangkok BRT situation is that the buses are not entirely segregated from other vehicles, with this solution, the buses were fully segregated from other vehicular traffic, and this would prohibit any other vehicles to get into the dedicated lanes and could reduce delays experienced by the buses.

Third, applying Transit Signal Priority to all at-grade intersections (TSP). This would allow the buses to run through intersections without having to dwell at the intersections and could significantly reduce the buses' intersection delay and, consequently, travel time.

And fourth, a combination of the second and the third solutions (FS+TSP), i.e. providing fully-segregated BRT lanes as well as signal priority for the buses at all at-grade intersections. This solution would give Bangkok BRT a rail-like characteristic in a sense that the buses would have absolute rights of way while not have to stop unnecessarily at intersections.

4.3 Indicators of Evaluation of the Solutions

Performances of each solution were evaluated based on impacts on both the buses as well as the network. Trade-offs were made in order to suggest the most suitable solution to improve the operation of Bangkok BRT since negative impacts to other traffic also needed to be considered in establishing any potential policies or strategies. Evaluation of the impacts of the solutions was based on how well it improved traffic conditions of the base model.

Indicators of the traffic performances to be evaluated obtained from AIMSUN and their definition are listed in Table 3.

Table 3. List of indicators to be evaluated and their definition[1]

Indicator	Unit	Definition
Delay time	sec/km	The average additional travel time experienced by a vehicle, *greater* delay time indicates *heavier* congestion
Travel time	sec/km	The average time spent by a vehicle traversing a road segment expressed as unit of time per distance, *greater* travel time indicates *heavier* congestion
Speed	km/hr	The average rate of motion expressed as distance per unit of time, *greater* speed indicates *less* congestion

[1] As defined in Highway Capacity Manual 2000 by TRB (2000).

In order to confirm the results, this study adopted the statistical analysis method namely "t-test". T-test is known as the inferential statistic to examine whether the data is in the significance level between the means of two groups or not. Also, t-test helps testing and confirming the hypotheses of a study. Therefore, t-test is a common statistic tool that being used widely. By adopting t-test, it includes t-stat value, degree of freedom, mean and variance of two compared groups, and significance level (p-value) between two testing groups. The significance level is defined by determining with the 95% of confidence level, in which the p-value should be less than 0.05 to state that the data is significant.

In this study, the hypothesis was one-tail tested by assuming that if the mean of base result is less than the other proposed strategies of improvement, it was assumed to be null hypothesis (H0). While, the alternative hypothesis (H1) was determined when the mean of base result is greater than the other proposed strategies of improvement.

5. RESULTS AND DISCUSSIONS

Several scenario tests were carried out to obtain the impacts of each solution on the roads along the BRT corridor during morning peak (7am-9am) and evening peak (4pm-6pm). Each sub-section provides the results of testing different scenarios.

However, the results of this study were tested the hypothesis by using the statistical method, t-test. This helped proving the significance level of the findings of the differences between before and after BRT improvement as shown in Table 4 and Table 5.

Table 4. Difference between base and other alternatives for BRT improvement using t-test (one-tail)

Average Delay (sec/km/veh)	Base mean (µ1)	23.6				
	Base variance	0.0543				
	Alternative solution	Mean (µ2)	Variance	Hypothesis	P value	Significance?
	AL	24.1	0.0788	$\mu1<\mu2$	0.0002	Y
	FS	23.2	0.0578	$\mu1>\mu2$	0.0002	Y
	TSP	15.8	0.0734	$\mu1>\mu2$	0.0002	Y
	FS+TSP	13.2	0.0680	$\mu1>\mu2$	0.0000	Y
Average Travel time (sec/km/veh)	Base mean (µ1)	130.5				
	Base variance	0.2600				
	Alternative solution	Mean (µ2)	Variance	Hypothesis	P value	Significance?
	AL	130.2	0.1560	$\mu1>\mu2$	0.0826	N
	FS	130.1	0.1441	$\mu1>\mu2$	0.0341	Y
	TSP	124.6	0.1384	$\mu1>\mu2$	0.0000	Y
	FS+TSP	119.7	0.1054	$\mu1>\mu2$	0.0000	Y
Average Speed (km/hr/veh)	Base mean (µ1)	27.9				
	Base variance	0.0351				
	Alternative solution	Mean (µ2)	Variance	Hypothesis	P value	Significance?
	AL	27.8	0.0497	$\mu1>\mu2$	0.2130	N
	FS	28.0	0.0334	$\mu1<\mu2$	0.1330	N
	TSP	29.1	0.1023	$\mu1<\mu2$	0.0000	Y
	FS+TSP	30.4	0.1166	$\mu1<\mu2$	0.0000	Y

Note: AL: Additional lane; FS: Fully segregation; TSP: Transit Signal Priority; Y: Yes; N: No

According to the results shown in Table 4 and Table 5, it revealed that the delay of the proposed alternative solutions were significantly reduced with the 95% of confidence level for most of the cases except the AL case for the BRT. Whereas, there were not sufficient evidence to state that the AL and FS were different from the base case with the 95% of confidence level, except the TSP and FS+TSP which had the effect of increasing delay significantly for the road network. This implied that the solutions affected to the road network having more delay.

Table 5. Difference between base and other alternatives for network road using t-test (one-tail)

Average Delay (sec/km/veh)	Base mean (μ1)	82.8				
	Base variance	0.4334				
	Alternative solution	Mean (μ2)	Variance	Hypothesis	P value	Significance?
	AL	82.3	0.4136	$\mu1>\mu2$	0.0565	N
	FS	82.4	0.3867	$\mu1>\mu2$	0.0823	N
	TSP	84.5	0.1251	$\mu1<\mu2$	0.0000	Y
	FS+TSP	87.9	0.1458	$\mu1<\mu2$	0.0000	Y
Average Travel time (sec/km/veh)	Base mean (μ1)	130.0				
	Base variance	0.1662				
	Alternative solution	Mean (μ2)	Variance	Hypothesis	P value	Significance?
	AL	129.5	0.0934	$\mu1>\mu2$	0.0035	Y
	FS	129.7	0.1147	$\mu1>\mu2$	0.0934	N
	TSP	131.7	0.0507	$\mu1<\mu2$	0.0000	Y
	FS+TSP	135.1	0.0925	$\mu1<\mu2$	0.0000	Y
Average Speed (km/hr/veh)	Base mean (μ1)	44.8				
	Base variance	0.1549				
	Alternative solution	Mean (μ2)	Variance	Hypothesis	P value	Significance?
	AL	45.1	0.0667	$\mu1<\mu2$	0.0315	N
	FS	44.6	0.1064	$\mu1>\mu2$	0.1337	N
	TSP	44.7	0.0617	$\mu1>\mu2$	0.3083	N
	FS+TSP	43.5	0.0803	$\mu1>\mu2$	0.0000	Y

Note: AL: Additional lane; FS: Fully segregation; TSP: Transit Signal Priority; Y: Yes; N: No

With the regards to the t-test result of travel time, it resulted that the proposed solutions could decrease the travel time of the BRT significantly except the AL which seemed to have no sufficient evidence to state that there was a difference between AL and base case within 5% error. Nonetheless, the solution of AL, TSP and FS+TSP were in the significance level under the probability of making a type I error (5%), in which the solutions affected more travel time for the road network. Except the case of FS, in which there was not enough evidence to state that FS and base case were different for the impact of road network.

Regarding the result of journey speed, it implied that there was strong evidence stating that the speed of TSP and FS+TSP was improved significantly with 95% of confidence level for BRT. This implied that the solution of TSP and FS+TSP could improve the speed of the BRT. While, there was not sufficient evidence that the solution of AL and FS was different from the base case for BRT speed. Nevertheless, only the FS+TSP solution performed significantly within the 5% error. In which, the speed of the FS+TSP was lower than the average speed of the base case for the road network. Whereas, the solution of AL, FS and TSP were not significantly resulted due to the fact that the speed of the base case and the solutions were not significantly different.

5.1 Additional Lane (AL) Solution

Additional lane solution adversely impacted both the buses and the network in every indicator during morning period. The solution increased delay time and stop time of the buses by 8.48% and 8.22%, respectively. However, its impacts during the morning were relatively low in other aspects with no other indicators being affected by far from 2%.

During evening period, on the other hand, the solution slightly lifted up all the indicators of the network, although none of them experienced a large improvement. For the buses, the solution also slightly lifted up almost all the indicators, only buses' delay time was increased by 1.99%, or an approximate of 0.5-sec/km up.

5.2 Full Segregation (FS) Solution

Full segregation solution improved the buses' operational performances in every indicator especially the buses' stop time that was decreased by 10.36% from 21.05 sec/km to 18.87 sec/km. At the same time, the solution adversely affected the network performances in every indicator, although by a little portion with no indicators being affected by more than 2%.

During evening period, the solution slightly improved every buses' indicator and almost every network's indicator, only the network's speed was reduced by 0.49%, or less than 0.5-km/hr change.

5.3 Transit Signal Priority (TSP) Solution

Transit signal priority solution also improved the buses' operational performances in every indicator. Two most significant improvements were delay time and stop time which were reduced by 43.68% and 52.64%, or from 26.99 sec/km to 15.20 sec/km and from 21.05 sec/km to 9.97 sec/km, respectively. The buses' travel time was decreased by 6.55%, or about 8 sec/km, while the speed was increased by 6.94%, or about 2 km/hr. The network's performances, on the other hand, remained relatively unchanged with only a 0.89% reduction in the network's speed.

The solution still performed well to improve the buses' performances during the evening peak. All indicators were improved with a marginally lower rate of change than those of the morning peak. Two significant improvements were still decreasing in the buses' delay and stop times by more than one-third.

5.4 Combination (FS+TSP) Solution

A combination of full Segregation and transit signal priority solutions also followed the same trends of its predecessors. All indicators showed better buses' performances with delay time and stop time reduction by more than 50%. Travel time and speed of the buses were also improved by more than 10%. However, this combination solution impacted a little more to the network's performances; most significant ones were delay time and stop time which were increased by 5.29% and 5.43%, respectively.

The solution was also able to improve the buses' performances during evening peak with a slightly smaller rate. Still, the buses' travel time and speed were improved by almost 10%. The network's delay time and stop time were still the major downside of this solution with the delay time increase by 6.16%, and the stop time by 5.80%.

5.5 Result Discussions

Comparisons of the impacts of the solutions on the indicators are shown as bar charts below. Figure 6 to 8 show comparisons of the solutions' performances during morning-peak and evening-peak traffic.

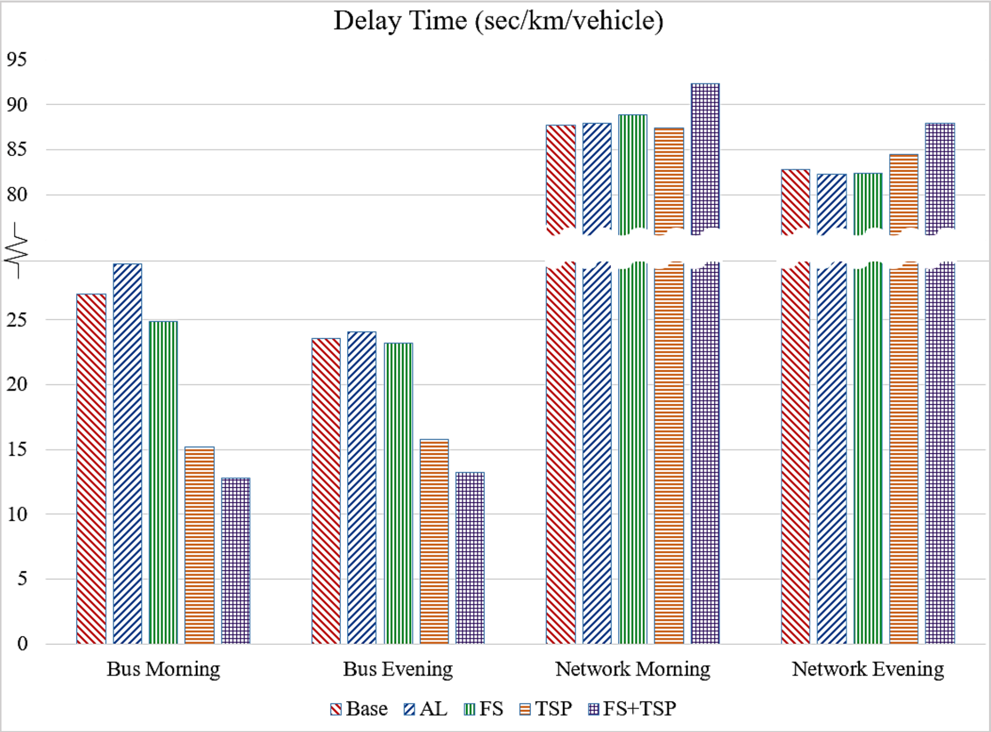

Figure 6. Comparison of the impacts of the solutions on delay time during morning-peak and evening-peak traffic

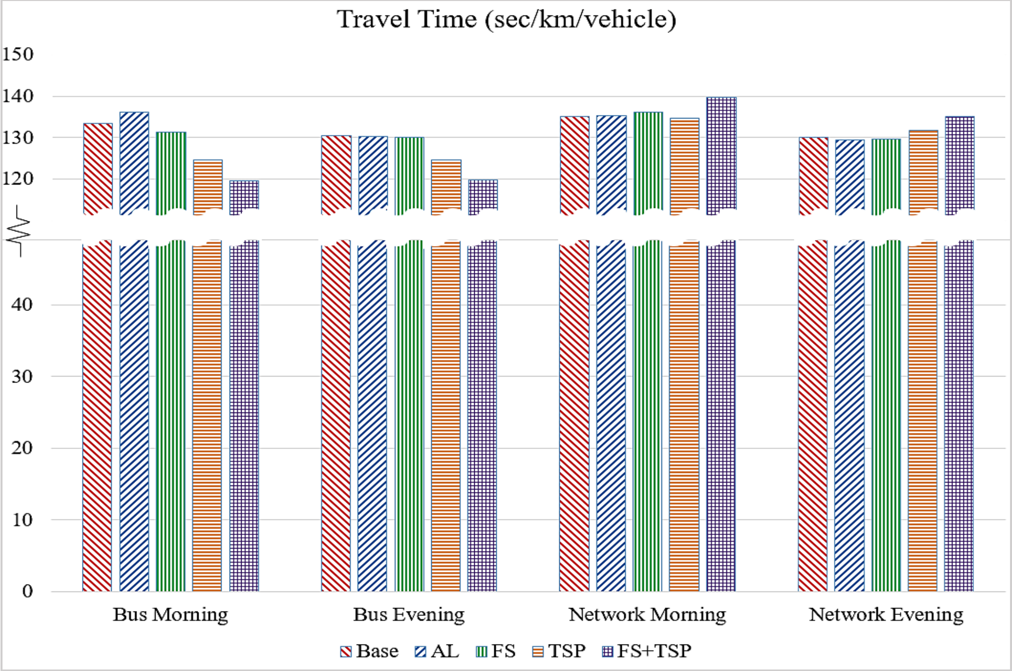

Figure 7. Comparison of the impacts of the solutions on travel time during morning-peak and evening-peak traffic

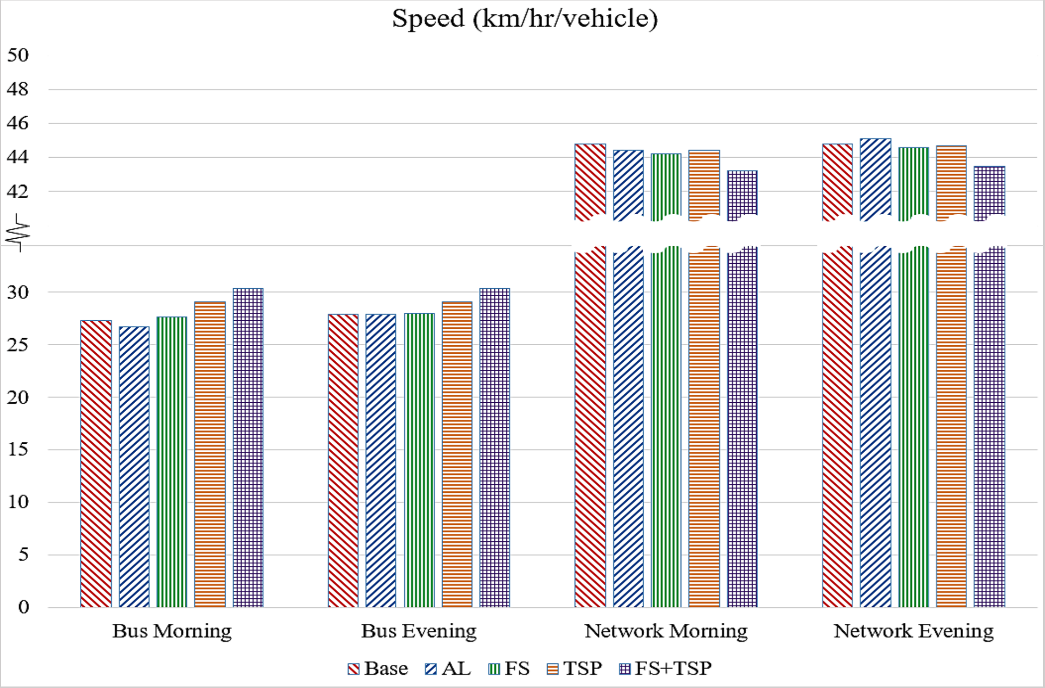

Figure 8. Comparison of the impacts of the solutions on speed during morning-peak and evening-peak traffic

The AL solution worsened both the buses' and the network's performances. The reversion of a traffic lane to accommodate buses in the opposite direction reduced available space for vehicles moving on the reversed section. This limitation of space might result to the output statistical data from the simulation, since the data was based on the average measurements of vehicles in the network, regardless of their direction of travel.

The FS solution performed well in improving Bangkok BRT operation. It improved all of the buses' indicators while had none or little negative effects on the network's indicators. This might result from the buses' complete rights of way that allowed them to run more freely. The results showed significant improvements in delay time during both periods.

The TSP solution managed to eliminate all unnecessary dwells of the buses at all four at-grade intersections along the corridor. This allowed the buses to be operated more efficiently which could be seen from large improvements in all of the buses' performances, especially the delay and stop times. Additionally, the solution had very little impacts to the surrounding traffic: No large underperformed indicators were observed in both of the analysis periods.

Lastly, the combined solution harnessed the benefits of its components. With this solution, the buses ran more efficiently with almost no disruption along the corridor. However, with more priorities given to the buses, other vehicular traffic was considerably affected: Distinct changes in delay time and stop time were observed during both of the analysis periods.

Taking into account all four traffic indicators while giving travel time the highest priority, the combination solution (FS+TSP), which provided fully-segregated BRT lanes as well as signal priority for the buses, stood out as the most effective solution to improve Bangkok BRT operation. The FS+TSP solution was able to cut the buses' travel times by 10.33% during morning peak hours and by 8.27% during evening peak hours. Those improvements could accumulate to shorter travel times of 3 min 20 sec (from 32 min 12 sec to 28 min 52 sec) in the morning and 2 min 36 sec (from 31 min 31 sec to 28 min 55 sec) in the evening for a bus traversing through the entire corridor length of approximately fifteen km. Average speed of the buses was also increased by 11.60% in the morning and 9.01% in the afternoon, or 3.16 km/hr and 2.51 km/hr, respectively.

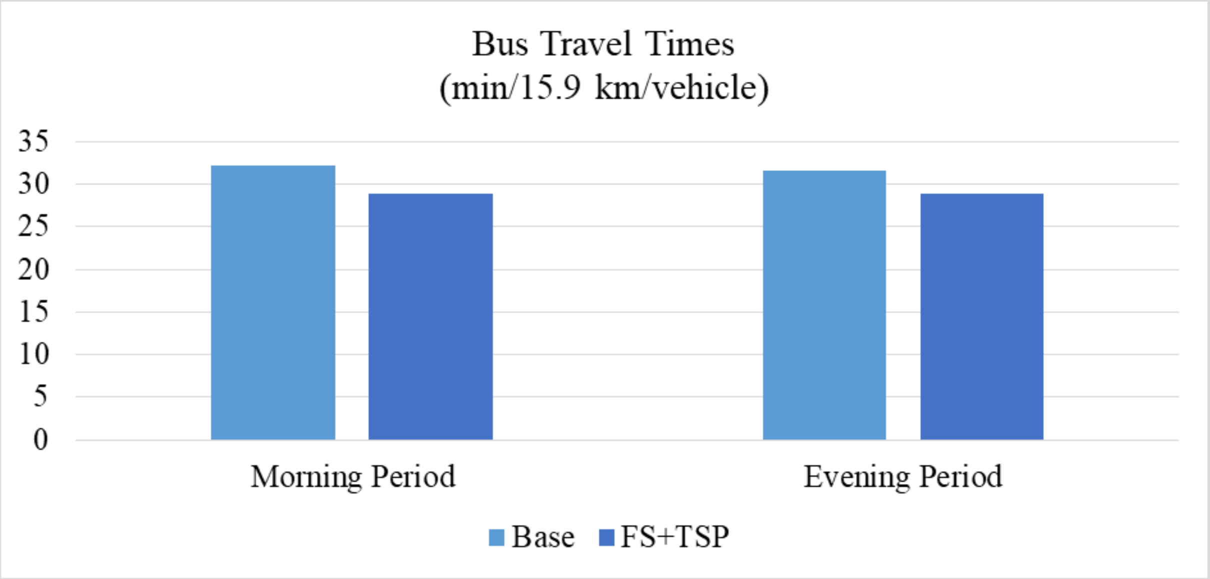

Figure 9. Comparison of bus travel times between base model and FS+TSP solution

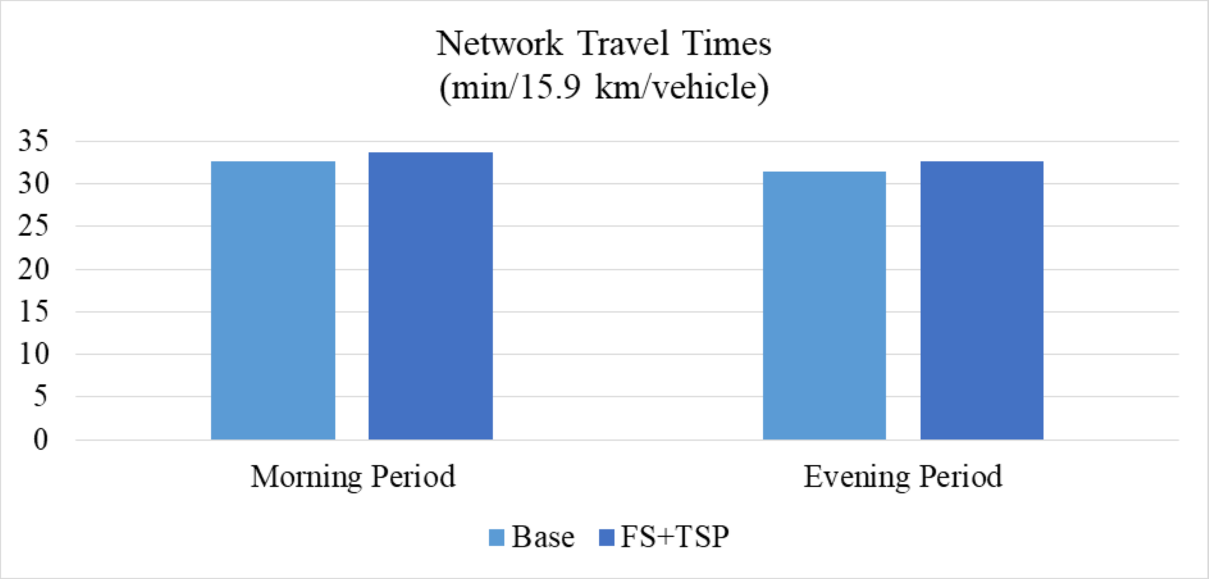

Figure 10. Comparison of network travel times between base model and FS+TSP solution

However, the solution also produced negative impacts to other vehicles. In the morning, the delay time of the system were increased by 5.29% (or 4.64 sec/km). The system's average speed was also reduced by 3.55% (or 1.59 km/hr). Meanwhile, the system's travel time was increased by 3.38%, that accounted for an increasing of 1-min-6-sec (from 32 min 36 sec to 33 min 42 sec) travel time for a car traversing across the entire corridor length of approximately fifteen km. In the evening, the impacts were slightly greater, which might be due to the changes of travel patterns. The delay time was increased by 6.16%, the travel time was increased by 3.92%, and the network's average speed was decreased by 2.86%.

5. RESULTS AND DISCUSSIONS

Current Bangkok BRT as well as some Asian cities cannot provide the full BRT operation system due to a lack of well management. Therefore, this paper proposed the alternative ways to enhance the performance of Bus Rapid Transit (BRT) in Bangkok under 4 solutions which were Additional Lane (AL), Full Segregation (FS), Transit Signal Priority (TSP), and Combination (FS+TSP) solutions. They were tested as scenarios via simulations. These aforementioned solutions were studied in order to discover how each solution would impact both to BRT and the whole road network prior to the real implementation. To confirm the results of the solutions provided by the simulation, this study adopted the statistical method namely t-test to examine the significance of the solutions with 95% of confidence level. As the matter of fact, this study found that the combination solution (FS+TSP) performed best among all proposed solutions. It literally could be able to reduce the travel times of buses from 8.27% to 10.33% in the peak hours. Meanwhile, it return less negative impact to car users by increasing the travel time 3.38% to 3.92% in the morning and evening rush hours. By taking this finding into account, it obviously revealed that total benefit of improvement will increase if BRT can attract more users BRT could benefit more than car users due to the large number of passengers who commute in the bus. The evaluation phase of this research is based only on traffic performances of the solutions. The suggested solution is considered the suitable solution solely because of its traffic performances, which is only a dimension in transport planning and policy development. From these preliminary findings, the good and weak points of each solution were discovered. Thus, for our further work, the calibration using road's capacity shall be carried out to obtain more accurate results, and other possible combinations of solutions shall be tested. Whilst, all the disadvantages found will be studied in more detailed in order to improve the BRT operation effectively. Nevertheless, the results and conclusion from this study are sorely based on operational performance which the further study in other aspects such as implementation costs and social acceptance should be considered. Conclusively, the findings from this study can be underlying baseline information for decision making and transportation planning to convince more people using BRT. BRT will be worthier when more car users shift to use it in term of relieving traffic congestion.

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