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Research article

Operation standards for exclusive bus lane on expressway using simulation and traffic big data

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Abstract: Korea operates exclusive bus lanes (XBLs) on many of its expressways. As XBLs convert one lane of regular-use traffic into bus-only traffic, they have a large impact on traffic flow, so careful judgment is required to determine if the operation is effective. However, XBLs have been operated based on only political judgment due to the lack of standards for the operation of expressway XBLs. Therefore, we sought to establish standards for the operation of expressway XBLs using the micro-traffic simulation program VISSIM and the multi-criteria value function methodology. Various scenarios were established based on traffic volume changes of passenger vehicles and bus traffic of four- and five-lane expressway networks. Through an expert survey, the average speed and speed-deviation values, which are the criteria for evaluating operational efficiency and safety, were determined. Also, value points were converted using average speed and speed deviation extracted from the simulation. In addition, quantitative operation standards were established using the converted value scores. Using the results of this study, we established standards for the operation of the XBLs and presented guidelines for related agencies such as police, bus groups, and corporations. The National Police have prepared guidelines for the operation of the XBLs. Citing the results of this study, the new guidelines were implemented in February 2021, and sections of some XBLs have been abolished. Through this study, quantitative standards for the operation of XBLs, one of the management lane techniques necessary for sustainable highway operation, were prepared and applied to actual highways. By properly applying the newly applied guidelines according to quantitative standards, there will be effects of reducing traffic congestion, improving travel time, and enhancing environmental characteristics such as exhaust gas emission. It is also expected to have a positive effect on safety.

Keywords: exclusive bus lane; expressway; micro-traffic simulation; multi-criteria decision-making; value score

1. Introduction

An exclusive bus lane (XBL) has been operating on the Sintanjin IC to Yangjae IC section of the Gyeongbu Expressway in Korea since 1994. The XBL is a high occupancy vehicle (HOV) lane that permits passage for only buses and vehicles with more than 9 seats, such as vans with 6 or more passengers, during given periods. If an XBL is operated, it is necessary to carefully determine the validity of its operation because it has a significant impact on traffic flow as it eliminates one lane for ordinary vehicles. However, XBLs have been operated based only on policy judgments due to a lack of objective standards for their operation. A particular case of interest is the XBL between Singal JC and Yeoju JC on the Yeongdong Expressway, which began operating in 2017. Various public opinions have emerged on whether the XBL should continue operation since it was operated under the special situation of the 2018 PyeongChang Winter Olympic Games. Information on XBLs currently operating on Korean expressways is shown in Table 1 and Figure 1. The map on the left side of Figure 1 shows the section where the XBL is operated. The Gyeongbu Expressway section is a 134.1 km section from Yangjae IC in Seoul to Sintanjin IC in Daejeon, and is operated during weekends and national holidays such as Seollal (Korean Lunar New Year's Day) and Chuseok (Korean Thanksgiving Day). Among them, the 39.7 km section from Yangjae IC to Osan IC is open on weekdays. In the case of Yeongdong Expressway, it is a 41.4 km section from Singal JC to Yeoju JC, and it is operated only on weekends and holidays. The photo in the upper right corner of Figure 1 shows an actual XBL operating, and the bus lane is classified through the blue lane marking. The photo in the lower right corner of Figure 1 shows a sign indicating the bus lane, and the operation section and time of each day are specified at the bottom of Table 1. Hannam IC is located further north than Yangjae IC and was the endpoint of the former Gyeongbu Expressway. Currently, it is managed by the Seoul Metropolitan Government, not by the Korea Expressway Corporation, but XBLs have been operating even after being released from the expressway for smooth entry into the Seoul Express Bus Terminal and downtown Seoul.

Table 1. Status of operation of XBLs for expressways in Korea in 2020.

Road	Operation start	Section	Operating day	Operating time
Gyeongbu Expressway	1994	Sintanjin IC–Yangjae IC	Weekend National holidays	07:00–21:00
			Seollal, Chuseok	07:00–01:00
	2008	Osan IC–Yangjae IC	Weekday	07:00–21:00
Yeongdong Expressway	2017	Singal JC–Yeoju JC	Weekend National holidays	07:00–21:00
			Seollal, Chuseok	07:00–01:00

Figure 1. Status of operation of XBLs and facilities for expressways in Korea.

2. Literature review

Currently, there are two systems related to XBLs in Korea. First is the 2005 guideline for the operation of XBLs produced by the Ministry of Construction and Transportation (currently the Ministry of Land, Infrastructure, and Transport (MoLIT)) [1]. The standards for installation apply to roads with three or more lanes in the same direction, with up to 100 buses passing per hour (or more than 3000 passengers) in specific locations. These locations, moreover, need political judgments by a nearby city or provincial governor regarding the necessity of installation to promote public transportation services. However, safety issues are not adequately considered because there are no criteria relating to highway operators that manage highways, as the guidelines are based solely on traffic volume. Other guidelines were developed by the Ministry of Land, Transport, and Maritime Affairs (currently MoLIT) in 2010 for the design of the Bus Rapid Transit (BRT) system [2]. The BRT-only lane installation criteria specify that the recommended demand for continuous flow is 120 units per hour based on road capacity and may vary depending on HOV and bus re-entry. Although the BRT guidelines provide a standard for continuous flow, they do not specify any details for express and intercity buses that pass on a regular basis. Looking abroad, the Federal Highway Administration (FHWA) in the U.S. has six types of operational strategies using the fare system, a dedicated lane system, and access control for a particular highway [3–8]. Among them, bus-related management lanes include high occupancy vehicle (HOV) lanes and high occupancy toll (HOT) lanes. The HOV lane allows access only to vehicles that meet a specific number of passengers, while the HOT lane imposes tolls on vehicles that do not meet the standards for highway demand management. However, there are many differences in the operation methods of the United States and Korea, so it is unreasonable to directly compare them. In the case of HOV and HOT operating in the United States, only two or three passengers are required to be in the vehicle. However, in the case of XBLs in Korea, at least six people must be in a nine-seat vehicle.

Managed lane related studies including XBL, HOV, HOT, and analysis methods using simulation are as follows: Kim and the Korea Transport Institute reviewed the feasibility of expanding XBLs on highways in areas where XBLs are available [9]. A survey was conducted on sections that meet the following conditions: roads with three or more lanes in each direction, road congestion conditions with repeated designations, and bus traffic conditions for expanded implementation [10]. According to the survey, the Seohaean Expressway fulfills road condition and congestion condition requirements but lacks bus traffic. All conditions were fulfilled in the case of the Yeongdong Expressway, but the effects of opening a bypass had to be investigated. In the case of Gyeongbu Expressway, the XBL system only operated on weekends, but expansion to weekdays was proposed if congestion became serious. Dahlgren discussed if HOV sharing and carpooling costs could impact the effectiveness of HOV lanes and suggested a HOT lane to improve the effectiveness of HOV lanes for certain environments [11,12]. However, as far as the authors are aware, theoretical discussion of an optimal design, in terms of the spatial location of starting an HOV lane, is limited. Lee conducted a study on changes in traffic flow when additional HOVs entered the XBL [13]. Ki et al. used a simulation program to analyze the effectiveness and possibility of installing HOV lanes on urban highways in Seoul [14]. Choi analyzed the effects of HOT lanes in Korea and an analysis of the cross-section for entering and exiting vehicles through the VISSIM program for the Gyeongbu Expressway and the Seoul Ring Expressway [15]. The analysis showed that the density, speed, and traffic volume of regular lanes improved when HOT lanes were introduced. Yang conducted a simulation analysis to select the appropriate lane-change length from the highway entrance to the XBL, and established a multi-linear return model [16]. In addition, parameter values in VISSIM were presented to increase the practicality of bus operation. Chu et al. analyzed the optimal starting location of an HOV lane for a linear monocentric urban area to maximize the social welfare of the transportation system, which is the difference between the total user benefit and travel cost [17]. Gibson et al. performed a general framework to estimate bus-user time benefits of a median busway including the effects on travel time and access time [18]. Anderson and Geroliminis proposed a dynamic bus lane policy, where control adjusts the proportion of cars to buses in one lane of a multilane artery instead of enforcing complete separation of vehicle types [19]. Zhang et al. performed an investigation of the open system BRT network on property values in Brisbane, Australia [20]. Obenberger et al. presented a process for monitoring and evaluating the ongoing operation of HOV facilities [21]. Menendez et al. analyzed the effectiveness of HOV lanes on highway bottlenecks and suggested a dynamic strategy that can be used to reduce not just people-hours of delay, but also vehicle-hours and their externalities [22]. Li et al. performed research on BRT systems with dedicated lanes using VISSIM and presented algorithms for speed control [23]. Yang and Wang performed research on dynamic bus lane systems using VISSIM [24]. Zyryanov and Mironchuk described some results of using AIMSUN for the evaluation of intermittent bus lane operation [25]. Szarata et al. conducted a simulation of three scenarios of no bus lanes, standard exclusive bus lanes, and dynamic bus lanes for four regions of Poland [26]. According to the results of traffic simulations, the dynamic bus lane option caused only a slight increase in travel time for private transport. In addition, studies on capacity and speed in BRT have been studied in several countries. Siddique and Khan performed capacity analysis through simulation on BRT corridors connecting the Central Business District (CBD) and surrounding areas in Ottawa, Canada [27]. Zhu et al. evaluated network operability according to the presence or absence of BRT using simulations in Beijing, China [28]. Jain et al. used GPS data installed on BRTs in India to identify congestion hotspots and study speed changes [29]. Through this existing literature, it can be seen that many studies have used various simulation programs and evaluation indicators for the analysis and evaluation of managed lanes.

Studies have been conducted on the continuous maintenance or abolition of expressway XBLs in Korea. The Gyeonggi Research Institute (2019) conducted a comparative analysis of the traffic volume of Yeongdong Expressway in 2016 and 2018 [30]. According to the analysis, the weekend traffic volume decreased by 15.1% after the XBL was implemented, which likely affected the total traffic volume of Yeongdong Expressway due to the opening of the Gwangju-Wonju Expressway and KTX Gangneung Line. Travel time increased by three minutes, suggesting a negative view of the XBLs.

The Korea Transport Industry Research Institute (2019) conducted a survey on the Yeongdong Expressway [31] which indicated that 85% of the respondents agreed with the XBL policy, and 70% of bus passengers said the speed was faster after the XBL installation. The traffic survey showed that bus traffic increased by 14.2%. In addition, passenger car traffic decreased by 9.4%, which had the effect of increasing the usage of public transportation by installing the XBL. Various results have been found on the effectiveness of highway XBLs analyzed by these various research institutes in Korea. However, these research results raise the question of whether objectivity had been secured. Road operators and local governments generally presented negative research results on XBLs, while bus institutions and labor sectors tended to show positive results on XBLs.

We reviewed related studies to evaluate changes in safety following XBL installation, and these are as follows: Solomon, West et al. and Garber et al. performed a safety analysis based on the speed deviation and presented a U-shaped curve, indicating a sharp increase in the accident rate as the absolute value of speed deviation increased [32–34]. West et al.'s results showed that if the speed deviation exceeds 15.5 mph, the accident rate increases dramatically. Garber's study showed that the accident rate increased if the speed variance value increased. Lamm et al. identified road design safety assessment plans based on the consistency of road speed. A measure was proposed to classify the difference in driving speed as good for speed differentials lower than 10 km/h, excellent for speed differentials from 10–20 km/h, and poor for speed differentials more than 20 km/h [35]. Lu et al. conducted a study of how speed differences affect traffic safety and defined hazardous situations when the interval speed difference exceeded 11 km/h. In addition, the probability of an accident was high if the speed difference was between 9 and 11 km/h [36]. Through various existing studies evaluating safety, evaluation indicators were identified to compare changes according to the presence or absence of XBLs on expressways.

The literature review has shown that many studies on XBL, HOT, and HOV have been conducted, but there are no cases of policy reflection. Thus, policy standards for XBLs are found to be insufficient in Korea. In addition, unlike the Gyeongbu Expressway, which was installed at a time of expansion of the Seoul metropolitan area (capital region) and settled for more than 20 years, the Yeongdong Expressway was installed due to the special circumstance of the PyeongChang 2018 Winter Olympic Games, and there were many complaints from road-users. In particular, it was reported through the press that after the Olympic Games, the XBL made traffic congestion for ordinary cars more serious, while bus traffic has not increased significantly, and efficiency has declined.

Therefore, the purpose of this study was to establish standards for installation and operation of expressway XBLs. In order to establish standards, expressway sections were implemented using VISSIM, a micro-traffic simulation program. Data was collected from actual loop-detectors on expressways, and expert surveys were conducted to establish standards for evaluation indicators. In addition, a multi-criteria value function was applied to consider both operational efficiency and safety. Also, a table was prepared to assess the application criteria for the initial installation of the XBL and whether public transportation usage increased to warrant its continuous operation. The results reflect the need for XBL policies to promote public transportation and provide standards for managing congestion caused by the installation of XBLs at an appropriate level. In addition, the Korea National Police Agency will be able to evaluate each expressway using the XBL operation standards created, based on the results of this study. A flowchart of research and guidance production is shown in Figure 2.

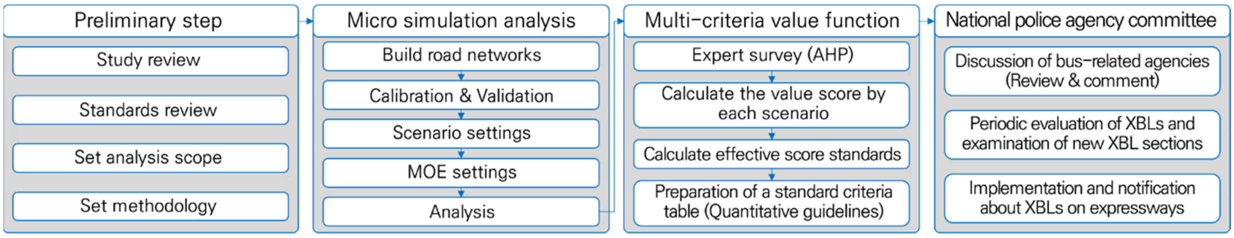

Figure 2. Flow chart for research and guidance production.

3. Data preparation

3.1. Traffic data collection

To conduct this study, traffic volume and speed data were collected. In the case of traffic volume data, the data was constructed by combining VDS traffic volume data provided by the Korea Expressway Corporation public data portal and traffic volume data provided by the Traffic Management System (TMS). VDS data has a problem in that it cannot classify passenger cars and small trucks because vehicle types are classified according to the fare system. On the other hand, TMS consists of only AADT data, but it is well distinguished between actual passenger cars, trucks, and buses. Therefore, in this study, a combination of two types of data was used. In the case of VDS data, a collection from 2017 to 2019 was used and was collected for all sections managed by the Korea Expressway Corporation. Data from 2020 onward was excluded from this study due to the observation of large changes in traffic volume due to the impact of COVID-19. Traffic volume and speed data by vehicle type was collected on an hourly basis for all sections. In addition, traffic volume and speed data by vehicle type was collected every 15 minutes from the Yangjae IC to Sintanjin IC section of the Gyeongbu Expressway and from Singal JC to Yeoju JC on the Yeongdong Expressway, where XBLs are in operation. TMS collected AADT-based section and vehicle type data from 2017 to 2019, the same as VDS. After combining the two data sets, traffic volume for passenger cars and trucks (non-bus traffic volume) was separated from bus and van traffic volume to construct traffic volume data by section, vehicle type, direction, and time. In addition, average travel speed data by highway section and vehicle type was collected through 15 minutes VDS data. Based on the collected traffic volume data, information was used to develop a traffic volume scenario for simulation analysis, and the speed data was used for simulation settlement and verification. Additionally, data for evaluating expressway traffic volume was also collected. The data for evaluation was calculated by combining the data from the VDS and TMS mentioned above to calculate traffic volume on an hourly basis. In addition, the average value of the traffic volume for the three busiest hours of the day was set as the processed traffic volume for evaluation, and the peak hour time was considered for each individual section of the expressway. The traffic volume data created in this way was used to determine whether to operate XBLs by substituting the traffic volume standards finally calculated from this study.

3.2. VISSIM network

VISSIM is a microscopic traffic flow simulation program that is used to evaluate efficiency, safety, and environmental properties, especially in conditions that are difficult to experiment in real roads [37–40]. Two expressways where XBLs were implemented were selected for the VISSIM simulation. The first is the Singal JC to Giheung-Dongtan IC southbound on the Gyeongbu Expressway. This section is 10 km long, is a five-lane expressway, and has 10–15% more than the average traffic volume of the five-lane expressways of the Gyeongbu Expressway. There is a steady high demand for long-distance buses from provincial areas and buses commuting from large cities near Seoul, such as Suwon and Hwaseong (Dongtan). The second is Yeoju JC to Hobeop JC westbound on the Yeongdong Expressway. This section is 12.7 km and is a four-lane highway. The section shows the average traffic volume of the four-lane section of the Yeongdong Expressway, and shows the characteristic that long-distance demand from the Gyeongsang-do region is concentrated at Yeoju JC and then disperses through Hobeop JC. In addition, this is also a section where habitual congestion occurs due to tourism demand to Gangwon-do every weekend. The locations of each case are shown in Figure 3.

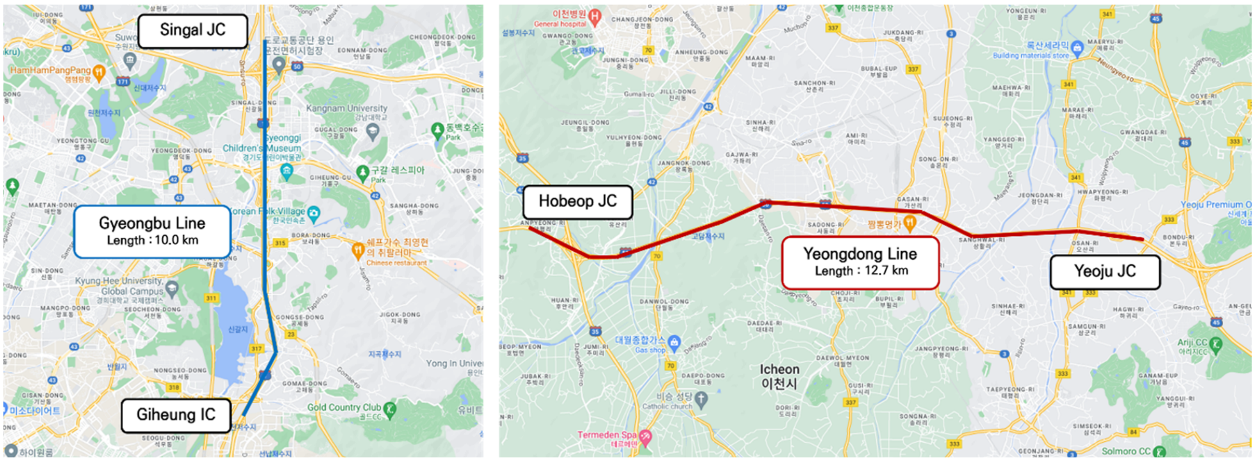

Figure 3. Analysis area.

Links were set up to implement XBLs on the simulated expressway. The lane width is 3.5 m, which is the basic value for expressways and is used as a standard value when calculating highway capacity in Korea. By setting “BlockedVehClasses” so that only buses can pass in the innermost lane, cars, vans, and trucks are prevented from entering. At each IC and JC, 10% of the traffic is allowed to enter and exit. Through this process, weaving for entry and exit, like a real expressway, was implemented within the simulation.

The traffic data used for the analysis was based on 15 minutes vehicle traffic data and average speeds collected from loop detectors within the expressway section from April to July 2019. The reality-based scenario was established using general traffic volume, holiday traffic, including the summer vacation season, and peak traffic in the mornings and afternoons. In addition, scenarios were prepared for increased traffic. Passenger cars and trucks were classified in terms of non-bus traffic volume, while buses and passenger cars with more than nine passengers were classified as buses. The minimum bus traffic required for the operation of an XBL is more than 100 buses per hour based on existing guidelines. The composition of the traffic scenario configuration for each expressway reflects reality as follows: the four-lane Yeongdong Expressway consisted of 2000 to 8000 non-bus vehicles and 100 to 600 buses. The five-lane Gyeongbu Expressway consisted of 2000 to 10,000 non-bus vehicles and 100 to 1500 buses.

4. Methodology

4.1. VISSIM simulation

VISSIM was used to prepare quantitative standards for XBL operations. Road evaluations based on a benefit analysis are mainly used in Korea. In this case, the analyst's subject matter expertise is usually employed, and the analysis results vary greatly depending on items applied and methods used. In addition, the existing benefit analysis method has the disadvantage of being performed without knowing the specific results of traffic problems caused by installation of XBLs. On the other hand, when simulations are used, assessment of XBLs can be carried out objectively through settlement and verification. In addition, it is possible to make predictions about changes in the amount of traffic and road conditions due to the installation of the XBL by establishing scenarios that reflect reality and future scenarios.

In this study, the network of each expressway analysis section was established using VISSIM, and the traffic volume and average speed data collected from loop detectors were entered. The parameters related to the vehicle's behavior were modified, and a network verification process was performed to check whether "the speed of the vehicle" and "the speed detected in the actual loop detector" were similar in the simulation. For verification, the U-value based on speed was used. The formula for the U-value is given in Eq (1). The closer the U-value is to zero, the more likely the two data points match; a value less than 0.1 is considered similar to actual data. Verification using the U-value indicates that the data values at all points were less than 0.1, indicating that the network was properly built. U-values for each highway section fall between 0.05 and 0.08 to satisfy the criteria [41,42].

$$\mathrm{U} = \frac{\sqrt{\sum_{i=1}^{N}(V_i-\widehat{V_i})^2}}{\sqrt{\sum_{i=1}^{N}{V_i}^2}+\sqrt{\sum_{i=1}^{N}\widehat{V_i}^2}} \tag{1}$$

where U: U-value, V_i: Velocity measured by loop detector, $\widehat{V_i}$: Velocity measured by simulation.

Analysis was performed by entering each scenario into the validated network. The average speed and speed deviation were used to evaluate each scenario. The average speed is the average speed of vehicles passing through the analysis section, and a higher speed represents a more efficient operation. The speed deviation represents the difference between the speed of an individual vehicle passing through the analysis section and the overall average speed, and a greater speed deviation implies higher severity in the event of an accident. The analysis was repeated ten times by changing the seed value for each individual scenario, and the initial 15 minutes of simulation analysis was used for warm-up and excluded from the analysis. The subsequent 60 minutes were selected as the target time for analysis.

4.2. Multi-criteria value function

The multi-criteria decision-making technique is an evaluation methodology in which multiple criteria can be considered when selecting the optimal alternative [43–45]. Therefore, it is possible to select an optimal alternative through an appropriate compromise between conflicting purposes. In this study, both operational efficiency and safety were desired, so a multi-standard decision-making technique was used.

Value functions were used to reflect operational efficiency and safety. The value function is a function that expresses the decision-maker's preference structure and is used for consistent and efficient decision-making. The index value function was applied to calculate the value of each effect measure. Exponential value functions are given in Eqs (2) and (3).

$$\mathrm{V}(x) = \begin{cases} \frac{1-e^{-c(x-x^0)}}{1-e^{-c(x^*-x^0)}} \\ \frac{x-x^0}{x^*-x^0} \end{cases} \text{(Increasing function)} \tag{2}$$

$$\mathrm{V}(x) = \begin{cases} \frac{1-e^{c(x-x^0)}}{1-e^{c(x^*-x^0)}} \\ \frac{x-x^0}{x^*-x^0} \end{cases} \text{(Decreasing function)} \tag{3}$$

Here, x^* is the most preferred value, and in this study, the maximum value within the 95% range was applied. x^0 is the least preferred value, and in this study, the lowest value within the 95% range was applied. c indicates the curvature of the function [42].

Subsequently, the Analytical Hierarchical Process (AHP) is used to combine the value functions of operational efficiency and safety [46–50]. The AHP is a decision-support technique that supports the systematic evaluation of mutually exclusive alternatives with numerous evaluation criteria. AHP is widely used in multi-standard decision-making involving qualitative elements. AHP stratifies various evaluation factors that make up the problem by dividing them into main components and detailed elements, and it derives the weight of each element through double contrast for each layer. Based on this, quantified results can be obtained by measuring the importance of evaluation elements and preferences between alternatives on a ratio scale. The AHP is aimed at integrating different measures into a single overall set of scores for ranking decision alternatives (DAs) [51]. These are the main steps in the AHP [52,53]:

1) Define the decision object.

2) Classify the variables that affect the decision and build a multi-level structure. The top level is the goal of the decision, the intermediate levels are criteria and sub-criteria of comparing decision alternatives, and the lowest level includes DAs.

3) Make comparisons between each criterion in an upper level and the same criterion in its below level in terms of relative importance; that is, forge a set of pair-wise comparison decision matrices. Let Z represent an $n \times n$ pair-wise comparison matrix, which can be expressed as

$$\mathrm{Z} = [a_{fg}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{4}$$

Let $C_1, C_2, \ldots, C_n$ denote the set of criteria, while a_{fg} represents a quantified judgement on a pair of criteria C_f and C_g. In order to make a contrast about the degree to which one criterion is more important than another, the original 1–9 scale is used [54]. The values of 1, 3, 5, 7 and 9 represent equal importance, weak importance, essential importance, demonstrated importance, and extreme importance, respectively; while the values 2, 4, 6 and 8 are used to compromise between the above values.

In this study, the reflection rate was calculated through a survey of 20 experts to calculate the weight of operational efficiency and safety. The survey found that the ratio of operational efficiency and safety was 69.5%: 30.5%. In addition, the weight of XBLs was additionally reflected in the sum of value points to meet the policy purpose of promoting public transportation. Statistical confidence intervals of 90 and 95% were used as thresholds dividing the minimum and recommended operation criteria of XBLs. Areas that satisfy the 90% significance level are defined as first-time minimum operational criteria, and areas that satisfy the 95% significance level are set as recommended operational criteria.

Finally, to determine the validity of the value function, the expert survey examined the range of thresholds affecting operational efficiency and safety. Based on the survey, threshold ranges obtained were between 8.2 and 16.5 km/h for efficiency and 7.8 to 16.4 km/h for safety. The criteria for effective scores were established using the value scores in each scenario that met the threshold range. The effective score standard was 0.0068 for four-lane highways and 0.0060 for five-lane highways.

5. Results and discussion

The average speed and speed deviation for each scenario were calculated using VISSIM, and the value score was prepared using the same program. In addition, XBLs were minimum and recommended operational standards were prepared using the score results.

5.1. Results for a four-lane expressway

The changes in speed and speed deviation with an XBL operation on a one-way, four-lane expressway are shown in Table 2. While the overall network speed reduction was not significant, less than 4 km/h when operating the XBL, if the traffic volume of regular vehicles was less than 4000 vehicles, the difference in speed was found to exceed 10 km/h in scenarios with more than 6000 regular vehicles. This appears to be a significant reduction in speed as the capacity of regular cars reaches its limit as it uses only three lanes. If the traffic volume of regular vehicles was 2000, the speed deviation of the entire network was shown to decrease when operating the XBL, but it was a change of only 0.1, so there was no significant difference in speed deviation. If there were more than 4000 cars, the speed deviation started to increase. In particular, the presence of 6000 regular vehicles showed a sharp increase in speed deviation when operating the XBL, as the regular lanes reached capacity and became congested, while the XBLs were easily driven at high speeds.

Table 2. Changes of speed and speed deviation with operation of XBLs on a four-lane expressway.

Four-lane Expressway		Non-bus Traffic Volume (Veh/h)							
		2000		4000		6000		8000	
		speed (km/h)	deviation	speed (km/h)	deviation	speed (km/h)	deviation	speed (km/h)	deviation
Bus Traffic Volume (Veh/h)	100	-0.92	-0.18	-3.26	+0.05	-9.62	+4.08	-13.42	+3.56
	150	-0.97	-0.11	-3.42	+0.13	-10.52	+4.81	-13.21	+3.60
	200	-0.93	-0.11	-3.56	+0.18	-10.95	+5.50	-13.52	+3.27
	250	-1.48	-0.08	-3.70	+0.25	-12.69	+6.74	-12.37	+3.00
	325	-0.79	-0.10	-2.64	+0.32	-14.51	+7.69	-11.00	+2.63
	400	-0.72	-0.07	-2.64	+0.56	-14.70	+8.65	-12.07	+3.18
	600	-0.91	-0.12	-2.95	+0.58	-18.18	+10.76	-11.65	+3.59

Table 3 shows the operation criteria for four-lane XBLs with a score for each scenario using speed,

speed deviation, and results for XBLs with a 90% significance level for an increase in public transportation usage. The standard score for determining the validity of value points on the four-lane highway is 0.0068, and an XBL can be operated in scenarios in which the difference between the weighted points when installing the XBL and the weighted points when not installing it is greater than 0.0068. Scenarios that met the weighted point condition are highlighted in gray shading and bold fonts in Table 3. After installing the XBL, if it is operated for several years, it is assumed that public transportation and bus use will be effective from the time of installation, so the evaluation of operational standards will be applied in a slightly stricter manner than minimum standards. As a result, the gray area moves toward the lower left direction. This trend can be seen through the gray areas shown in the left and right tables of Table 3. For example, if the traffic of a general vehicle is 4000 and the traffic of a bus is 250 vehicles, it is possible to install an XBL for the first time, but the traffic does not meet the criteria when performing an operational assessment. If public transportation activation progresses, the volume of regular vehicles will decrease, bus traffic will increase slightly, and the value will shift to the lower left.

Table 3. Standard for operation of XBLs on a four-lane expressway according to score.

Four-lane Expressway		Minimum standard for operation of XBL Non-bus traffic volume (Veh/h)				Recommended standard for operation of XBL Non-bus traffic volume (Veh/h)			
		2000	4000	6000	8000	2000	4000	6000	8000
Bus Traffic Volume (Veh/h)	100	**0.0074**	0.0015	-0.0078	-0.0211	**0.0073**	-0.0001	-0.0097	-0.0336
	150	**0.0087**	0.0061	-0.0054	-0.0178	**0.0089**	0.0002	-0.0073	-0.0298
	200	**0.0089**	**0.0074**	-0.0027	-0.0121	**0.0098**	0.0028	-0.0047	-0.0282
	250	**0.0100**	**0.0111**	0.0005	-0.0108	**0.0107**	0.0040	-0.0015	-0.0221
	325	**0.0111**	**0.0178**	0.0023	-0.0078	**0.0112**	**0.0079**	0.0014	-0.0177
	400	**0.0125**	**0.0220**	0.0058	-0.0065	**0.0118**	**0.0106**	0.0034	-0.0097
	600	**0.0165**	**0.0236**	**0.0083**	-0.0043	**0.0133**	**0.0142**	0.0057	-0.0065

Note: Gray shading and bold fonts highlight the scenarios meeting the weighted point condition.

5.2. Results for a five-lane expressway

The changes in speed and speed deviation according to XBL operation on a one-way, five-lane expressway are shown in Table 4. If the traffic volume of regular vehicles was less than 6000 vehicles, the overall network speed reduction was reduced by less than 3 km/h after operating the XBL, but the difference in speed increased in scenarios in which the traffic volume of regular vehicles was more than 8000. This appears to be a significant reduction in speed as the regular vehicle capacity reaches its limit. If the traffic volume of regular vehicles is 2000, the speed deviation of the entire network will decrease when operating an XBL, but if the number of vehicles is 6000 or more, the speed deviation will increase when operating an XBL. However, the increase was less than that for the four-lane expressway. Since the number of lanes has increased, the basic road capacity itself has increased, and the proportion of XBL decreases, which reduces the burden on general lanes.

Table 5 shows the operation criteria for XBLs with a score for each scenario using speed, speed deviation, and results for XBLs with a 90% significance level for an increase in public transportation usage. The standard score for determining the validity of the value points on the five-lane highway is 0.0060, and the XBL can be operated in scenarios in which the difference between the weighted points when installing the XBL and the weighted points when it is not installed is higher than 0.0060. A scenario with gray shading in Table 5 met the weighted point condition. After installing an XBL, it is assumed that public transportation use will be effective from the time of installation, so the evaluation of operational standards will be applied in a slightly stricter manner. As a result, the gray area moves toward the lower left direction. However, if there is too much bus traffic, only one lane will not be able to handle the volume. Therefore, the bottom left-most area does not appear to meet the operational criteria again. If traffic volume scenarios are in this area, operators should consider abolishing XBLs to create mixed traffic or consider expanding the XBLs.

Table 4. The changes of speed and speed deviation with the operation of XBLs on a five-lane expressway.

Five-lane Expressway		Non-bus Traffic Volume (Veh/h)									
		2000		4000		6000		8000		10,000	
		speed (km/h)	deviation	speed (km/h)	deviation	speed (km/h)	deviation	speed (km/h)	deviation	speed (km/h)	deviation
Bus Traffic Volume (Veh/h)	100	+0.20	-0.17	+0.52	-0.24	-1.46	+3.66	-6.84	+2.47	-9.81	+5.54
	300	-0.04	-0.06	-0.56	+0.07	-0.59	+3.00	-7.2	+2.79	-10.54	+5.79
	500	-0.36	-0.11	-1.00	+0.23	-1.48	+2.42	-7.85	+2.97	-11.7	+5.79
	700	-0.31	-0.13	-1.63	+0.26	-1.72	+2.01	-8.27	+2.86	-10.91	+5.46
	900	-0.32	-0.23	-2.13	+0.36	-1.74	+1.49	-8.76	+3.68	-11.33	+5.90
	1200	-0.75	-0.25	-2.12	+0.10	-1.76	+0.88	-9.32	+2.69	-11.77	+5.92
	1500	-1.06	-0.84	-2.51	-2.83	-2.03	+0.11	-10.44	+3.72	-11.82	+5.48

Table 5. Standard for installation and operation of XBLs on a five-lane expressway according to score.

Five-lane Expressway		Minimum standard for operation of XBL Non-bus Traffic Volume (Veh/h)					Recommended standard for operation of XBL Non-bus Traffic Volume (Veh/h)				
		2000	4000	6000	8000	10,000	2000	4000	6000	8000	10,000
Bus Traffic Volume (Veh/h)	100	**0.0068**	0.0052	0.0048	-0.0004	-0.0123	**0.0061**	0.0038	0.0035	-0.0056	-0.0117
	300	**0.0087**	**0.0075**	**0.0060**	0.0026	-0.0076	**0.0085**	**0.0060**	0.0048	0.0016	-0.0092
	500	**0.0099**	**0.0090**	**0.0071**	0.0053	-0.0037	**0.0090**	**0.0077**	**0.0060**	0.0028	-0.0051
	700	**0.0108**	**0.0162**	**0.0082**	**0.0068**	-0.0002	**0.0096**	**0.0146**	**0.0070**	0.0056	-0.0027
	900	**0.0076**	**0.0087**	**0.0120**	**0.0073**	0.0017	**0.0067**	**0.0079**	**0.0111**	**0.0061**	0.0000
	1200	0.0029	**0.0072**	**0.0124**	**0.0082**	0.0028	0.0001	**0.0064**	**0.0115**	**0.0068**	0.0013
	1500	-0.0003	0.0058	**0.0147**	**0.0093**	0.0042	-0.0016	0.0052	**0.0134**	**0.0077**	0.0023

Note: Gray shading and bold fonts highlight the scenarios meeting the weighted point condition.

5.3. XBL operation criteria

Using the results presented in Sections 4.1 and 4.2, an XBL minimum and recommended operation criteria table is presented. Based on the value scores in the scenario in which the simulation was built, intermediate values were produced using interpolation. The non-bus traffic volume was subdivided into 500 units per hour, while the bus traffic volume was subdivided into 25 units for 4-

lane expressways and 100 for 5-lane expressways. The results of the value scores were used to prepare detailed criteria for each expressway. The subdivided criteria are shown in Figure 4. The green area is the recommended point where it is possible to operate an XBL, and the yellow area is the minimum point where it is possible to operate an XBL. On the other hand, the red area is not suitable for setting up an XBL. Both tables show that it is appropriate to operate an XBL toward the lower left. This means that when the bus volume is activated by operating an XBL, the transportation demand of passenger cars partially moves to the bus. Something unusual is found in the table on the five-lane expressway, which is too low to the left, and if the ratio of bus traffic to non-bus vehicles becomes too high, it is inappropriate to operate an XBL again. This means that, since an XBL is limited to one lane, bus traffic volume is larger than the capacity of the XBL. Therefore, when the red area at the bottom left is reached, it should be considered to add an XBL. In fact, in the case of the expressway section that has reached the area, long-distance buses mainly use XBLs, and buses leaving the expressway through nearby lamps show bus traffic being distributed to multiple lanes using regular lanes.

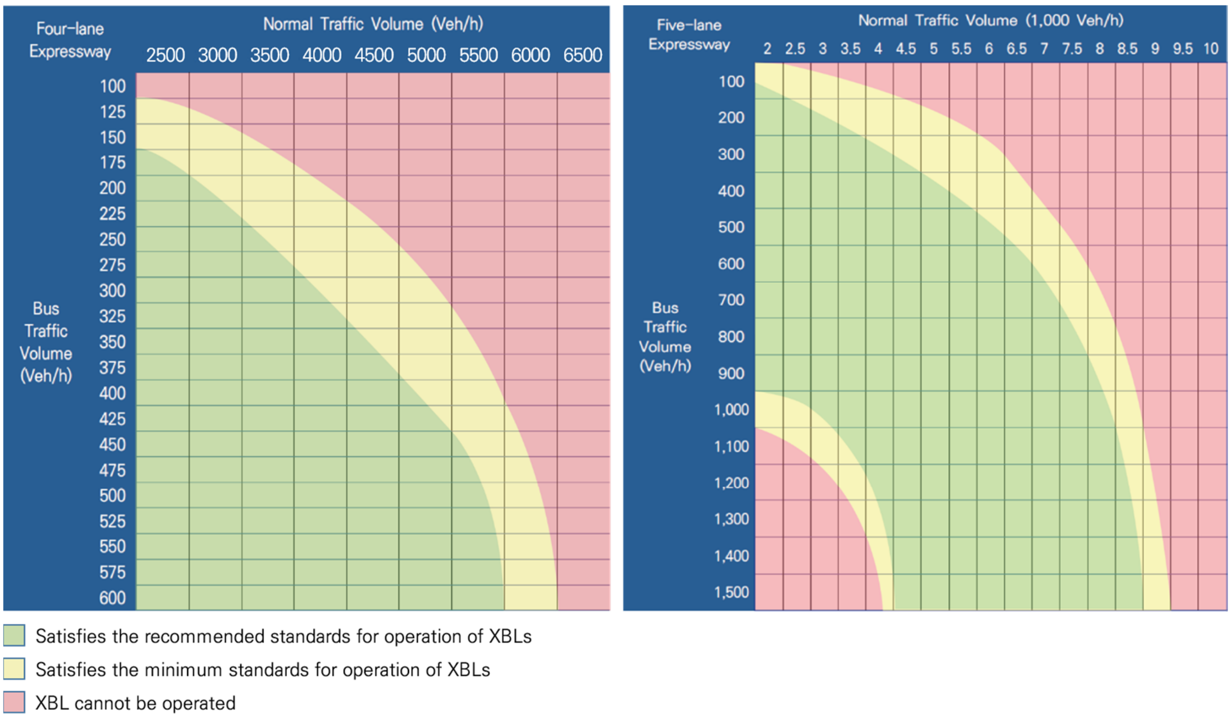

Figure 4. Expressway XBL operation criteria table.

5.4. Verifying the feasibility of installing and operating XBLs

The criteria table presented in Figure 4 was used to verify whether the traffic standard was appropriate for the installation or operation of an XBL by applying it to actual expressways. Sections to be verified are part of Gyeongbu Expressway, Yeongdong Expressway, and Seoul 1st Ring Expressway. Verification was performed for sections in which traffic volume by vehicle type was provided per hour. The results of the traffic volume verification for each section are shown in Figure 5.

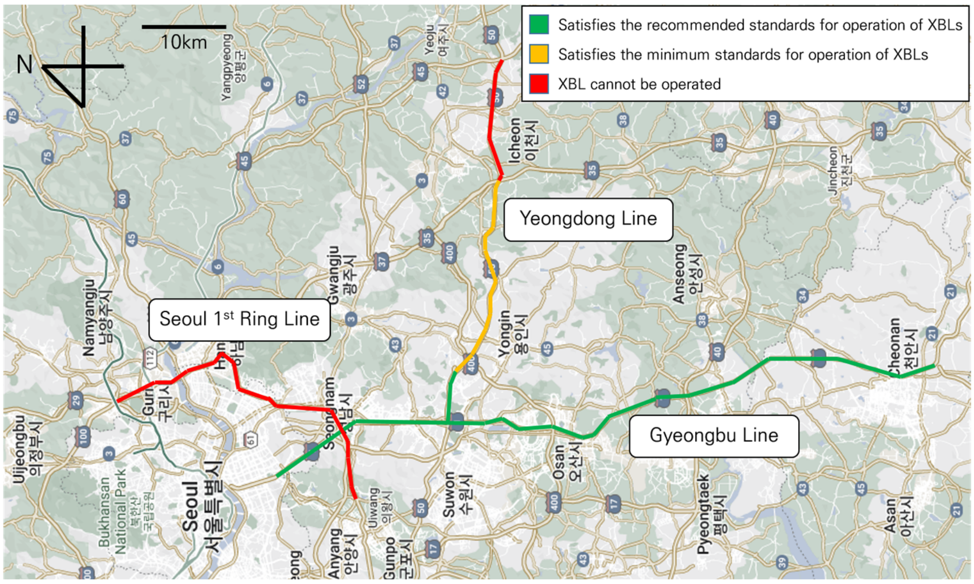

Figure 5. Verification results of each expressway.

As a result of verifying traffic volume, the Gyeongbu Expressway was found to meet XBLs recommended standards in all verification sections. This is because the major cities that the Gyeongbu Expressway passes through, such as Seongnam, Suwon, and Hwaseong, each have a population of 1 million, and there is overlapping demand from large regional cities such as Busan, Daegu, Daejeon, and Gwangju to Seoul. Yeongdong Expressway satisfies the minimum standards in most cases, but does not meet the minimum standards in some sections. The cities that Yeongdong Expressway passes through each have a population of less than 500,000, so there is little demand for commuting to Seoul, which influenced these results. On the other hand, in the case of the Seoul 1st Ring Expressway, the standards were not met in all sections. Since the LOS (Level of Service) of this expressway has reached E with only passenger car traffic, if an XBL is installed, the LOS is likely to reach F. According to the results of the traffic volume verification, it was decided to abolish XBLs for some sections of the Yeongdong Expressway, and this change was applied to the expressway on February 27, 2021. The map of the adjusted section is shown in Figure 6.

Figure 6. Adjusted XBL operation section on Yeongdong expressway.

6. Conclusions

In this study, the micro-traffic simulation program VISSIM was used to analyze traffic flow based on the amount of highway traffic and to quantitatively prepare standards for the installation and operation of highway XBLs using calculated value points. To reflect the policy objective of promoting public transportation, XBL installation standards were designed with a weight of 6% on the bus's value score, and operation criteria were prepared without a weight of 6% considering the establishment of the XBL. In addition, minimum standards were set so that installation and operation criteria could not be met if bus traffic was not sufficient.

The simulation analysis confirmed that if the traffic volume of general vehicles nears the road capacity, the speed will be drastically reduced, and the speed deviation will rapidly increase, so this point is considered first when installing XBLs. In addition, the results of the value score were used to prepare detailed criteria for each highway. The subdivided criteria are shown in Figure 4. The green area is the point where it is possible to operate XBLs, and the yellow area is the point where it is possible to install XBLs, but it is necessary to conduct traffic assessments for continued operation. On the other hand, the red area is not suitable for setting up an XBL.

In January 2021, the Korean National Police Committee cited the contents of this study and decided to announce the implementation of the Yeongdong Expressway XBL, which will be adjusted from the existing Singal JC to Yeoju JC (41.4 km) to the Singal JC to Hobeop JC (26.9 km).

Through this study, quantitative criteria for the installation and operation of expressway XBLs were established and used data to evaluate the maintenance or abolition of XBLs after performing an evaluation of actual expressway sections. In fact, the operation section of exclusive bus lanes was adjusted and implemented through the results of this study as well as through consultations with bus experts, organizations, and agencies. In addition, through periodic committee meetings, the feasibility evaluation of XBL operation sections and the evaluation of the proposed new XBL installation sections were successful. However, there are limitations in this study. First, only analysis of four- or five-lane expressways was conducted; three-lane roads were not considered. Currently, there are sections of the Gyeongbu Expressway where XBLs are installed despite only being three lanes. The 32.6 km section from Cheonan JC to Nami JC is only a three-lane section, but bus-only lanes are operated on weekends. In the research stage, this section was not considered as a special case, but if the standard for installing bus-only lanes under the relevant conditions is specified through additional research, it will be of great help to consider the installation of bus-only lanes in a wide variety of sections. Therefore, a quantitative evaluation of these sections and further research for new installation standards will be required. Second, this study analyzed only expressways. Currently, there are many urban highways in large cities in Korea, and these roads play a major role in connecting large cities and the surrounding areas. For example, Seoul's Olympic-daero plays a role in connecting Seoul to the surrounding cities along the Han River. These roads are subject to different design standards from expressways. Therefore, research needs to be conducted on roads other than highways. In particular, the Korean government is considering installing XBLs on various urban highways to solve traffic congestion in metropolitan areas. Although some of the results of this study can be utilized, additional research should be supported for accurate review and policy decision-making. Third, this study analyzed only the expressway main line and did not take into account the traffic flow at the entry and exit sections, the starting point and end point of the XBL. Currently, the main problem in the XBL operation section of the expressway in Korea is additional congestion from weaving caused by buses coming and going from the XBL. In order to solve this problem, it is necessary to conduct additional research at the same point as the expressway entrance [55]. Fourth, only quantitative analysis was performed; qualitative conditions were not considered. Qualitative conditions in the current evaluation system are to be assessed by experts of the committee. Thus, new research will also need to be conducted to establish objective criteria in this evaluation. Lastly, it was not possible to consider how many people were in each vehicle types. If additional research is conducted to reflect the number of passengers on each bus, it will be possible to review not only the change in the number of vehicles but also changes in the number of passengers.

Through this study, quantitative standards for the installation and operation of XBLs, one of the management lane techniques required for sustainable highway operation, were prepared and applied to actual highways to reduce traffic congestion and improve travel time. There will be environmental enhancement effects such as exhaust gas emission. It is also expected to have a positive effect on safety. In addition, Korea continues to develop the suburbs of Seoul as a new city, and a wide-area bus-oriented transportation network has been established to connect the new city to Seoul. So, it is expected that it will be used as a standard for XBL installation and operation on existing or new roads.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

Juneyoung Park is a guest editor for the special issue of the ERA, and was not involved in the editorial review or the decision to publish this article. All authors declare there are no competing interests.

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