Study on the Quantitative Effects of New Bridge Construction on Traffic Conditions

Seongmin Kim, Kitae Jang, and In Gwun Jang, *Member, IEEE*

***Abstract*—This research quantitatively analyzes the effect of the KAIST Bridge construction on Daehak-ro roadway in Daejoen, South Korea. Daehak-ro, which splits major research facilities and residential areas in Daejeon, serves high traffic demands during the peak hours and therefore heavy traffic congestion commonly occurs in the roadway. In order to solve this problem, the KAIST Bridge is under construction and is expected to reduce high traffic congestion at peak hours. However, constructing the KAIST Bridge in the congested roadway may result in increased total travel time, which is often referred to as Braess paradox. Based on collected traffic data before the bridge construction, various demand patterns are designed and imposed to investigate the effects of bridge construction. Network traffic performances before and after the bridge construction are compared using a traffic simulation software, CORSIM.**

***Index Terms*— Traffic analysis, Braess paradox, bridge construction, traffic congestion.**

I. Introduction

GROWING traffic congestion is a serious concern for many developed societies [1], [2], [3], [4]. Korean government has invested a budget to increase a roadway capacity by 16% in terms of roadway length [5]. However, overall cost induced from congestion has increased by more than a billion dollar annually and over 64% of this cost arises from urban roadway networks [6].

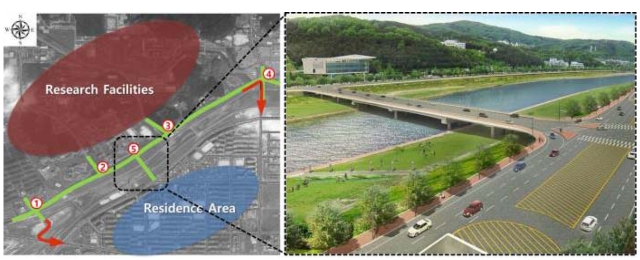

Fig. 1. Construction plan of the KAIST Bridge

As presented in Fig. 1, Daehak-ro splits major research facilities and residential areas in Daejeon, South Korea. Because the arterial serves high traffic demand during the peak hours, heavy traffic congestion occurs on Daehak-ro. In order to solve this problem, a new bridge (so-called KAIST Bridge) is currently under construction and is expected to distribute high traffic demands at peak hours.

However, it have been worried that adding a new link to a congested roadway network can result in increased travel time [7],[8],[9]. In order to save travel time, people will select their new routes after the completion of the bridge construction. This may cause a bottleneck phenomenon at the northern junction of the bridge, which is planned to transform a link to an intersection. Thus, due to aforementioned user equilibrium and bottleneck effects, new bridge construction may result in another traffic congestion on the arterial road, as Braess paradox (Fig. 2) describes.

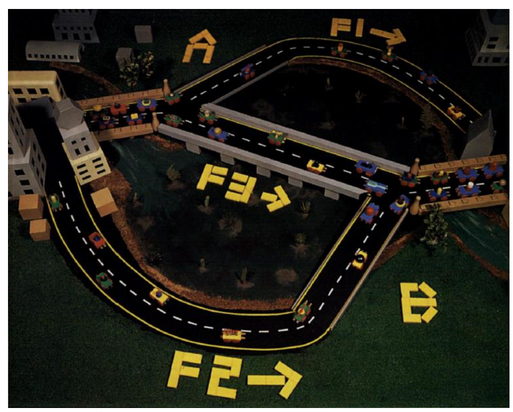
Fig. 2. Braess paradox

The goal of this research is to analyze the effects of KAIST Bridge construction on the Daehak-ro roadway. Using a traffic simulation software, CORSIM, the network traffic performances are compared for the various demand patterns which are anticipated after the bridge construction.

II. Study Site and Traffic Data Description

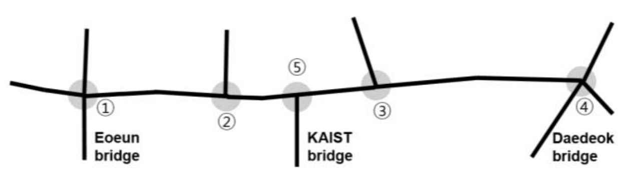

Fig. 3. Study site (Daehak-ro, Daejeon, South Korea)

The study site includes five intersections which are numerically labeled in the Fig. 3. Currently, only two bridges

S. Kim is with the Cho Chun Shik Graduate School of Green Transportation, KAIST, Guseong-dong 373-1, Yuseong-gu, Daejeon, Republic of Korea (e-mail: seongminkim@kaist.ac.kr).
K. Jang is with the Cho Chun Shik Graduate School of Green Transportation, KAIST, Guseong-dong 373-1, Yuseong-gu, Daejeon, Republic of Korea (e-mail: kitae.jang@kaist.ac.kr).
I. G. Jang is with the Cho Chun Shik Graduate School of Green Transportation, KAIST, Guseong-dong 373-1, Yuseong-gu, Daejeon, Republic of Korea (e-mail: igjang@kaist.edu).

978-1-5090-5753-5/16 $31.00 © 2016 IEEE
DOI 10.1109/APWC.on.CSE.2016.17

(i.e., Eoeun bridge at Intersection 1 and Daedeok bridge at Intersection 4) discharge high traffic flows between research facilities and residential areas. Considering this roadway topology, KAIST Bridge is under construction at Intersection 5. In order to collect traffic data at Intersection 1, 2, 3, and 4 before bridge construction, video recording was taken during the afternoon peak period (July 22, 2014). The collected traffic data were split ratios and traffic inflows in each link, as described in Fig. 4. In addition, cycle length, signal phase composition, and green time were collected (Table I).

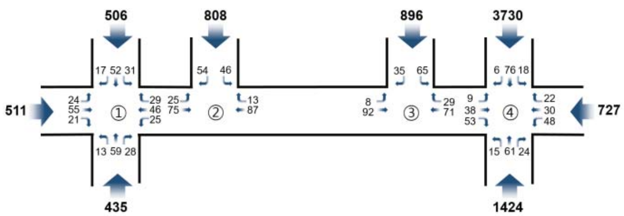

Fig. 4. Corrected traffic inflow (veh/hr) and split ratio (%) in each link

TABLE I
CURRENT TRAFFIC SIGNAL SETTING BEFORE KAIST BRIDGE CONSTRUCTION

Intersection	Signal	ø1	ø2	ø3	ø4	ø5	Cycle
1	Phase						
	Ratio	0.23	0.16	0.16	0.31	0.14	
	Time	33	23	23	44	20	143
2	Phase						
	Ratio	0.15	0.69	0.15			
	Time	20	90	20			130
3	Phase						
	Ratio	0.18	0.06	0.53	0.24		
	Time	25	8	74	33		140
4	Phase						
	Ratio	0.21	0.28	0.16	0.18	0.17	
	Time	35	47	27	30	28	167

III. TRAFFIC DEMAND PATTERNS AFTER KAIST BRIDGE CONSTRUCTION

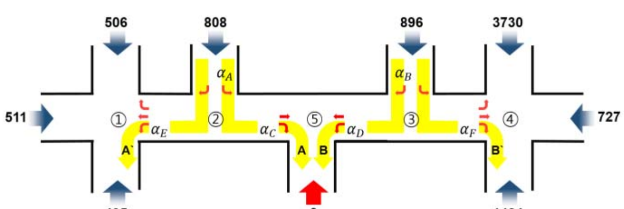

Fig. 5. Estimated six split ratios regarding traffic demand patterns

Because traffic data after bridge construction are unknown, it is necessary to anticipate traffic demand pattern, based on the following assumptions:

①Except for the six split ratios presented in Fig. 5, all traffic data are preserved after KAIST Bridge construction.
②Traffic demands for Route A and B increase, whereas those for Route A' and B' decrease.

The first assumption means that only the six split ratios (α_A , α_B , α_C , α_D , α_E , and α_F in Fig. 5) will change in the traffic data after KAIST bridge is constructed. It is also assumed that a total inflow and outflow in three bridges will be conserved after the bridge construction, therefore setting a traffic inflow toward the KAIST Bridge zero. Considering that a main direction of traffic flow is from top to bottom during afternoon peak hours, this assumption does not significantly affect overall traffic conditions. The second assumption means that many travellers in adjacent links near the KAIST Bridge will select routes for a new bridge instead of currently existing bridges. Under this assumption, α_A and α_B should be higher than their original values (i.e., 46% and 35%, respectively). Based on two assumptions, six split ratios were determined and the corresponding traffic demand patterns were established.

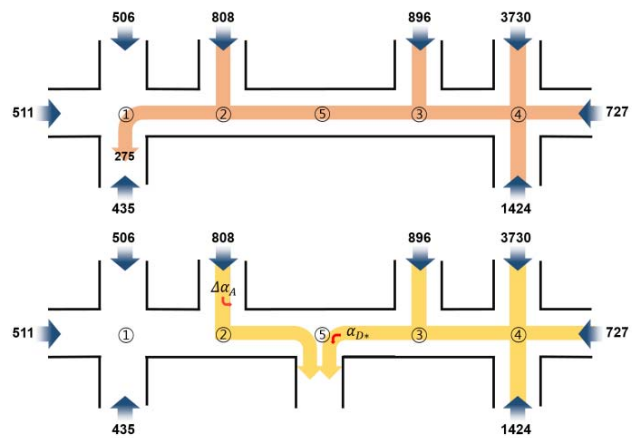

Fig. 6. Changes of traffic outflows in southern link at Intersection 1 before (above) and after (bottom) KAIST Bridge construction.

Before construction, traffic outflow in the southern link at Intersection 1 ($Q_{1,S}^{out}$) is 275veh/hr, as shown in Fig. 6. On the other hand, outflow after construction ($Q_{1,S}^{out*}$) is assumed to be lower than $Q_{1,S}^{out}$. Thus, the outflow at Intersection 1 after construction ($Q_{1,S}^{out*}$)is an original outflow ($Q_{1,S}^{out}$) minus the summation of outflows for new yellow routes ($\Delta\alpha_A Q_{2,\mathrm{N}}^{in} + \alpha_{D*} Q_{5,\mathrm{E}}^{in}$). Here, $\Delta\alpha_A$ represents the additional split ratio of traffic inflow in the northern link at Intersection 2 to eastward direction and α_{D*} is the split ratio of an original traffic inflow in the eastern link at Intersection 5 to southward direction. The outflow rate after construction is then expressed as follows:

$$Q^{out*}_{1,\mathrm{S}} = Q^{out}_{1,S} - (\Delta\alpha_A Q^{in}_{2,\mathrm{N}} + \alpha_{D*} Q^{in}_{5,\mathrm{E}}) \geq 0 \;. \qquad (1)$$

Considering that a lower bound of the outflow rate after construction is zero, a following inequality can be derived as:

$$\alpha_{\mathrm{D}*} \leq 0.83 - 1.04\alpha_A \;. \qquad (2)$$

Because a lower bound of split ratio is zero, $\alpha_{D*} Q^{in}_{5,\mathrm{E}}$ should be higher than or equal to zero. Thus, additional traffic demand for route A ($\Delta\alpha_A \times Q^{in}_{2,\mathrm{N}}$) should be less than or equal to $Q^{out}_{1,S}$ can be formulated as follows:

$$Q^{out}_{1,S} - \Delta\alpha_A \times Q^{in}_{2,\mathrm{N}} \geq 0 \;. \qquad (3)$$

From Eq. (3), it can be derived that

$$\alpha_A \leq 0.80 \;. \qquad (4)$$

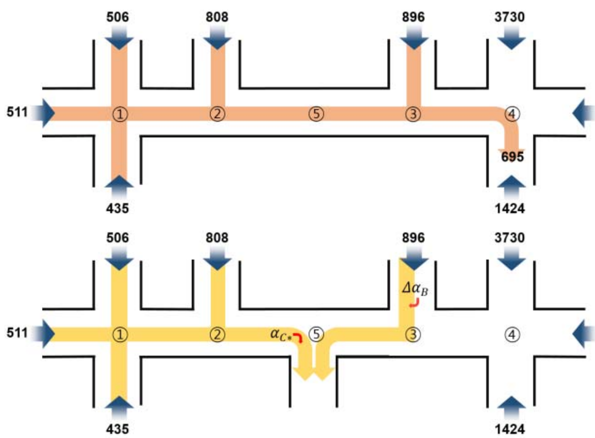

Fig. 7. Changes of traffic outflows in southern link at Intersection 5 before (above) and after (bottom) KAIST Bridge construction.

In a similar same way, the outflow at Intersection 4 after construction ($Q^{out*}_{4,S}$) is expressed as follows:

$$Q^{out*}_{4,\mathrm{S}} = Q^{out}_{4,S} - (\Delta\alpha_B Q^{in}_{3,\mathrm{N}} + \alpha_{C*} Q^{in}_{5,W}) \geq 0 \;. \qquad (5)$$

Then, from Eq. (5), inequalities which are similar to Eq. (2) and (4) can be derived as follows:

$$\begin{aligned} \alpha_{C*} &\leq 1.27 - 1.31\alpha_B \\ \alpha_B &\leq 1.13 \end{aligned} \qquad (6)$$

α_C (or α_{D}) denotes the split ratio of a traffic inflow in the eastern (or western) link at Intersection 5 to southward direction after construction and can be evaluated in terms of α_A and α_{C*} (or α_B and $\alpha_{\mathrm{D}*}$), as follows:

$$\begin{aligned} \alpha_C &= \frac{\alpha_{C*} \times Q^{in}_{5,W} + \Delta\alpha_A \times Q^{in}_{2,\mathrm{N}}}{Q^{in}_{5,W} + \Delta\alpha_A \times Q^{in}_{2,\mathrm{N}}} = \alpha_C(\alpha_A, \alpha_{C*}) \\ \alpha_D &= \frac{\alpha_{\mathrm{D}*} \times Q^{in}_{5,\mathrm{E}} + \Delta\alpha_B \times Q^{in}_{3,\mathrm{N}}}{Q^{in}_{5,\mathrm{E}} + \Delta\alpha_B \times Q^{in}_{3,\mathrm{N}}} = \alpha_D(\alpha_B, \alpha_{D*}) \end{aligned} \qquad (7)$$

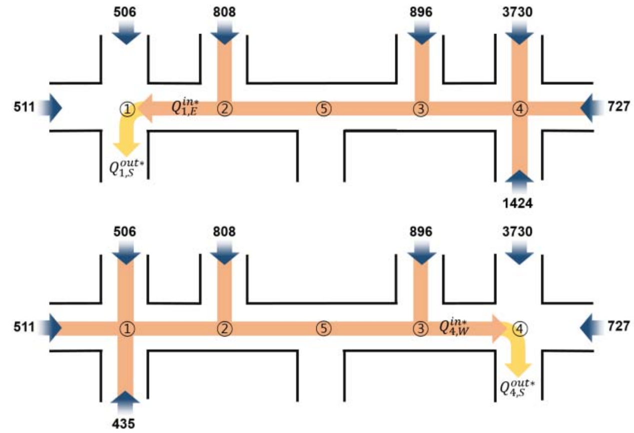

Fig. 8. Estimation of split ratios E and F

At Intersection 1, α_E is the outflow in a southern link ($Q^{out*}_{1,S}$) divided by the inflow in an eastern link after construction ($Q^{in*}_{1,E}$). Based on assumptions and collected traffic data, $Q^{in*}_{1,E}$ can be evaluated by conservation law. Therefore, the split ration E (α_E) can be evaluated as follows:

$$\begin{aligned} \alpha_E &= \frac{Q^{out*}_{1,\mathrm{S}}}{Q^{in*}_{1,\mathrm{E}}} \\ &= \frac{Q^{out}_{1,S} - (\Delta\alpha_A Q^{in}_{2,\mathrm{N}} + \alpha_{D*} Q^{in}_{5,\mathrm{E}})}{(1-\alpha_A) \times Q^{in}_{2,\mathrm{N}} + 0.87 \times (1-\alpha_D) \times (\alpha_B \times Q^{in}_{3,\mathrm{N}} + 0.71 \times Q^{in}_{3,\mathrm{E}})} \\ &= \alpha_E(\alpha_A, \alpha_B, \alpha_D) \end{aligned} \qquad (8)$$

Similarly, split ratio F (α_F) can also be estimated as follows:

$$\begin{aligned} \alpha_F &= \frac{Q^{out*}_{4,\mathrm{S}}}{Q^{in*}_{4,W}} \\ &= \frac{Q^{out}_{4,\mathrm{S}} - \Delta\alpha_B \times Q^{in}_{3,\mathrm{N}} - \alpha_{\mathrm{C}*} \times Q^{in}_{5,\mathrm{W}}}{(1-\alpha_B) \times Q^{in}_{3,\mathrm{N}} + 0.92 \times (1-\alpha_C) \times (\alpha_A \times Q^{in}_{2,\mathrm{N}} + 0.75 \times Q^{in}_{2,\mathrm{W}})} \\ &= \alpha_F(\alpha_A, \alpha_B, \alpha_C) \end{aligned} \qquad (9)$$

Using Eqs (7), (8), and (9), Split ratios C, D, E, and F can be evaluated if split ratios A, B, C*, and D* are determined. Using Eqs (2), (4), and (6), feasible regions of split ratios A, B, C*, and D* can be presented, as depicted in Fig. 9.

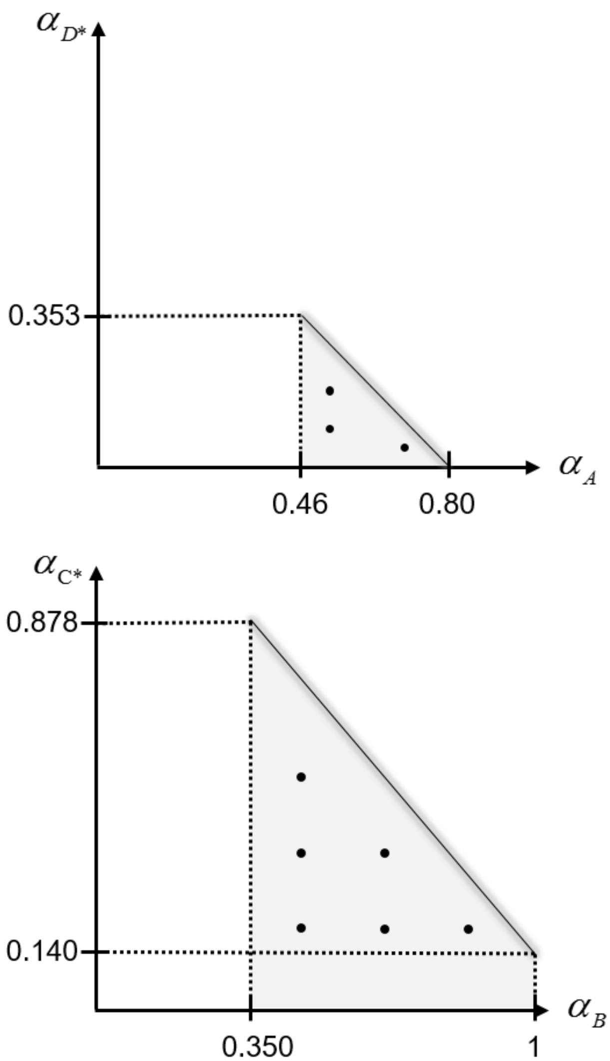

Fig. 9. Feasible regions of split ratios A, B, C*, and D*

As shown in Fig. 9, three and six points were selected for (α_A and α_{D^*}) and, (α_B and α_{C^*}), respectively. Table ii indicates a total of eighteen traffic demand patterns, based on the assumptions and the collected traffic data. Case 0 denotes the current situation before construction, therefore setting split ratios C and D at 0%.

For these traffic demand patterns, downward discharging capacity from the KAST bridge (Fig. 10) is critical. This discharging capacity can be controlled by relevant signal time ratios at adjacent intersections [10]. Therefore, the simulation experiments were conducted in two different conditions, i.e., either 25% as a normal situation or 10% as an extreme situation.

TABLE III
TRAFFIC DEMAND PATTERNS

Case	α_A	α_B	α_C	α_D	α_E	α_F
0	46%	35%	0%	0%	25%	53%
1	50%	40%	23%	15%	16%	44%
2	50%	40%	23%	24%	9%	44%
3	50%	40%	42%	15%	16%	34%
4	50%	40%	42%	24%	9%	34%
5	50%	40%	62%	15%	16%	21%
6	50%	40%	62%	24%	9%	21%
7	50%	60%	23%	30%	16%	33%
8	50%	60%	23%	38%	9%	33%
9	50%	60%	42%	30%	16%	19%
10	50%	60%	42%	38%	9%	19%
11	50%	80%	23%	41%	16%	18%
12	50%	80%	23%	47%	9%	18%
13	70%	40%	36%	10%	5%	44%
14	70%	40%	52%	10%	5%	34%
15	70%	40%	68%	10%	5%	21%
16	70%	60%	36%	26%	5%	33%
17	70%	60%	52%	26%	5%	19%
18	70%	80%	36%	37%	5%	18%

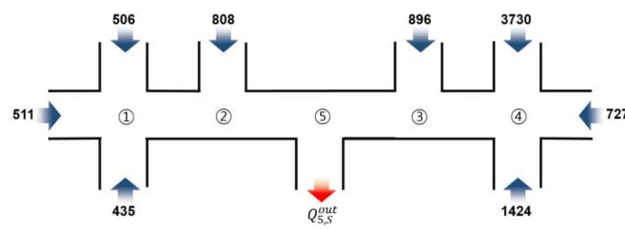

Fig. 10. Downward discharging capacity from the KAIST Bridge

IV. RESULTS

Traffic simulations were conducted to analyze the effects of bridge construction on network traffic performances, using CORSIM. During a one-hour simulation, traffic performance before bridge construction is evaluated in terms of VMT, average speed, and delay time, as listed in Table iv.

TABLE V
SIMULATION RESULTS BEFORE KAIST BRIDGE CONSTRUCTION

	Before KAIST Bridge
Vehicle-Miles Traveled	6385.52
Average Speed (mph)	6.11
Delay Time (veh-hours)	833.70

TABLE VI
SIMULATION RESULT AFTER KAIST BRIDGE CONSTRUCTION

Case	$Q_{1,S}^{out}$	$Q_{5,S}^{out}$	$Q_{4,S}^{out}$	Signal time ratio 25% VMT	Signal time ratio 25% Delay time	Signal time ratio 25% Ave speed	Signal time ratio 10% VMT	Signal time ratio 10% Delay time	Signal time ratio 10% Ave speed
0	275	0	695	6385.52	833.70	6.11	6385.52	833.70	6.11
1	165	313	492	6695.11	753.25	6.86	6695.84	737.59	6.98
2	87	391	492	6868.57	693.15	7.45	6875.25	698.70	7.42
3	165	472	333	6820.53	656.89	7.72	6785.22	712.29	7.24
4	87	550	333	6992.11	632.16	8.09	6996.27	666.38	7.79
5	165	630	175	6890.39	608.93	8.22	6749.28	721.31	7.14
6	87	708	175	7046.60	585.46	8.60	6941.03	689.72	7.54
7	165	493	313	6761.23	731.74	7.07	6777.50	752.56	6.93
8	87	571	313	7107.71	691.53	7.66	7084.35	722.87	7.39
9	165	651	154	6867.54	659.48	7.74	6771.82	708.64	7.25
10	87	729	154	7130.06	679.24	7.78	7094.70	696.34	7.61
11	165	672	133	6840.36	720.18	7.22	6914.91	686.56	7.55
12	87	750	133	7209.91	673.36	7.90	7154.80	689.45	7.72
13	42	436	492	6897.04	632.01	8.01	6887.74	675.40	7.62
14	42	594	333	6983.60	594.86	8.44	6912.32	675.27	7.64
15	42	753	175	7104.35	532.23	9.25	6871.62	696.51	7.43
16	42	615	313	7139.15	651.61	8.04	7144.60	681.46	7.78
17	42	774	154	7248.06	574.96	8.89	7078.80	672.50	7.80
18	42	794	133	7317.77	514.37	9.66	6388.31	764.43	6.54

After construction, simulation results for a total of 18 cases are listed in Table vii. $Q_{out\ 1}$, $Q_{out\ 2}$, and $Q_{out\ 3}$ are total outflows from three bridges (Eoeun bridge, KAIST bridge, and Daedeok bridge, respectively). In Table viii, blue color represents the best case, whereas red one represents the worst case. Note that, in Case 18, it is best in a normal situation, but becomes worst in an extreme situation. This is because traffic network performances are sensitive to discharging capacity of the KAIST bridge. Because all demand scenarios outperform the current traffic condition (i.e. Case 0 in Table ix), bridge construction can be regarded to be effective in relieving traffic congestion.

To compare various traffic demands in more detail, queue lengths at the elapsed time of 1hr are illustrated in Fig 11. Before construction, queues initiate at both entrances of Eoeun and Daedeok bridges, and queues spread out across the network, as shown in Fig 11(a). On the contrary, queues initiate at the entrance of KAIST bridge and spillover occurs more quickly in an adjacent link (Fig 11(b)).

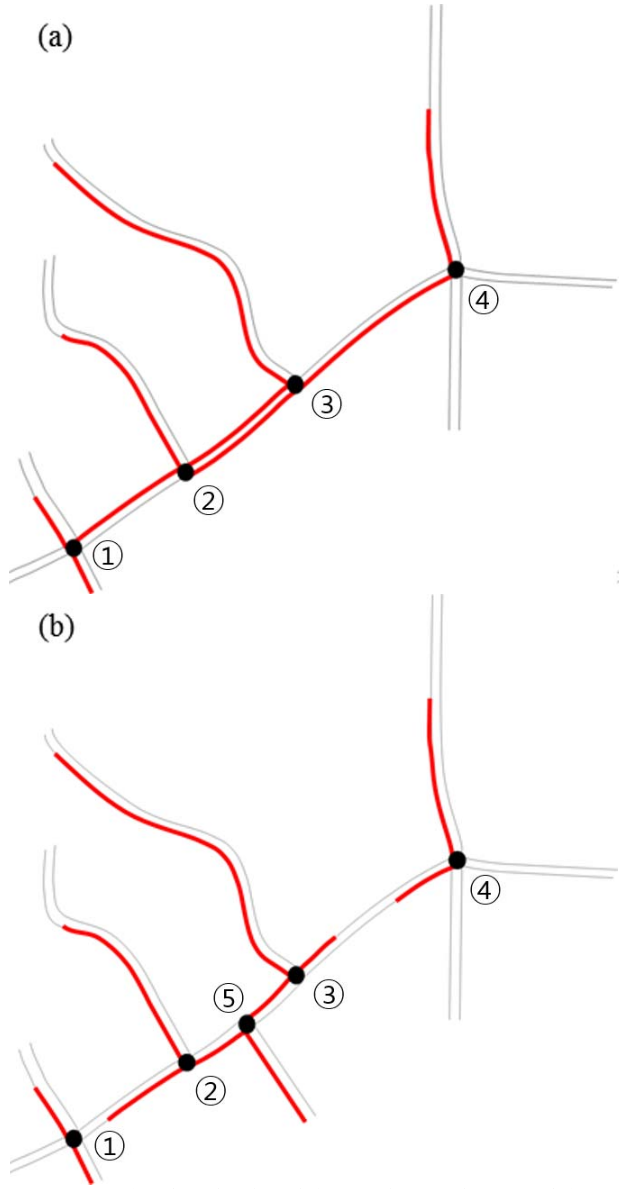

Fig. 11. Queue length at the elapsed time of 1hour (a) before; and (b) after bridge construction

V. CONCLUSION

This paper analyzed the quantitative effects of bridge construction on network traffic performances, using traffic simulation software. Based on reasonable assumptions and collected traffic data, various traffic demand scenarios were established in order to anticipate traffic conditions. The simulation results showed that all traffic performances after bridge construction outperform those before construction. However, in a specific case, bridge construction can be less effective in relieving traffic congestion due to bottleneck phenomenon.

REFERENCES

[1] "Global urbanization in Asia," Asian Development Bank, Mandaluyong City, Philippines, 2012.

[2] D. Schrank, B. Eisele, T. Lomax, and J. Bak, "Urban Mobility," 2015.

[3] J. I. Levy, J. J. Buonocore, and K. von Stackelberg, "Evaluation of the public health impacts of traffic congestion: a health risk assessment," Environ. Heal., vol. 9, no. 1, p. 65, 2010.

[4] H. Frumkin, "Urban sprawl and public health.," Public Health Rep., vol. 117, no. 3, pp. 201–217, 2002.

[5] Director for Information Management, ed., *Statistical Yearbook of Ministry of Land, Transport and Maritime Affairs 2012*, Minister of Land, Transport and Maritime Affairs Director General for Policy Planning, Korea, 2012.

[6] Hanseon Cho, Dongmin Lee and Sangjun Park, *2008 Traffic congestion costs: estimation and trend analysis*, The Korea transport institute, Korea, 2010.

[7] D. Braess, "Über ein Paradoxen aus der Verkehrsplanung," Unternehmensforschung, vol. 12, pp. 258–268, 1968.

[8] B. Calvert, W. Solomon, and I. Ziedins, "Braess's paradox in a queuing network with state depending routing," J. Appl. Prob., vol. 34, pp. 134–154, 1997.

[9] Richard Arnott, Kenneth Small, *The Economics of Traffic Congestion,* The Scientific Research Society, 2012

[10] K. Jang, H. Kim, and I. G. Jang, "Traffic signal optimization for oversaturated urban networks : queue growth equalization," pp. 1−8, 2015.