A TRAFFIC CONTROL STRATEGY FOR CONGESTED EXIT-RAMP AREA IN SEOUL RING-ROAD

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Abstract: Traffic control strategy for heavily congested exit ramps in urban freeway, especially for Ring-Road in Seoul, is presented in this paper. A new concept of traffic signal control was prepared for the traffic signals engaged in the exit ramp and the immediate area. Traffic signal control methodology for oversaturated traffic conditions such as equity offset and imbalanced splits were applied. The exit ramps suffering from serious traffic congestion were selected for the test of the proposed control strategy. After simulation trials, it was found that the control strategy was effective in preventing main-line queue spill-back, and managing queue lengths between the exit traffic and the adjacent street traffic. The exit-ramp control system is under construction now. This system will start operation in summer, 2001. The research team will conduct the field operation and monitor the system performance.

Key Words: urban freeway, exit-ramp traffic control, signal control for oversaturated traffic condition

1. INTRODUCTION

The Ring-Road in Seoul, called Naebu-Sunwhan-Ro, was opened to traffic in 1999. The function of the road is to relieve congestion in the city · center, by offering a more convenient alternative to the motorist. It is a 40-km-long uninterrupted flow facility. Since this road was built over the pre-developed urban area, its highway alignment is poor in some sections. Most of the road consists of bridges, and there are two tunnels. Because of sharp curves in several locations, its sight distances are so limited that there exists high potential of traffic accidents. Only six months after the road has been opened, some sections suffered from serious traffic congestion and high accident frequency. The city government of Seoul decided to install an extensive freeway traffic management system (FTMS) for the Ring-Road in 1999, by investing about 30 million US dollars. The FTMS will consist of 230 vehicular detectors, mostly image-processing sensors, 21 CCTVs, 50 variable massage signs, 9 entrance-ramp control subsystems, 3 exit-ramp control subsystems, 14 speed enforcement subsystems. The system design has been completed, and the field installment is under way. The FTMS will initiate test operation in the summer of 2001.

Before designing the installation of the field equ ipment, like sensors and traffic signal controllers, extensive study was done for developing the control strategies, to cope with the unique problems of traffic congestion and accidents occurring on the Ring-Road. One of the major problems in the traffic operation aspect is serious traffic congestion on some exit ramps and their vicinities. These exit ramps are connected to the existing signalized arterial streets, which already carry heavy traffic. Since long queues have been built in the existing streets, the traffic exiting from the Ring-Road seldom has a chance to merge into the street, resulting in excessive queue back-up to the mainline of the Ring-Road. On Hongeun Ramp, for instance, more than 2 km of the mainline queue occur during the peak period on the week days. The paper aims to present the traffic control strategy to prevent the queue back-up phenomenon on the exit-ramp area.

2. EXIT-RAMP CONTROL CONCEPT

The conventional way of dealing with heavily congested exit ramp areas is to attempt to divert exit traffic through providing traffic information. Even if information provision might be effective in relieving the congestion to a certain extent, this is not an effective measure. The most effective measure is to close the subject exit ramp.(US DOT 1996) This measure will cause inconvenience to the rerouted traffic due to the closed ramp. However, a new approach for exit ramp traffic control is to install a new traffic signal at the end of the exit ramp. Without a traffic signal, the exiting vehicles hardly find the gap for merging on to the existing street, which results in excessively long queue to the freeway mainline. A main issue in developing the exit-ramp control strategy was how to make the vehicles exiting from the exit ramp to the street merge smoothly into the middle of queue built in the adjacent street. Basic idea of the strategy is to interrupt the middle of queue with a traffic signal, reserve some space for the exiting vehicles, and finally let the exiting vehicle merge into the street. In regards of hardware, a signalized intersection was newly designed at the merging area between the street and the exit ramp, and the signal controller in the intersection would be interconnected to the signal controller at the existing intersection located downstream to the new intersection. The concept of equity offset, commonly used for the traffic control of the over-saturated urban streets, was employed for the coordination scheme of the two signal controllers.(McShane *et al* 1998) This control strategy might require too much sacrifice of the street traffic, while giving priority to the exiting traffic. In order to avoid the equity problem, the queue-length management between the street traffic and exiting traffic was considered in the control strategy. This queue management could be accomplished by applying the imbalanced split concept to the signal control for the exit-intersection.

The final goals of the exit-ramp control strategy are to obtain the maximum output at the exit-ramp area during the control period and to provide equity between the exit-ramp traffic and the street traffic. In summary, the specific objectives for the traffic control are as follows:

Objective I. Reservation of Space for Smooth Exit;
Objective II. Fully Utilization of Exit-intersection Capacity;
Objective III. Efficient Utilization of Queue Storage Capacity;
Objective IV. Queue Length Management in Exit Traffic and Street Traffic; and
Objective V. Minimization of System Delay.

The traffic signal control method satisfying the objectives listed above will be described in the next section.

3. MODEL DEVELOPMENT

Figure 1 illustrates a typical exit-ramp area on urban freeway. In this figure, Intersection A is pre-existent with a four-phase operation. Intersection B is a newly designed one for the exit control. This intersection will be operated in two-phase. The variables used in this figure are defined as follows:

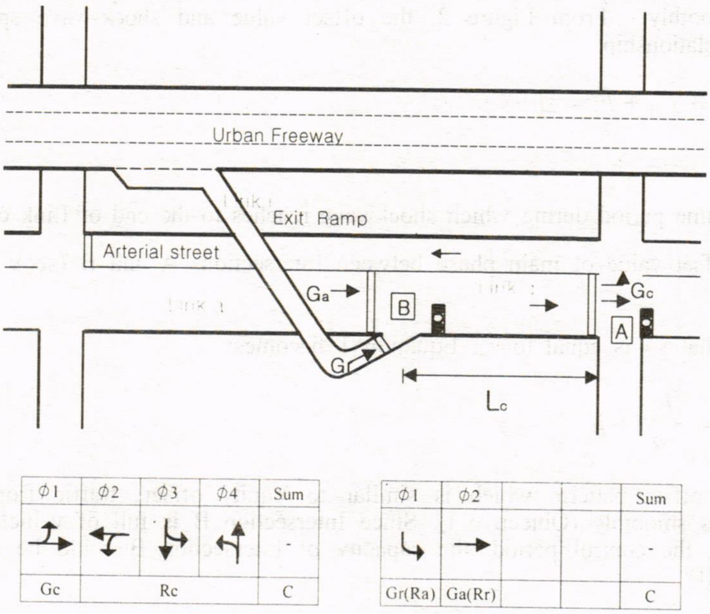

Figure 1. Typical Exit-Ramp Area in Ring Road

Link c : Link between Intersection A and B
Link r : Exit ramp link
Link a : Link upstream from Intersection B
L_c, L_r, L_a : Length of links c, r and a in meter
N_c, N_r, N_a : Number of lanes in Links c, r and a
u : shockwave speed in Link c, 4.7m/sec
h_c, h_r : queue discharge headway in Links c and r in sec
s_{sc} : start-up lost time in Link c in sec
s_c, s_r : lost time per phase in Links c and r in sec
d_r, d_a : traffic demand in Links r and a in sec

The problem of the exit-ramp control can be reduced into traffic signal control of the two intersections under the oversaturated condition. The following traffic signal timing variables should be designed: system cycle length, offset between main direction greens of two intersections, and green splits of the intersections. Intersection A is a major intersection. Green splits in Intersection A determine the capacity of exit area. Links r and a share this capacity. The system cycle length could be determined from the traffic conditions of Intersection A. During the exit ramp control period, traffic condition of Intersection A can be assumed to be oversaturated. Under this condition, the cycle length will be maintained at a prespecified upper limit. In this paper, it is also assumed that the green splits of Intersection A is predetermined. The main focus of the exit-ramp control is to determine offset value and green splits of Intersection B, given the system cycle length and Intersection-A green-splits.

Figure 2 illustrates vehicle trajectories occurring at Link c. During Phase 2 (phase for street traffic, G_a or R_r), the street traffic will start to cross Intersection B. Some time later Intersection B will be blocked by the street traffic. The blocking vehicles will remain in the middle of Intersection B until backward recovery shock-wave emanated from Intersection A reaches to Intersection B. At this moment, Phase 2 is forced to terminate and then the blocking vehicles start to clear the intersection. After that, the queue storage space will start to occur at the end of Link c. At the same time, Phase 1 (phase of exit-ramp traffic, G_r) will turn on and the exit-ramp traffic will egress to Link c smoothly. From Figure 2, the offset value and shock-wave speed has the following relationship:

$$s_{sc} + T_A + h_c = \varDelta + s_{sr} \tag{1}$$

where,

T_A : the time period during which shockwave reaches to the end of Link c (sec), $\frac{L_c}{u}$

$\varDelta$: the offset value of main phase between Intersections A and B (sec)

Assuming that s_{sc} is equal to s_{sr}, Equation 1 becomes:

$$\varDelta = \frac{L_c}{u} + h_c \tag{2}$$

Using this offset pattern, which is similar to 'equity offset', traffic from exit ramp could egress smoothly (Objective I). Since Intersection B is full of vehicles all of the time during the control period, the capacity of Intersection B could be utilized fully (Objective II)

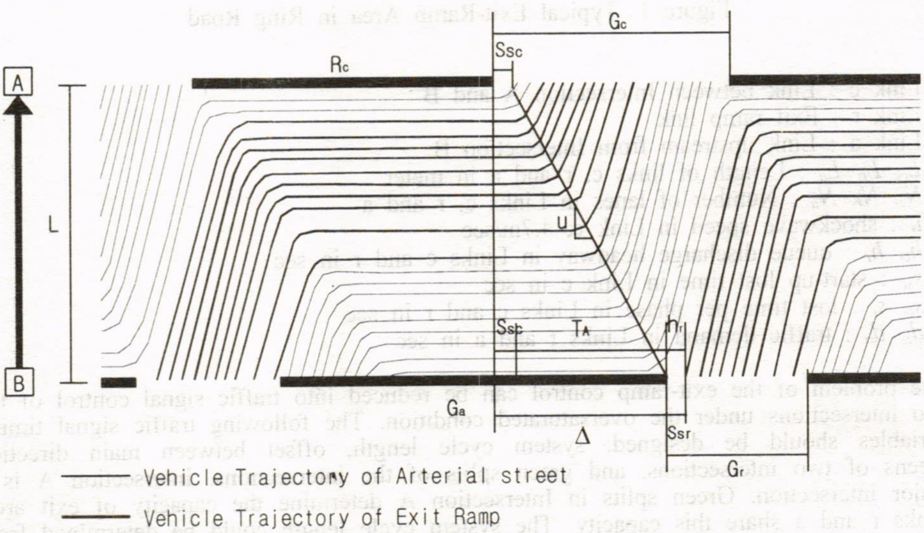

Figure 2. Vehicle Trajectories at Link c

The capacity of Intersection B is bound to the green time of Intersection A, G_c. As this green time increases, the capacity of Intersection B becomes larger. The green time cannot be enlarged sufficiently, however, because the traffic signal at Intersection A should also serve competing approaches. The application of the offset pattern described above only gives priority to exit-ramp vehicles over street traffic. Due to the limitation of the intersection capacity, a long queue will be built on Links a and r. Relative queue lengths between the two links depends on the green splits of Intersection B. The traffic operator will have the queue-length management policy providing priority to certain approach or equity. New variable, called queue-length change ratio, is defined as follows:

$$r_i = \frac{\Delta Q_i}{L_i}$$

where, ΔQ_i is queue-length change rate and L_i is queue storage capacity of Link I. The queue-length change ratio means, how fast the queue storage capacity of subjective link is filled by waiting vehicles. The relative queue-length ratio between Links r and a can be defined as follows:

$$\alpha = \frac{r_r}{r_a} \tag{3}$$

Four priority options are possible:

Exit-Ramp Absolute Priority ($a=0$);
Exit-Ramp Relative Priority ($0<a<0$);
Equity ($a=1$); and
Street Priority ($a>1$).

The exit-ramp absolute priority will result in no queue in the exit ramp at the expense of a very long queue in the street. Under the equity option, the queues in Links r and a will grow at the same fill-up speed, which will delay queue spillback as late as possible. With this option, the queue storage capacity of the competing approaches could be fully utilized (Objective III). The street priority will cause long queues to the exit ramp, which is not desirable.

Once the priority option is selected, the queue-length management can be accomplished through appropriate green splits of Intersection B. The queue-length change ratio (ΔQ_i) is expressed as follows:

$$\Delta Q_i = \frac{d_i - f_i}{N_i} \tag{4}$$

where d_i is traffic demand, f_i is discharge rate or capacity, and N_i is the number of lanes of each phase.

The discharge rates in vehicle per hour of exit-ramp approach (f_r) and main approach in Intersection (f_c) are

$$f_r = \frac{G_r - s_r}{h_r} * (3600/C) * N_r \tag{5}$$

$$f_c = \frac{G_c - s_c}{h_c} * (3600/C) * N_c \tag{6}$$

where, C is the system cycle length in seconds. G_r and G_c are green intervals of respective approaches.

The discharge rate of street phase in Intersection B cannot be expressed in a similar way. As illustrated in Figure 2, the street traffic can pass through Intersection B during the limited portion of green interval given the offset pattern. The discharge rate of the street phase can be expressed as follows;

$$f_a = f_c - MIN(d_r, f_r)$$

where d_r is traffic demand of exit-ramp. Assuming oversaturated traffic condition of exit ramp, d_r is greater than f_r. Then,

$$f_a = f_c - f_r \tag{7}$$

Substituting Equations 5, 6, and 7 into Equation 4, ΔQ_r and ΔQ_a becomes

$$\Delta Q_r = [d_r - \frac{G_r - s_r}{h_r} * (3600/C) * N_r]/N_r \tag{8}$$

$$\Delta Q_a = [d_a - \{\frac{G_c - s_c}{h_c} * (3600/C) * N_c - \frac{G_r - s_r}{h_r} * (3600/C) * N_r\}]/N_a \tag{9}$$

Substituting Equations 8 and 9 into Equation 3, the relative queue-length ratio is

$$\alpha = \frac{N_a L_a \{d_r - \frac{G_r - s_r}{h_r} * (3600/C) * N_r\}}{N_r L_r [d_a - \{\frac{G_c - s_c}{h_c} * (3600/C) * N_c\} + \{\frac{G_r - s_r}{h_r} * (3600/C) * N_r\}]} \tag{10}$$

Rearranging Equation 10 in terms of G_r, the equation becomes

$$G_r = \left(\frac{d_r L_a N_a - \alpha d_a L_r N_r + \alpha f_c N_r L_r}{\alpha N_r L_r + L_a N_a} \right) \frac{h_r C}{3600 N_r} + s_r \tag{11}$$

Intersection B will be operated in two phases. G_a is determined as follows;

$$G_a = C - G_r \tag{12}$$

Inspecting Equations 11 and 12, the green splits in Intersection B is determined based on the relative queue-length ratio. The queue lengths of competing approaches in Intersection B could be adjusted as the traffic operators' intention (Objective IV).

4. TEST

4.1 Test Site and Methodology

Among the exit ramps on the Ring Road in Seoul, the Hongeun Ramp and Hongjae Ramp suffer from serious traffic congestion. Figure 3 shows conceptual geometry of these ramps and vicinity areas. Hongjai Intersection is an intersection between Euiju-Ro and Yeonhee-Ro. The intersection is located downstream of both exit ramps. Hongjai Intersection is a major intersection carrying heavy traffic volume. Since Euiju-Ro is a major artery in Seoul, large portions of green time are assigned to this direction. Resultingly, a limited portion of green time is assigned to Yeonhee-Ro, the east-west direction. That is because sufficient capacity cannot be provided by Yeonhee-Ro. Heongeun Ramp and Hongjae Ramp are connected in Yeonhee-Ro. Queue spillback phenomena occurs in these exit ramps every weekday.

In order to apply the exit-ramp control strategy, each intersection in Figure 3 needs to be matched to the intersection defined in Figure 1. Hongeun Intersection, that is, Intersection 1 in Figure 3 will be Intersection A in Figure 1. Intersections 2 and 4 in Figure 3 are newly designed intersections for exit-ramp control, that is, Intersection B in Figure 1.

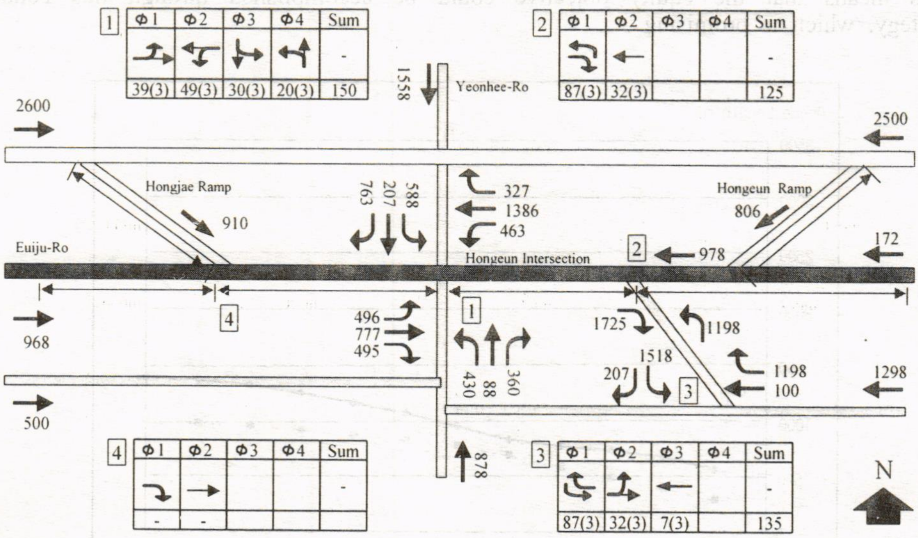

Figure 3. Test Site Description

The control strategy was developed based on the traffic engineering theories. The performance of the strategy could not be tested in the field because the exit-ramp-control subsystem is under construction now. The performance test was conducted using a simulation tool. CORSIM was selected as the simulation tool because of its capability on modeling freeway and urban streets together.(FHWA 1993)

To verify model performance, the following cases were simulated:

Case 1. No Control
Case 2. Exit-Ramp Absolute Priority ($a=0$);
Case 3. Equity ($a=1$).

Case 1 (no control) is existing condition. Field survey was conducted, measuring traffic volume, speed, and queue length. The CORSIM model was calibrated to simulate the current condition reasonably. The simulation works were conducted for 60 minutes, and replicated four times for each case. The queue length data was observed and reduced for a 5-minute interval in the CORSIM trial.

4.2 Results

Only test results of Hongeun Ramp will be described in this paper due to the page limitation. Figure 4 represents current condition. Queue length in Exit Ramp reaches upto 1400 meters after one-hour simulation. Figure 5 shows the simulation results of the exit-ramp absolute priority. In this case, theoretical queue length in the exit ramp is zero. In the simulation result, the queue length in the exit ramp is minimal, as expected. The queue length in the street (Yeonhee-Ro) becomes very long instead. This is also an expected result because this priority option does not consider the growth of the queue length in the street.

Figure 6 shows the result of equity option (Case 3). Theoretically, queue grows upto its storage capacity in 20 minutes after simulation starts. Simulation shows similar result. The queue lengths built in both approach after simulation are in similar range. This means that the equity objective could be accomplished through this control strategy, which is promising.

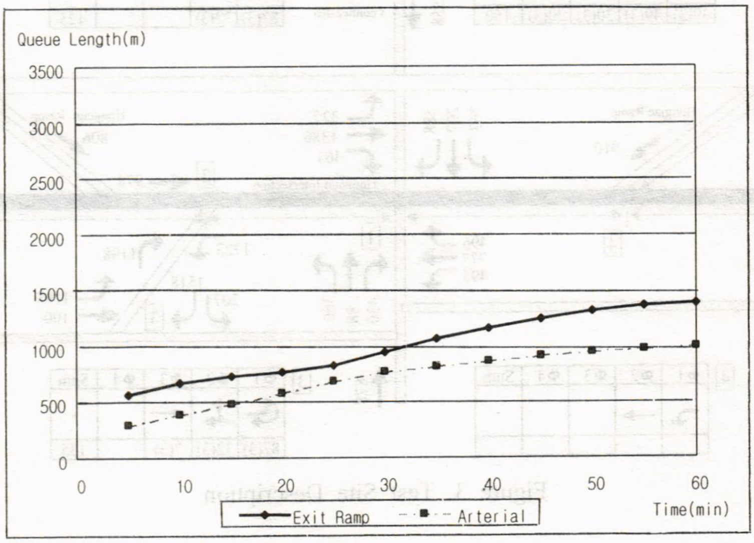

Figure 4. Queue Profile - No Control (Case 1)

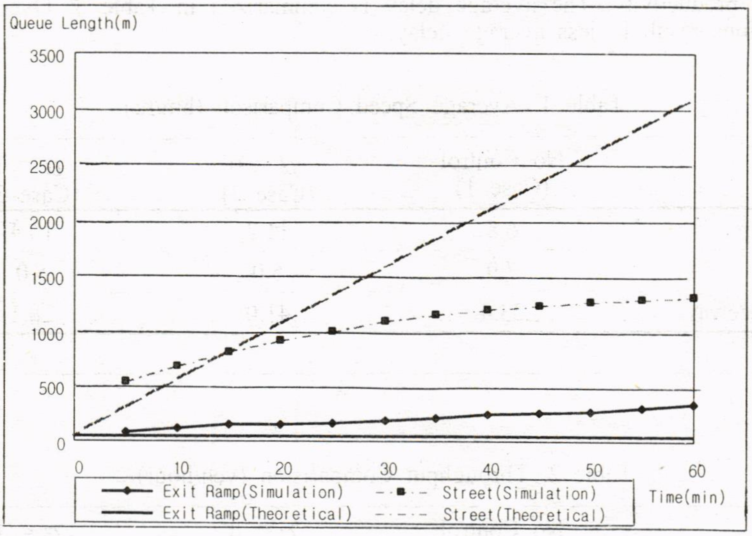

Figure 5. Queue Profile - Exit Ramp Asolute Priority (α = 0, Case 2)

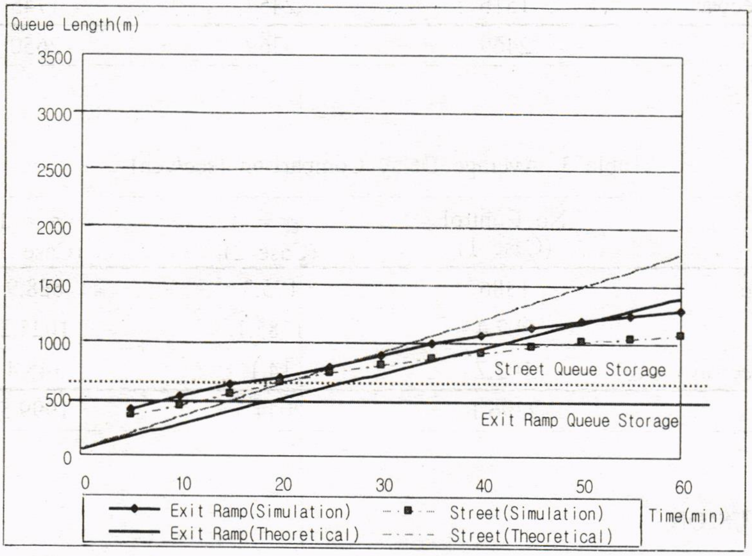

Figure 6. Queue Profile - Equity Option (α = 1, Case 3)

The change of average speed is summarized in Table 1. Since Case 2 is the exit-ramp absolute priority, the average speed in the exit ramp increases upto 16.6 km/hour and the average speed in the freeway main line increases drastically. This is because queue spillback phenomena was dismissed through the exit-ramp control.

Table 2 shows the summary of the vehicle number passed during control period. Every control option results in better productivity than no control. Exit-Ramp priority shows best productivity. The average delay is summarized in Table 3. Overall, every control options result in less average delay.

Table 1. Average Speed Comparison (km/hr)

	No Control (Case 1)	$\alpha = 0$ (Case 2)	$\alpha = 1$ (Case 3)
Exit-Ramp	6.8	11.2	10.4
Arterial	7.9	5.0	5.0
Urban Freeway	23.4	41.0	28.1
Sum	-	-	-

Table 2. Throughput Comparision (veh/hour)

	No Control (Case 1)	$\alpha = 0$ (Case 2)	$\alpha = 1$ (Case 3)
Exit-Ramp	200	664	305
Arterial	753	253	600
Urban Freeway	1516	2452	1745
Sum	2469	3369	2650

Table 3. Average Delay Comparison (sec/veh)

	No Control (Case 1)	$\alpha = 0$ (Case 2)	$\alpha = 1$ (Case 3)
Exit-Ramp	1386	195.3	828.9
Arterial	907.4	1385.1	1025.2
Urban Freeway	102.7	14.1	145.4
Sum	2396.1	2044.5	1999.5

5. CONCLUSION

Traffic control strategy for heavily congested exit ramps on urban freeway, especially Ring-Road in Seoul was presented in this paper. A new concept of traffic signal control was prepared for the traffic signals engaged in the exit ramp and the immediate area. The exit ramps suffering from very serious traffic congestion were selected for the test of the proposed control strategy. After simulation trials, it was found that the control strategy presented in this paper was effective in preventing main-line queue spill-back, and managing queue lengths between the exit traffic and the adjacent street traffic.

The result of study will have to be validated by actual observation to be conducted when the exit ramp control is implemented. The exit-ramp control system is under construction now. This system will start operation in the summer of 2001. The research team will conduct the field operation and monitor the system performance. The research team will also study the improvement of the control strategy for real-time control environments.

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