ABSTRACT

The Advanced Traffic Control System of Tokyo Metropolitan Police Department, a system designed to handle traffic control in the twenty-first century, was completed and put into operation in February, 1995. As part of this system, we designed a new signal control system called STREAM. STREAM aims to alleviate traffic congestion, distribute traffic and reduce the number of traffic accidents. It is applicable for all traffic conditions, from undersaturation to oversaturation.

In this paper, we will discuss the concept of control, the system configuration, traffic information processing, the control methods and the results obtained from introducing STREAM.

1. CONCEPT OF STREAM

As the demand on roads in Tokyo becomes greater by the year, traffic accidents and traffic congestion are also on the rise. To cope with this traffic environment, we completed and put into operation the Advanced Traffic Control System (ATCS) of Tokyo Metropolitan Police Department in February, 1995. As part of ATCS, we developed a new signal control system called STREAM (Strategic Realtime Control for Megalopolis-Traffic).

STREAM is a realtime signal control system which is aimed at alleviating traffic congestion, distributing traffic and reducing the number of traffic accidents. STREAM is applicable to all traffic conditions, from undersaturation to oversaturation. The concept of control is explained below.

1) When there is light traffic, STREAM aims not only to reduce delay and stops but also to make the traffic flow safe by moderating the speed of vehicles. It therefore uses a tool to set up offset which corresponds to the cycle length and uses a pattern selection method for realtime offset control.

2) When traffic demand is nearly saturated, STREAM curbs congestion by improving the efficiency of green time at critical intersections and maximizing the traffic capacity. It is provided with a critical intersection control method (Congestion Alleviation Control: CAC) for achieving this. CAC directly calculates the split and cycle length every 2.5 minutes based on the queue and traffic volume calculated from vehicle detector information. STREAM also incorporates right turn vehicle actuation which is run every second by a signal controller at each critical intersection.

3) When traffic demand is oversaturated, STREAM runs priority control for competing traffic flows at critical intersections. If congestion has exceeded a certain limit within a specific area such as the city center, STREAM controls inflow to that area. Priority control is made possible by the CAC function and inflow control is provided by Intentional Policy Control.

As of April, 1995, STREAM had gathered information from about 16,000 vehicle detectors and was controlling about 6,800 signals.

2. SYSTEM CONFIGURATION AND SUMMARY OF FUNCTIONS

The ATCS consists of subsystems which are connected by means of an optical LAN and which share functions. As shown in Figure 1, the STREAM system consists of several Area Computers, a Traffic Information Processing Computer and Signal Control Supervisor Computer.
A summary of the functions of each computer is given below.

1) Area Computer
Each Area Computer can accommodate 1,024 signal controllers and 4,096 vehicle detectors. The signal controllers are connected to the Area Computer by individual telecommunication lines and vehicle detectors are connected to each signal controller.

A brief description of the functions of the Area Computer is given below.
- Samples the detection pulse at intervals of 50 msec, synchronizes it with the signal status at intervals of 1 second and gathers vehicle detector information such as the traffic volume and occupancy at intervals of 2.5 minutes. It transmits the results to the Traffic Information Processing Computer.
- Controls signal controllers at a cycle of 1 second (performs offset transition, monitors vehicle actuation by means of the signal controllers and monitors operation ) based on the time table received from the Signal Control Supervisor Computer.
- Gathers speed and vehicle classification information by means of an image processing vehicle detector and vehicle license plate information by means of an automatic license plate reader. It also enables control on variable information boards.

2) Traffic Information Processing Computer
The Traffic Information Processing Computer can handle information gathered from 29,000 detectors. It mainly calculates traffic information, such as congestion conditions along main routes and the travel time for each section based on detector information, at a cycle of 2.5 minutes. This information is used not only for signal control but for providing traffic information and monitoring traffic conditions.

3) Signal Control Supervisor Computer
The Signal Control Supervisor Computer can control 12,500 signal controllers (intersections). Based on detector information and congestion information, the Signal Control Supervisor Computer determines the signal control parameters such as cycle length, split and offset, calculates the time table for each intersection and transmits this data to the Area Computer at cycles of 2.5 minutes.

3. TRAFFIC INFORMATION PROCESSING

3.1 Arrangement of Vehicle Detectors

Figure 2 shows a standard arrangement of vehicle detectors on an approach at a critical intersection. The detectors, which measure the traffic volume and saturation flow, are positioned in all lanes at a distance of 150 m (or 30 m) from the stop line at an intersection. In the right turn bay the detector is placed 30 m from the stop line and is used not only for measuring the traffic volume but also for right turn vehicle actuation. Detectors for estimating the congestion length and travel time are placed at distances of 150 m, 300 m, 500 m from the stop line and then at the following distances:

- They are placed at intervals of 250 m in areas close to the city center and at intervals of 500 m in the suburbs.

Previously most vehicle detectors have been the ultrasonic type, but recently an image processing type and an infrared type for measuring all lanes have been developed.
Figure 3 Traffic information process

1) Signal-synchronized traffic volume and occupancy
The traffic volume is calculated at certain intervals by calculating the number of detection pulses and occupancy is calculated by cumulating the detection pulse width. In the conventional system the values were added at a fixed interval (5 minutes), but since this interval is not in synchronization with the signal cycle, there were fluctuations in the data obtained.

STREAM gathers detection pulses in synchronization with the cycle of a signal located upstream or downstream of each detector. It then calculates the traffic volume for the unit time and occupancy from data obtained in the last two cycles.

2) Average speed
The average speed is found by multiplying the ratio of the traffic volume and occupancy by the effective vehicle length [detection area + average vehicle length]. The average vehicle length can be compensated by determining the vehicle classification.

3) Congestion degree
The congestion degree is an index which indicates the degree to which the queue located near the detector has grown. In the conventional system the average speed is found in level 1 if it is equal to or less than the threshold value and in level 0 if it is greater than the threshold value.

STREAM uses three threshold values (V1, V2 and V3) as shown in Figure 4 and calculates the congestion degree as a continuous amount between 0 and 1 in order to handle random changes in speed data.

4) Route congestion length
With the conventional system, several detectors were installed (usually at distances of 300 m, 500 m and 1,000 m from the stop line) on each approach at critical intersections and the level of congestion of the approach was calculated by combining the congestion degree (0 or 1) given by each detector. STREAM, however, calculates continuous congested sections based on the congestion degree (a continuous amount between 0 and 1) given by detectors placed along a route to judge the congested sections along a major road accurately.

5) Saturation flow
The saturation flow is calculated when a road is congested by dividing the traffic volume, which is measured by a detector installed 150 m from the road on each approach leading to a critical intersection, by the green time.

6) Travel time
The travel time is calculated separately for each main-section (a section along the major road network between the intersection of two major roads and another intersection nearby).

The travel time for a congested section within a
The travel time for a congested section is calculated by finding the ratio (travel time for a sub-section) of the number of vehicles present to the traffic volume for each sub-section in which the traffic volume is uniform and adding this ratio for each sub-section in the congested section. The basic method for calculating this is represented by the following equation:

$$ T = \sum L_i \cdot K_i / Q_i $$

Where
- $T$ : Travel time for the congested section
- $L_i$ : Distance of sub-section $i$
- $K_i$ : Average density of sub-section $i$
- $K_i = K_m - aQ_i$ (Km and a are constants)
- $Q_i$ : Traffic volume in sub-section $i$

The travel time for a non-congested section is calculated from the travel speed which is originally set based on simulation.

4. SIGNAL CONTROL METHOD

STREAM consists of a macro control function which operates every 2.5 minutes and a micro control function which operates every second.

The macro control function is run on the Signal Control Supervisor Computer and determines the signal parameters based on detector information and congestion information. It is explained in detail below.

The micro control function runs on the signal controllers and finely adjusts the green time based on detector information from nearby intersections. Its main functions are right turn vehicle actuation and flow rate maximization control.

4.1 Split Control

The split at a critical intersection is a parameter which has the most influence on traffic processing capacity. Allotment of suitable green time is the most important factor for delaying congestion growth at near-saturation.

Previously, the split for a critical intersection was determined according to the pattern selection as shown in Figure 7.

In split control, the traffic index $M$ is the sum of the traffic volume $Q$ and occupancy $O$ given by the detector installed 150 m on each approach. This control method makes use of the characteristic that "when a queue has built up so that it nearly reaches the location of a detector, the traffic volume becomes subject to restrictions on the upper limit of capacity at that point but occupancy increases according to the queue length." However, this control method has the following drawbacks:
- The index $M$ is relative to the traffic volume and queue length and when the system controls traffic between several approaches, the indexes must be mutually compensated.
- The threshold values which classify the patterns and the split value for each pattern must be related when they are set.
- Regular revision every few years is required as traffic conditions change every year.
- This control method is effective for controlling the interval between two main phases at a multi-phase intersection but cannot be applied to other phases.

The following section discusses how STREAM handles split control at a critical intersection. The split at an ordinary intersection is selected in connection
with the cycle length.

4.1.1 Congestion Alleviation Control (CAC)
CAC is a control method which determines an appropriate split according to the traffic conditions at a critical intersection especially at near-saturation. It aims to delay the growth of congestion. CAC is also capable of controlling intersecting road traffic in accordance with traffic policies during congested conditions.

1) Load ratio
In realtime control, the amount obtained by adding the vehicles in queue to the inflow must be used in order to determine saturation flow and load ratio $\rho$ for each traffic movement on each approach is expressed by the following equation:

$$\rho = \frac{Q_{in} + r \cdot k \cdot E}{s}$$  \hspace{1cm} (2)

Where
- $Q_{in}$: Inflow [veh/2.5 min]
- $E$: Vehicles in queue [veh]
- $s$: Saturation flow [veh/2.5 min]
- $k$: Usage ratio of E (0 $\leq$ $k$ $\leq$ 1) [1/2.5 min]
- $r$: Usage ratio of E when vehicles are queued ahead (0 $\leq$ $r$ $\leq$ 1)

The way in which the system handles the type of measurement shown in Figure 8 is explained below.

![Figure 8 Measurement of load demand](image)

When there is a queue, it is difficult to measure inflow $Q_{in}$ directly. Therefore, $Q_{in}$ is calculated according to the following equation using outflow $Q_{out}$ which can be measured.

$$Q_{in} (t_n \sim t_{n+1}) = Q_{out} (t_n \sim t_{n+1}) + [E (t_{out}) - E(t_n)]$$ \hspace{1cm} (3)

$\rho'$ is found by dividing the congestion length by the average space headway. Actually, average space headway is a function of outflow, but in this system it is a constant of 10 [m/veh].

Saturation flow $s$ is measured during congested conditions as described above, and the set value is adopted at undersaturation.

The coefficient $k=0.25$ is set in order to prevent overshooting because of the estimation error of congestion length. And the coefficient $r=0.5$ is set to decrease the load ratio of a movement when the system detects congestion downstream.

2) Calculating split
The split for each phase is calculated based on the load ratio of each traffic movement as shown simply by the following equation:

$$\rho_i = \frac{\gamma_i}{\sum_{i} \rho_i}$$ \hspace{1cm} (4)

Where
- $\rho_{ij}$: Load ratio of movement $j$ on an approach in phase $i$
- $\rho_i$: Load ratio of phase $i$
- $\sum_{i} \rho_i$: Load ratio of the intersection
- $\gamma_i$: Split of phase

This method has the following important functions:
- It performs processing required when one traffic movement corresponds to several phases. This processing is omitted from the above equation.
- During congested conditions, the phase load ratio $\rho_i$ is modified as the following equation shows according to the priority of each phase $p_i$ (0 $\leq$ $p_i$ $\leq$ 1).

$$\rho'_i = \frac{\rho_i}{\rho + p_i (\rho_i - \rho_{i+1})}$$  \hspace{1cm} (5)

- The cycle length is increased or (and) the split is compensated so that the green time is at least equal to the minimum green time.

3) Features
The features of this control method are as follows:
- Since the number of vehicles in the queue is included in the load ratio of each movement, the system can provide continuous control from undersaturation to near saturation.
- The control method can be applied to multi-phase intersections, since it calculates the split directly.
During congested conditions, traffic can be controlled in accordance with traffic policies. That is, when $p_i$ in equation (5) are all 0, this method controls congestion of critical movement in each phase equally (makes the travel time through the congestion equal). If a different $p_i$ has been set for each phase, the phase whose $p_i$ value is greatest is given priority.

Since the load ratio of a movement drops in accordance with coefficient $r$ in equation (2) when the system detects congestion downstream, the split for competing phases increases and the total outflow volume of the intersection can be increased.

4.1.2 Intentional Policy Control (IPC)

IPC changes the signal control parameters for the specified intersections or links when traffic information such as the traffic volume and congestion length satisfy the preset conditions. This function is not based on traffic engineering theory but is useful for implementing various traffic policies such as the following:

- When congestion in the city center has exceeded the limit, IPC reduces the split at intersections on road heading toward the city center to curb inflowing traffic.
- When the left lane on a two-lane approach is congested because the left-turn traffic is affected by pedestrians, IPC increases the vehicle green and pedestrian red time in order to reduce the congestion.

4.2 Controlling the Cycle Length

The aim of controlling the cycle length as part of co-ordinated control is to minimize delay and stops along a route and create a safe traffic flow at undersaturation, and to maximize the traffic processing capacity at critical intersections at oversaturation. A theoretical calculation method for providing this type of control in realtime has not yet been established.

In STREAM, the cycle length is set between the preset upper and lower limits as explained below. The cycle length is determined for each sub-area unit. When the difference in the cycle length between two adjacent sub-area units is smaller than the set threshold value, STREAM controls the two sub-area units as one sub-area and recognizes the greater cycle length. The cycle length for each sub-area unit is calculated using equation (6) based on the load ratio of a critical intersection within the sub-area unit.

$$C = \frac{(a_1 \cdot L + a_2)}{(1 - a_3 \cdot \rho)}$$

Where

- $L$ : Loss time
- $\rho$ : Load ratio of the intersection ($\rho = \sum \rho_i$)
- $a_1$, $a_2$, and $a_3$ : Coefficients

The coefficients $a_1 = 1.5$, $a_2 = 0$ and $a_3 = 1.0$ are usually set so as not to give an excessive cycle length. During morning peak hours, the coefficient $a_3 = 1.2$ is assumed so that the control method can cope with the rapid increase in traffic. This control method includes the following functions:

- It compensates the cycle length by increasing it when the split calculated according to the explanation in section 4.1 is not feasible from the point of view of guaranteeing the minimum green time.
- The maximum value of one change when the cycle length is falling is set to 10 seconds to enable the control method to cope with fluctuations in the load ratio.

4.3 Offset Control

The offset at undersaturation is determined from the relationship between the offset and the cycle length and from the demand on the road by inbound and outbound traffic. A method which changes the offset to minimize delay and stops first appeared as part of the Tokyo Traffic Control System in the first half of the 1970s, but this method has the following drawbacks:

- Vehicle detectors must be set up in each link for both directions of traffic flow.
- It is possible to minimize delay and stops for each link but minimization cannot be guaranteed for the entire sub-area.
- Policies relating to management of traffic flow such as controlling vehicle speed cannot be implemented.

The method currently used is the pattern selection method which relies on the traffic volume (inbound and outbound) and the cycle length for each sub-area as shown in Figure 9. The offset for each pattern is set in advance using an offset design tool.
During congested conditions, the inflow traffic from an intersecting road at an intersection within the congestion can be controlled by the offset. If the opposite direction of traffic flow is non-congested, delay and stops can be minimized by giving priority to the direction. This type of control during congestion is implemented by detecting the congestion and selecting the offset for each link.

5. RESULTS OF APPLICATION

Over a two-week period in December, 1994, we ran application tests on STREAM (CAC) at 308 critical intersections on Tokyo's major road network. During this period congestion also started occurring at ordinary intersections downstream from critical intersections, so we adjusted the split at about 100 intersections.

In February, 1995 we started operating STREAM at the 308 intersections mentioned above to coincide with the start of operations of the ATCS.

5.1 Control Performance

Figure 10 uses results indicating conditions before and
after STREAM was introduced to show the effect of control at morning peak hours at Nishi-Sugamo intersection (the intersection of National road No. 17 and Ring road No. 5). As shown in Figure (a), under the previous control system only one direction of traffic flow was congested between 7 a.m. and 8 a.m. and there was ineffective green time for the competing direction. However, it is easy to see from the results of STREAM in Figure (b) that the relationship between congestion in both directions and the split is well balanced.

5.2 Resultsof Control

5.2.1 Method of evaluation

We evaluated the results of introduction of STREAM on major roads (total length of 1,515 km and about two lanes each way on average) in the central area of Tokyo. The period of evaluation was 12 hours from 7 a.m. to 7 p.m. on working days in February, 1994, before STREAM was introduced and again in February, 1995, after STREAM was introduced.

In order to evaluate accurately the changes in daily demand on the roads, the correlation between the demand and the service level must be taken into account. With this evaluation, the demand is represented by total travel distance and the service level is represented by total travel time, total delay within the congestion and congestion length-time and the relationship between both indexes is represented by a regression line.

The traffic indexes used for evaluation are all gathered by the traffic control system. The method for calculating the indexes is explained below.

1) Total travel distance \( L_Q \) [veh \( \cdot \) km/12 hours]
\[
L_Q = \sum l_i \cdot Q_i
\]  
(7)

Where
- \( l_i \): Main-section length
- \( Q_i \): Traffic volume for 12 hours

Table 1

<table>
<thead>
<tr>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Total travel distance [1,000 veh ( \cdot ) km]</td>
<td>21,619</td>
<td>21,619</td>
<td>0</td>
</tr>
<tr>
<td>Total travel time [1,000 veh ( \cdot ) hour]</td>
<td>1,194</td>
<td>1,086</td>
<td>9.1</td>
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<tr>
<td>Total delay [1,000 veh ( \cdot ) hour]</td>
<td>448</td>
<td>343</td>
<td>23.4</td>
</tr>
<tr>
<td>Congestion length-time [km ( \cdot ) hour]</td>
<td>8,423</td>
<td>6,066</td>
<td>28.0</td>
</tr>
</tbody>
</table>

1: Main-section length

Q: Traffic volume for 12 hours

Figure 11 Results of control
2) Total travel time $TQ$ [veh\cdot hour/12 hours]

$$TQ = \sum \sum T_{it} \cdot Q_{it} \quad (8)$$

Where

- $t$: time
- $T$: Average travel time for 15 minutes
- $Q$: Traffic volume for 15 minutes

3) Total delay within congestion $DQ$ [veh\cdot hour/12 hours]

$$DQ = \sum \sum (T_{it} - T') \cdot Q_{it} \quad (9)$$

- $T'$: Travel time during non-congestion

4) Congestion length-time $LT$ [km\cdot hour/12 hours]

$$LT = \sum \sum L_{it}$$

$$LT = \sum \sum L_{t,i} \quad (10)$$

- $L$: Average congestion length for one hour

5.2.2 Results of control

Figure 11 shows the relationship between the total travel distance and other traffic indexes before STREAM was introduced (measured over 16 days) and after (measured over 20 days). In this Figure, each plotted value represents the data for one day. We omitted data for three days from the data measured before STREAM was introduced because other indexes were abnormally high in relation to the total travel distance. We calculated each regression line separately and verified that it was significant at the 95 percent level.

Table 1 uses various traffic indexes measured before and after STREAM was introduced in relation to the average total travel distance on working days in February, 1995 to show the results of control. The results show that total travel time fell by 9 percent, total delay time fell by 23 percent and congestion length-time fell by 28 percent.

5.3 Results in Economic Terms

We calculated the results of introduction of STREAM in economic terms based on the amount of decrease in the total travel time. The method of calculation and the results are shown in Table 2. The results showed an economic saving of 110.1 billion yen annually.

### Table 2 Result in economic terms

<table>
<thead>
<tr>
<th>Items</th>
<th>Benefit (billion yen/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saving in time (TM)</td>
<td>1,072</td>
</tr>
<tr>
<td>Saving in fuel consumption (TF)</td>
<td>29</td>
</tr>
<tr>
<td>Total</td>
<td>1,101</td>
</tr>
</tbody>
</table>

| $TM = \delta T \cdot M \cdot Y_1 \cdot D$ |
| $TF = \delta T \cdot F \cdot Y_2 \cdot D$ |

$\delta T$: Reduction in total travel time (108,000 veh\cdot hour)

$M$: Passengers (ave. 1.8 people/veh)

$Y_1$: Time unit (2,205 yen/hour)

$D$: Working days (250 days/year)

$F$: Gasoline consumption (1.08 liter/hour)

$Y_2$: Gasoline unit (100 yen/liter)

6. CONCLUSION

The results of introduction of Congestion Alleviation Control which is the main function of STREAM at 308 critical intersections within Tokyo showed that total travel time during the daytime (7 a.m. to 7 p.m.) fell by 9 percent, total delay fell by 23 percent and congestion length-time fell by 28 percent. The result in economic terms was an annual saving of at least 100 billion yen. From these results we confirmed that STREAM is effective in reducing congestion and that during congested conditions at the above 308 intersections, competing traffic flows are handled more equally than in the previous control system.

Future traffic control measures to be introduced in Tokyo include the following:

1) To apply Intentional Policy Control to effective critical intersections and further reduce congestion in the city center by curbing inflowing traffic.

2) To reduce congestion by installing more vehicle detectors and applying STREAM both to more intersections within the central area of Tokyo and to a new sub-center which is planned to be introduced in 1996 to serve the suburban area of Tokyo.

3) To adjust the sub-area, cycle length and offset set for the night-time to strengthen measures to prevent accidents.

We hope that this paper serves as a reference for all cities which have congestion problems.

We would also like to express our sincere appreciation to Assistant Professor Masao Kuwahara at the University of Tokyo and Assistant Professor Hirokazu Akahane at Chiba Institute of Technology for
their advice on the method of evaluation of control results.

7. References