Signal Coordination Control Practices in Japan

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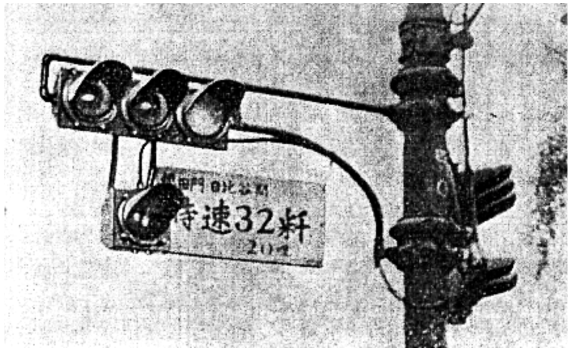
1. History (Coordinated Control, Responsive Control) in Japan

Signal Coordination Control



[Tokyo]

- **1933: 1st introduction of cabled signal coordination control**
  - 1 line, 15 intersections (DC break-off singnal & time switch)

➔ green-wave [32km/h posted]

➔ 1st un-cabled coordination in **1936** (10 intsns) [with synchronized clocks]

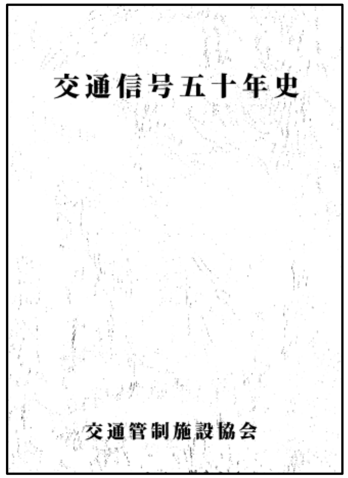
➔ 19 lines, 107 intsns, 33.5 km in **1940**

[World War II]➔ 1st **semi-actuated** coordination control in **1953**

(1 line with 5 intsns); flexible cycle

- **1963: 1st trial of installing traffic-actuated signal coordination control**
  - a line with 18 intsns (detectors & controllers;

120 patterns=6 cycles* 4 splits*5 offsets)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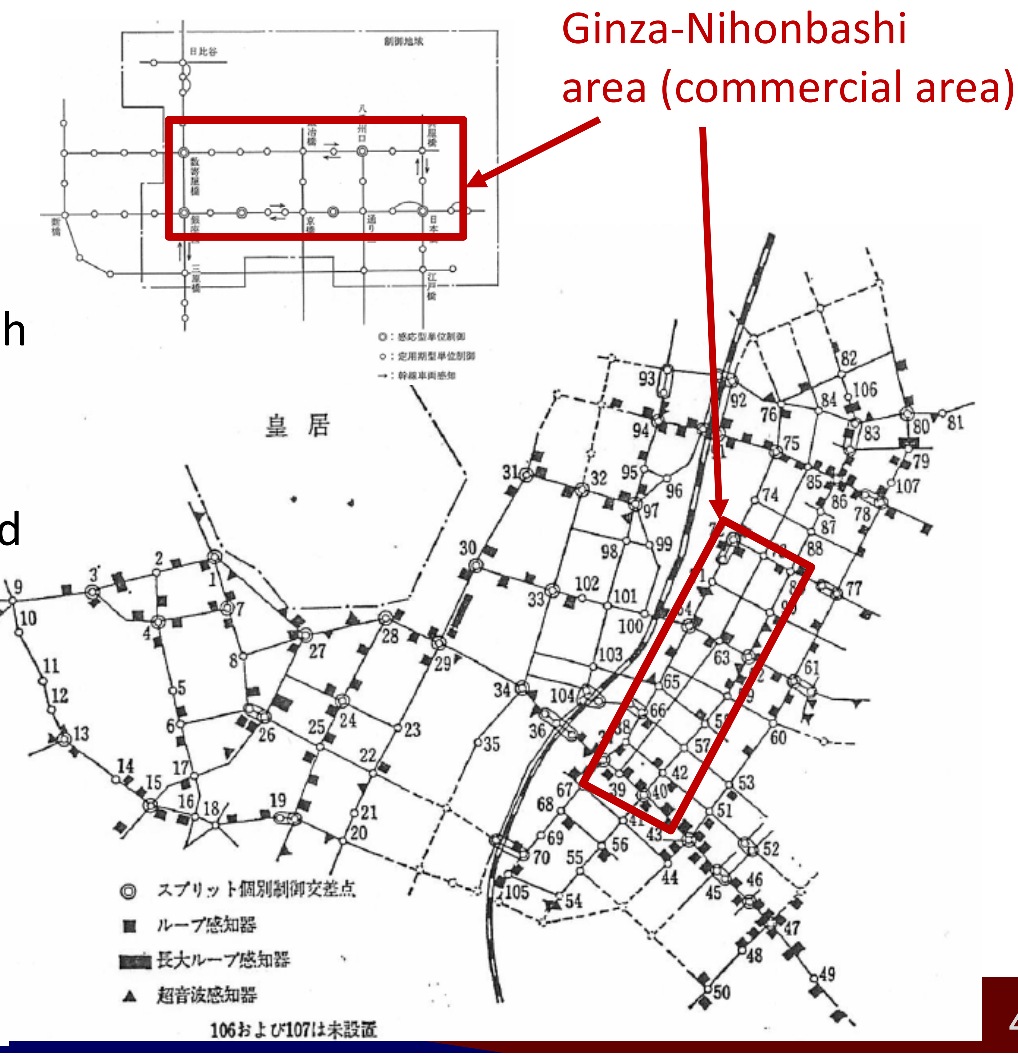
交通管制施設協会

[ref.: *"Traffic Signal 50 years History"* (1975) in Japanese]

1. History (Coordinated Control, Responsive Control) in Japan

Signal Coordination Control (contd.)

- **1966: 1st introduction of area-wide signal coordination control**
  - 35 intersections, in Ginza area, Tokyo
  - A trial of Centralized Traffic Control Center with local signal controllers & detectors
  - Introduction of fundamental idea of arterial traffic responsive control ➔ nationwide spread
- **1970: 1st full-scale introduction of signal coordination control**
  - **Centralized** Traffic Control Center (**TCC**) with 123 intersections in approx. 5,000 km^2



[ref.: *"Traffic Signal 50 years History"* (1975) in Japanese]

1. History (Coordinated Control, Responsive Control) in Japan

<u>Manual Publication in Japan</u> [all published by **JSTE** (Japan Society of Traffic Engineers)]

1969 Intersection Design Manual

1969 Signal Installation/Operation Manual

1977 Intersection Plan/Design Manual

1983 Traffic Signal Control Manual (detailed description of coordination)

1984 Intersection Plan/Design Basic Manual

1994 Traffic Signal Manual (description of pattern selection)

2002 Intersection Plan/Design Basic Manual -Revision

2006 Traffic Signal Manual -Revision (description of MODERATO)

2018 Intersection Plan/Design Basic - Plan/Design Operation - Manual

1. History (Coordinated Control, Responsive Control) in Japan

- Current number of systems & signals [as of April , 2017]

Centralized TCC: 168 (= 47[pref. head] + 28 [large cities] + 88 [sub-**TCC**])

National Police Agency (NPA), JAPAN defines the fundamental specificatio of **TCC**.

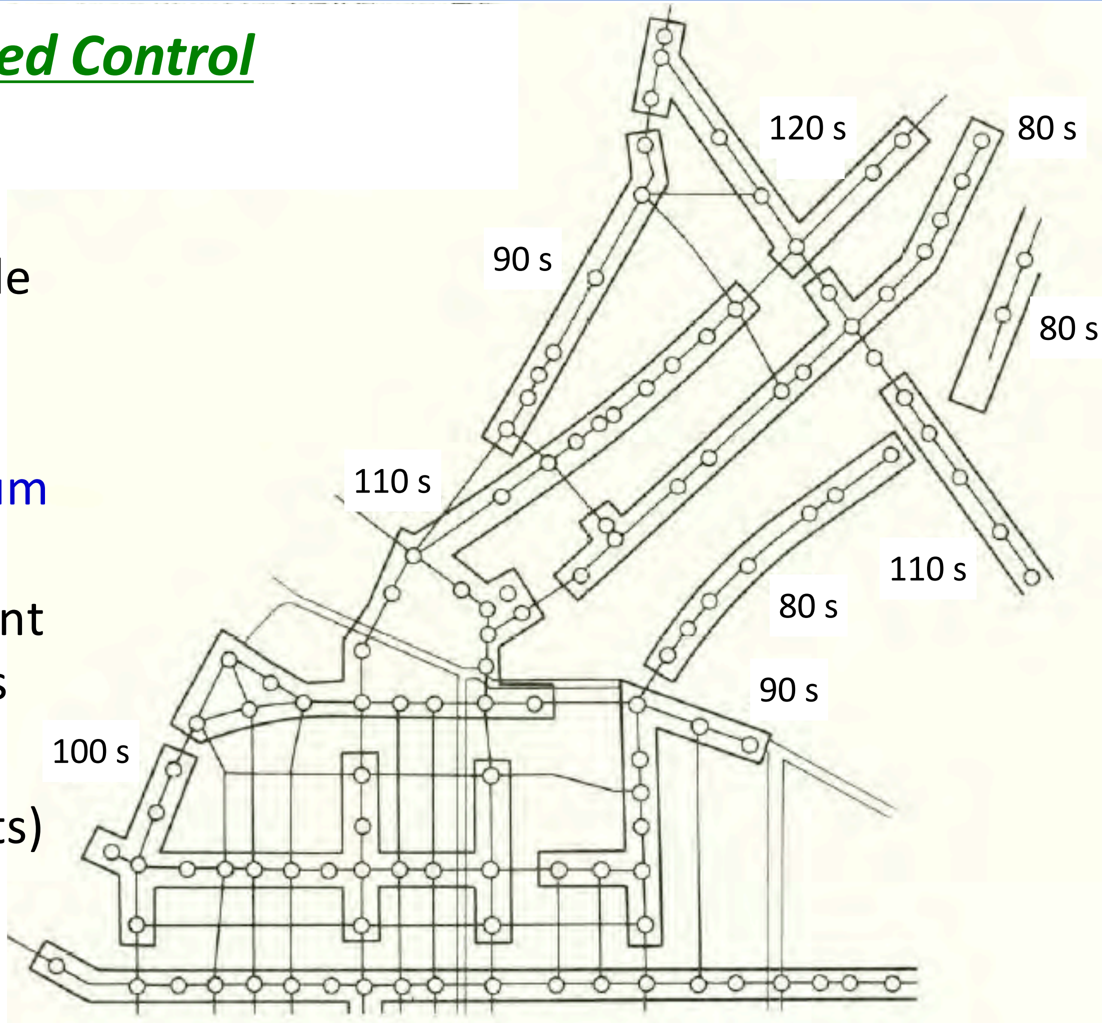
TCC Providers: 日本信号株式会社 NIPPON SIGNAL CO., LTD. KYOSAN OMRON Panasonic SUMITOMO ELECTRIC Connect with Innovation

# of coordinated signl.:	73,684 [connected to **TCC**]		8,851 km^2
	26,010 [unconnected/coordinated],	5,073 arterials,	5,623 km^2
	914 [push button/coordinated],	446 arterials,	51 km^2
# of isolated signl.:	15,804 [actuated control]		
	54,718 [predetermined control]		
	30,772 [push button]		
	6,159 [others]		**total # signals = 208,061**

2. Popular applied signal control theory and practice in Japan

example Images of Centralized Coordinted Control

- Areawide urban road network consists with groups of sub-networks.
- A group of sub-networks has a common cycle length (***C***), tree-structure connections of nodes (signalized intersections).
- A sub-network consists with a set of minimum coordinated signals with a common cycle length, which can be connected with adjacent sub-networks(s) with the same cycle lengths and form a group.
- Signal Coordination (determination of offsets) is based on the link length (***L***) and ***C*** with predetermined vehicle speed (***V***)

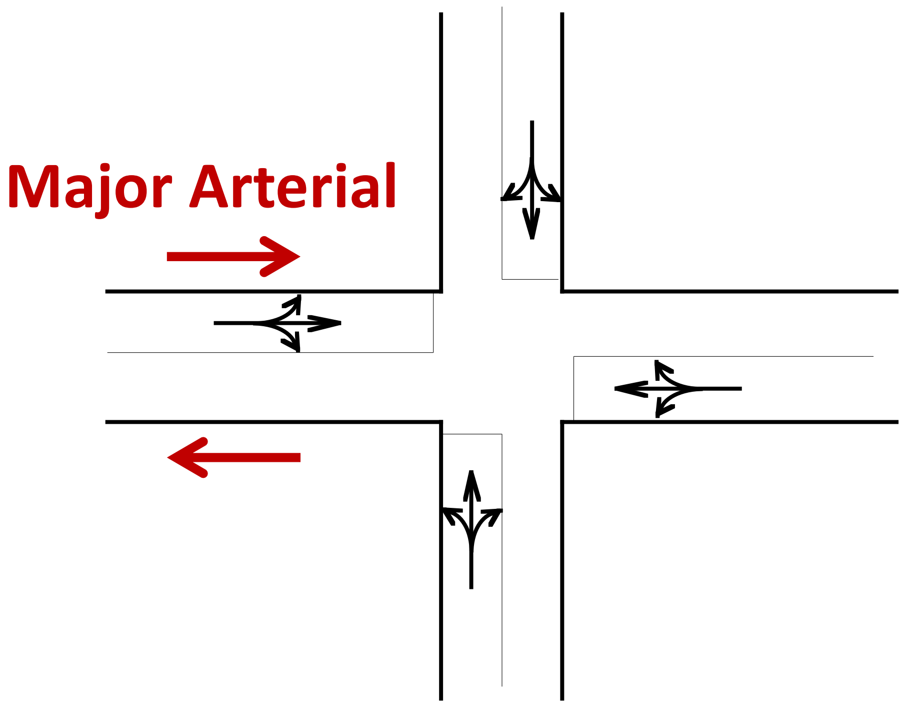


ref.) *"Traffic Signal Manual"* (1994), JSTE in Japanese

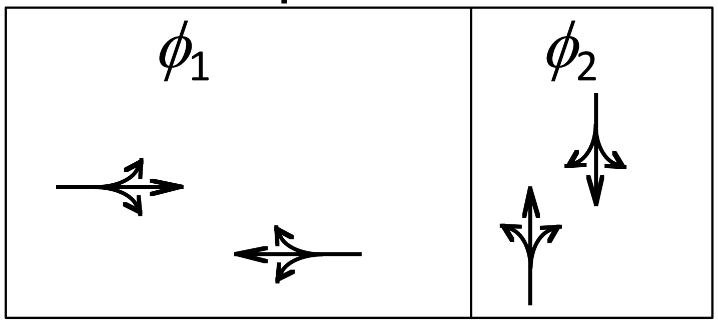
2. Popular applied signal control theory and practice in Japan

Signal phase

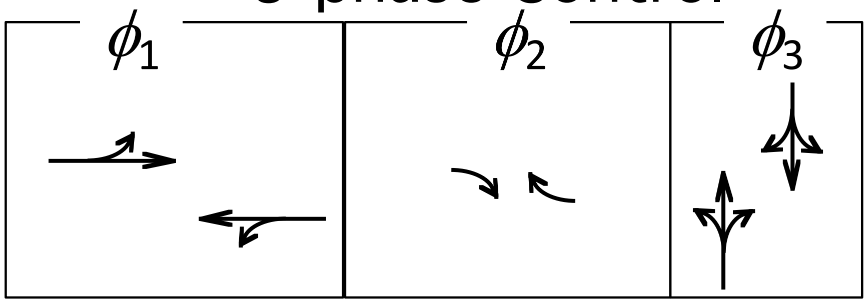
The part of signal cycle allocated to any combination of movements receiving the right-of-way simultaneously.



2-phase Control



3-phase Control



2. Popular applied signal control theory and practice in Japan

Signal control parameters

Cycle length: C [sec]

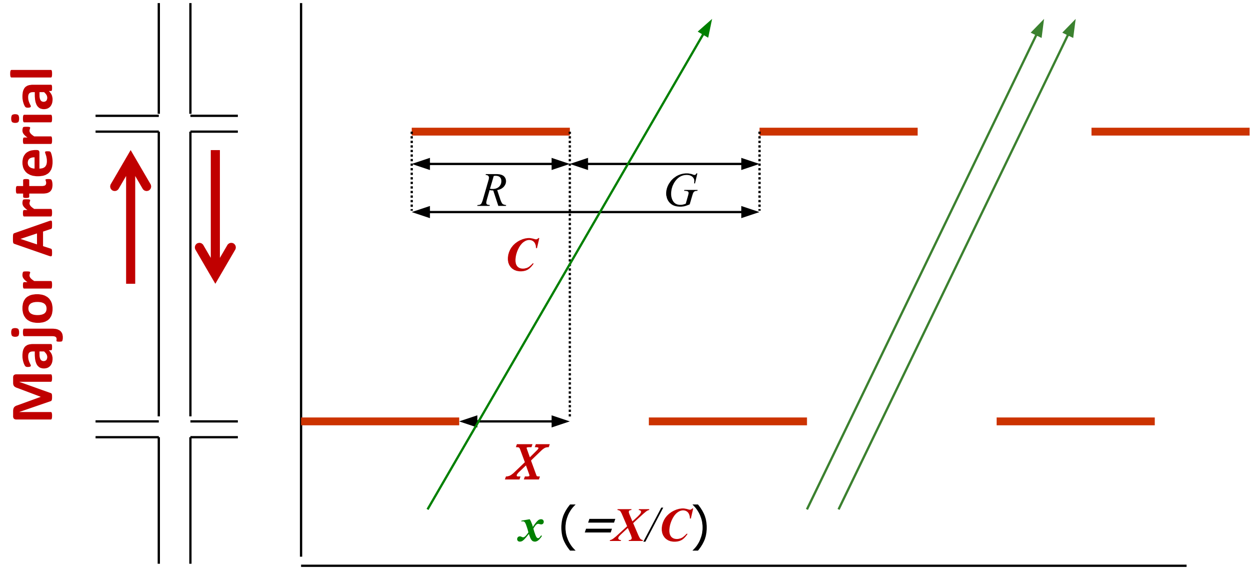
Time duration of one cycle of signal phases

Green Split: g [%] (=G/C, G: effective green time [sec])

Time ratio of one green duration out of the cycle time

Offset: x (=X/C) [%]

Time difference (ratio to C) of green start between two **adjacent** intersections



2. Popular applied signal control theory and practice in Japan

Minimum & Optimum cycles

Uniform arrival

$$C_{min} = \frac{L}{1-\rho}$$

Random arrival

$$C_{\text{poi}} = \frac{1.5L+5}{1-\rho}$$

➔ $$C_{gen} = \frac{a_1 L + a_2}{1 - a_3 \rho}$$

Example: when L=10[s], ρ=0.8, then

Cmin = 50 [s]

Cpoi =100 [s]

Cycle is determined at the critical intersection, and applied as a common cycle for all intersections in the group

In reality;

- Capacity is important for 'high-demand' condition.
  ➔ random arrival hypothesis is not acceptable
- Arrival patter is controlled by up-stream intersection when the displacement between two intersections are close
  ➔ Real optimality may exit between C_{min} & C_{poi}

Cycle Length Determination Example

Conditions

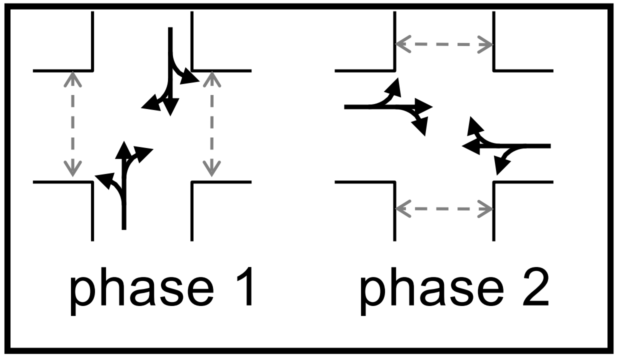
each lost time for one signal change is 5 [s]

→ ΣL=10 [s], $\mu_1=\mu_2=\mu_3=\mu_4$=1800 [veh/hr]

λ_1=900 [veh/hr], λ_2=400 [veh/hr],

λ_3=300 [veh/hr], λ_4=450 [veh/hr]

Phase plan



phase 1: ρ_1=900/1800=0.5

Phase 2: ρ_2=450/1800=0.25

intersection: $\rho=\rho_1+\rho_2$=0.75

$$C_{min}=\Sigma L/(1-\rho)=10[s]\div(1-0.75)=10\div0.25=40\ [s]$$

$$C_{poi}=(1.5\Sigma L+5)/(1-\rho)=(1.5\times10+5)\div(1-0.75)=20\div0.25=80\ [s]$$

3. Signal coordination and area-wide control in Japan

Spatial classification

- Isolated signal control
- **Arterial coordination**
- **Network coordination**

Control classification

- Pre-timed control
  - Single-program pre-timed control
  - Multi-program pre-timed control
- **Responsive control**
  - **Program selection control**
  - **Program formation control**

3. Signal coordination and area-wide control in Japan

Multi-program pretimed control ... widely used

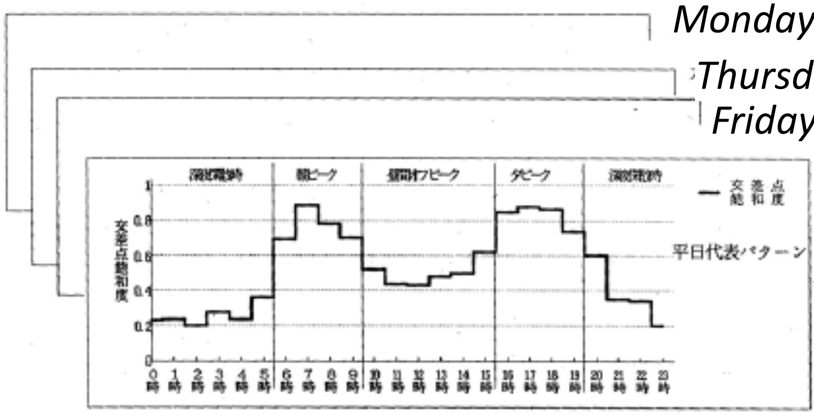
One of the pre-determined programs (phase plan and parameters) is implemented according to time of day & day of week.

flow ratio of intersection

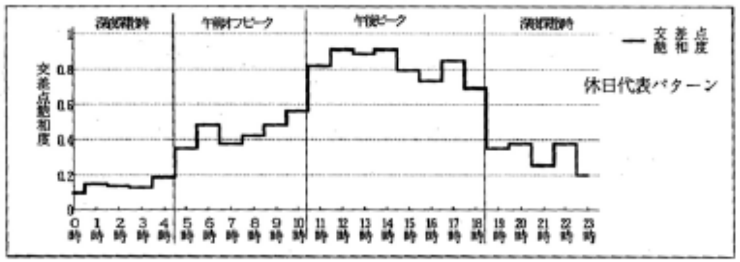
Monday

Thursday

Friday



Typical weekday pattern



Typical weekend pattern

➔ Predetermined Coordination Control
applied at 26,010 [unconnected/coordinated], 914 [push button]

3. Signal coordination and area-wide control in Japan

Responsive control

- Control parameters are selected or calculated depending on the traffic situation measured by roadside detectors [🡐 replacement with Probe].

- Macroscopic / microscopic response
  - example of microscopic response [semi-actuated, full-actuated]
    right-turn vehicles, bus, train or trams, pedestrian
  - example of macroscopic response [traffic responsive control by **TCC**]
    arterial-based; selection or generation of parameters cycle, split & offset;
    over-saturated arterial application exists.

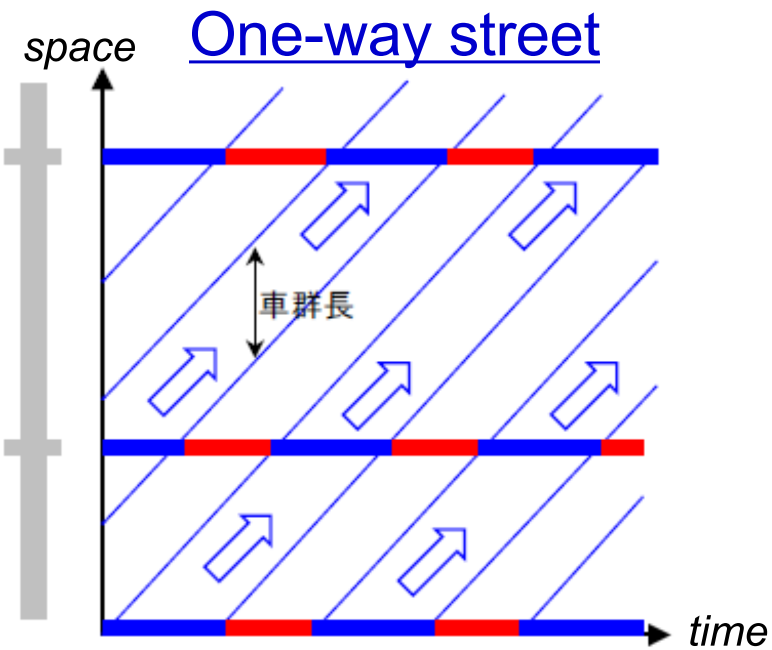
🡒 **Control by Centralized Traffic Control Centers**
applied at 73,684 intersecitions

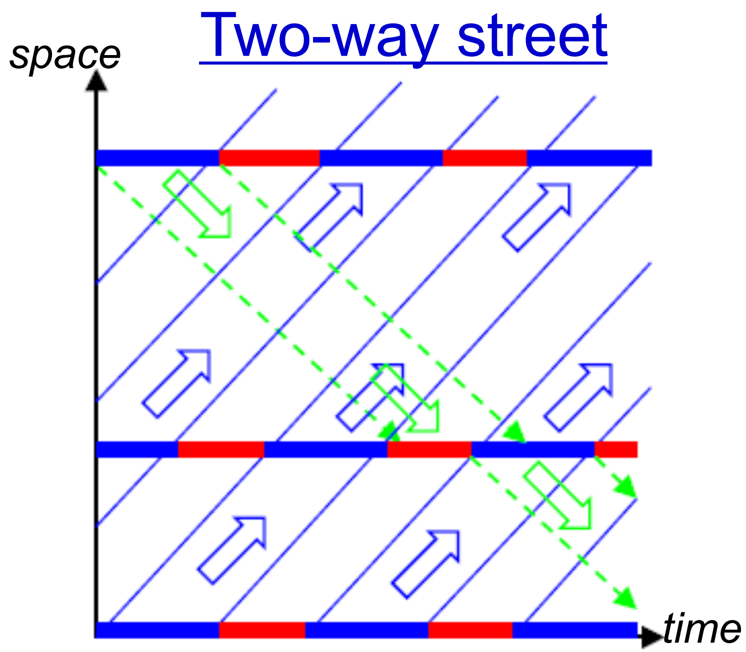
3. Signal coordination and area-wide control in Japan

One-way street:
  optimum offset = travel time between intersections

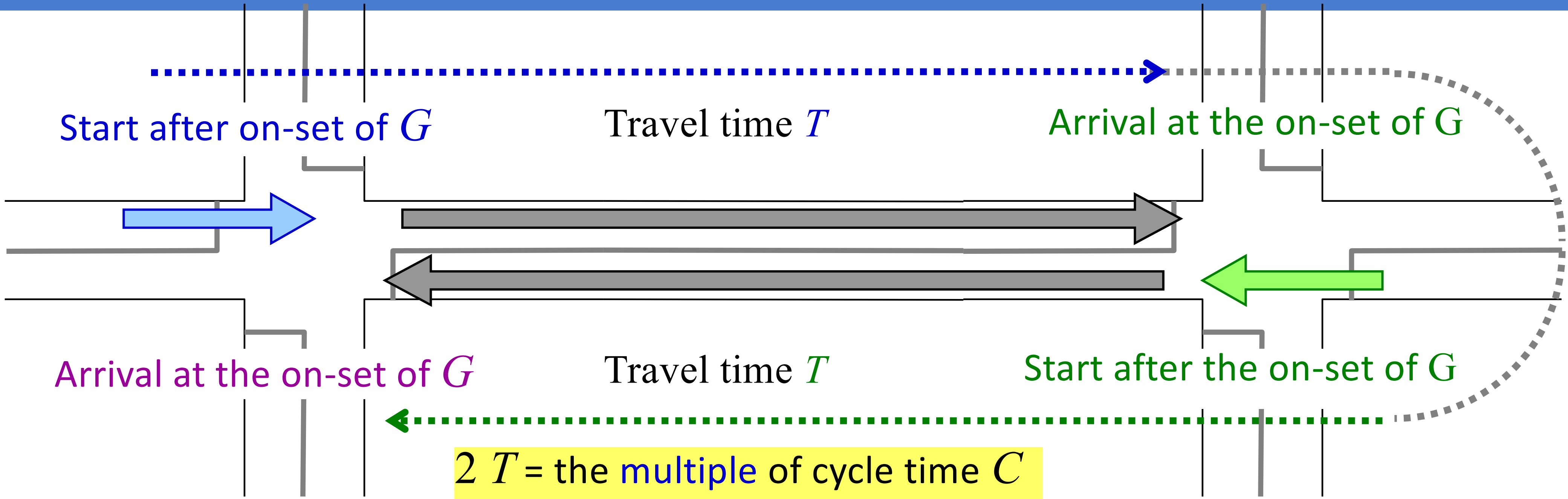
Two-way street: optimum offset = ?
  need to consider traffic in both direction

- Cycle time have to be the same among coordinated intersections, then coordination is kept.





3. Signal coordination and area-wide control in Japan



$2\ T$ = the multiple of cycle time C

ex.) conditions: C = 60 [s], Travel sped = 30 [km/h] = 8.33 [m/s]

T=L/V

multiple =1 : T = 30 [s] → best coordination for the distance 250m

=2 : T = 60 [s] → 500m

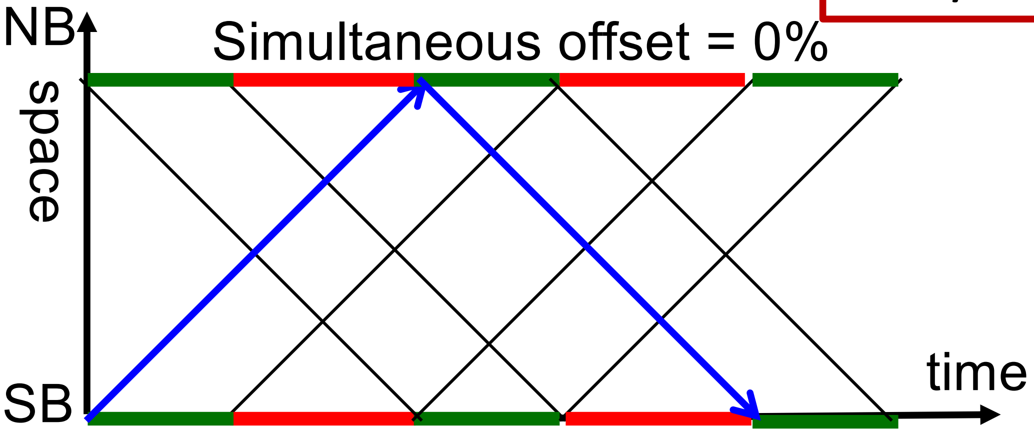
=3 : T = 90 [s] → 750m

On the other hand, at the multiple of 0.5, 1.5, ...,there is no way to coordinate for both directions.

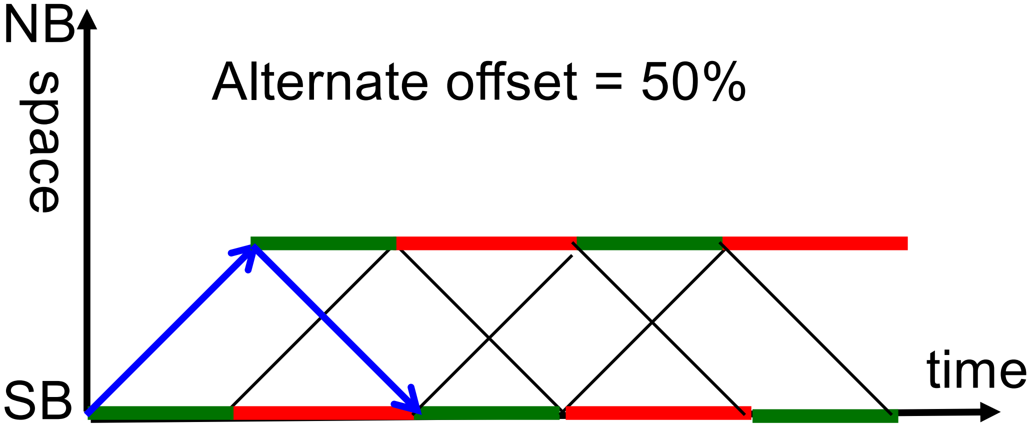
3. Signal coordination

T*=*L*/*V

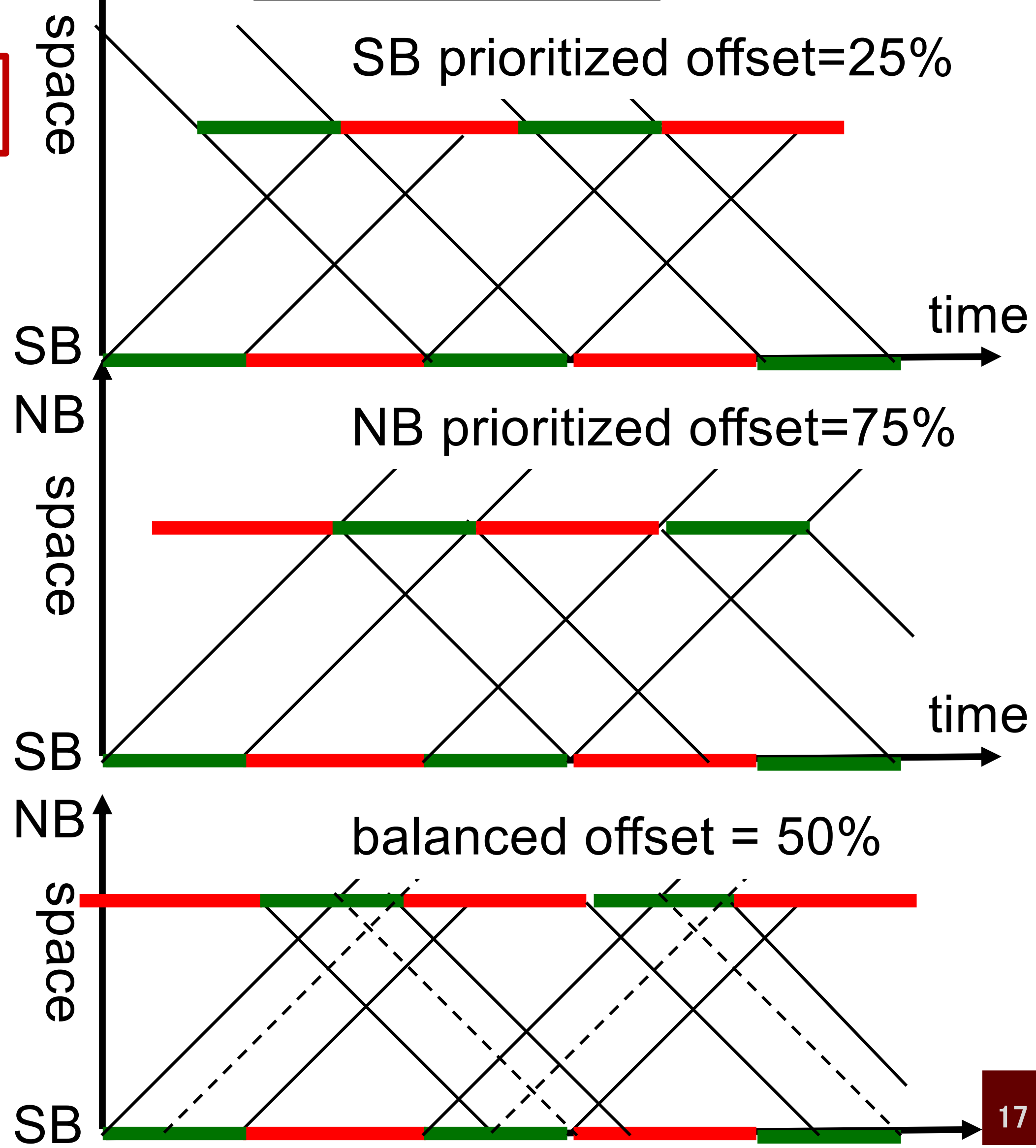
Case: $2T = 2C$



Case: $2T = C$



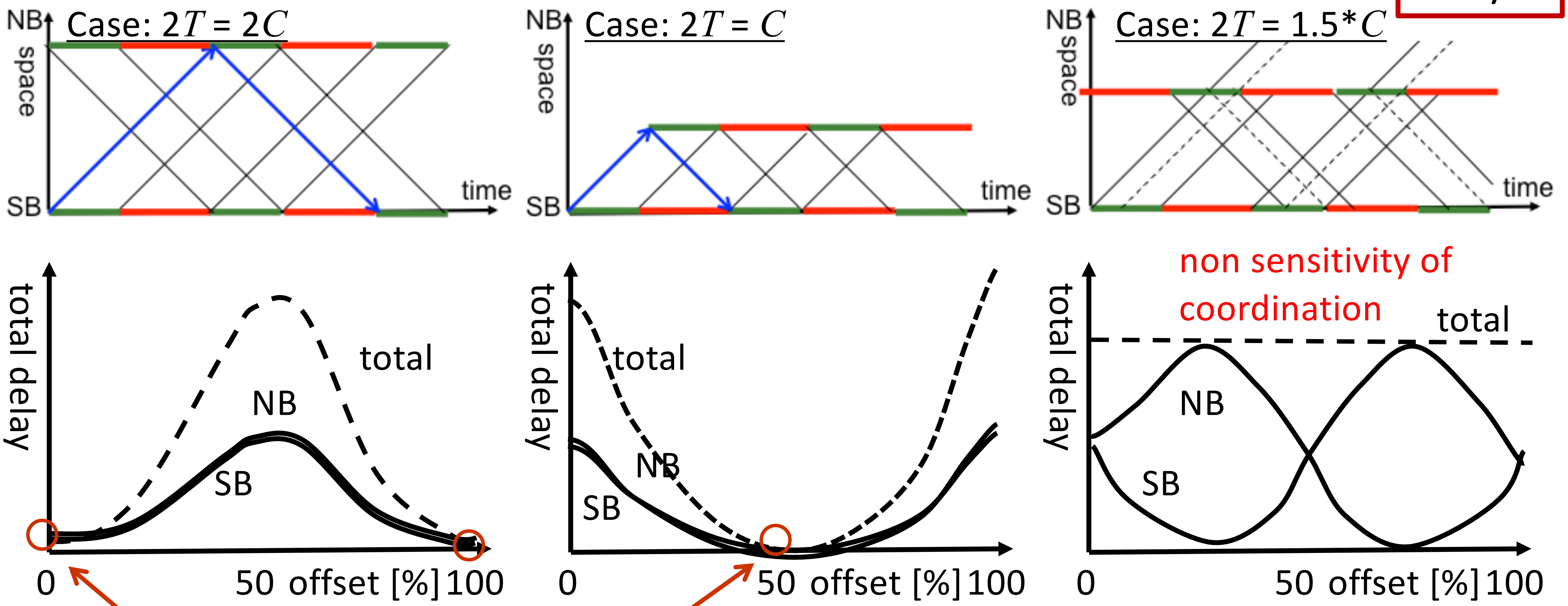
Case: $2T = 1.5*C$



3. Signal coordination

Coordination effects on control delay

T*=*L*/*V



Simultaneous offset = 0%

Alternate offset = 50%

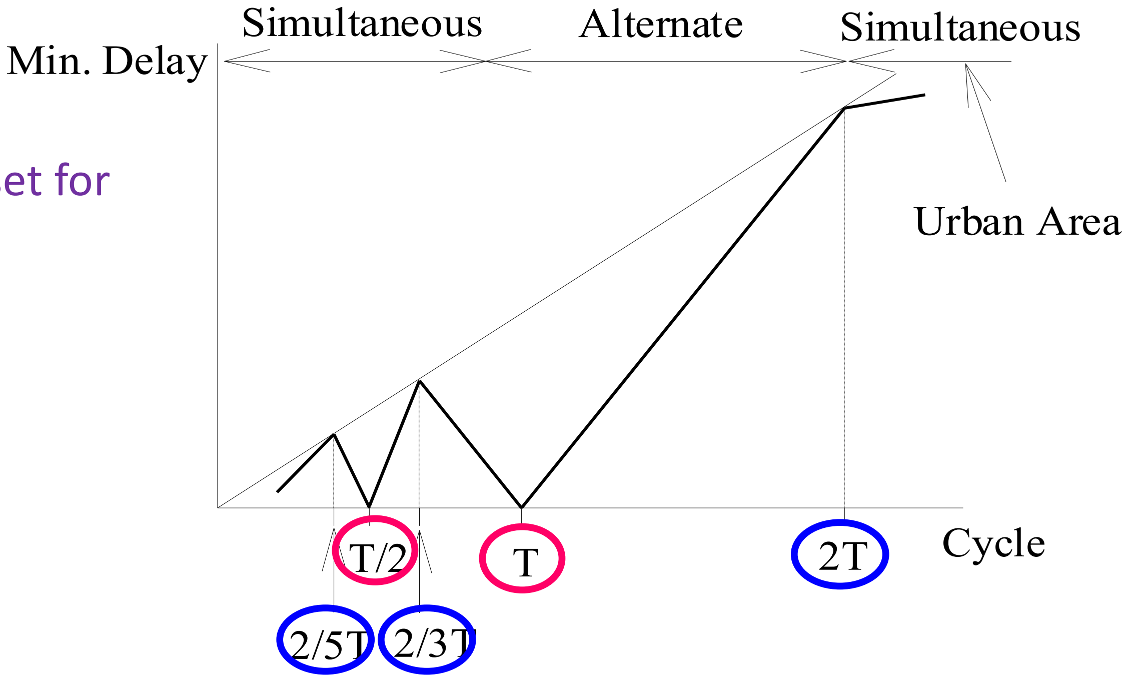
3. Signal coordination

Cycle length and minimum delay; discussion with 50% green split.
(written in Japanese signal manual)

$T = L / V$

$$\begin{cases} C = \dfrac{T}{n} & \text{High coordination effect} \\ C = \dfrac{2T}{2n-1} & \text{Low coordination effect} \end{cases}$$

delay with optimized offset for the given cycle time



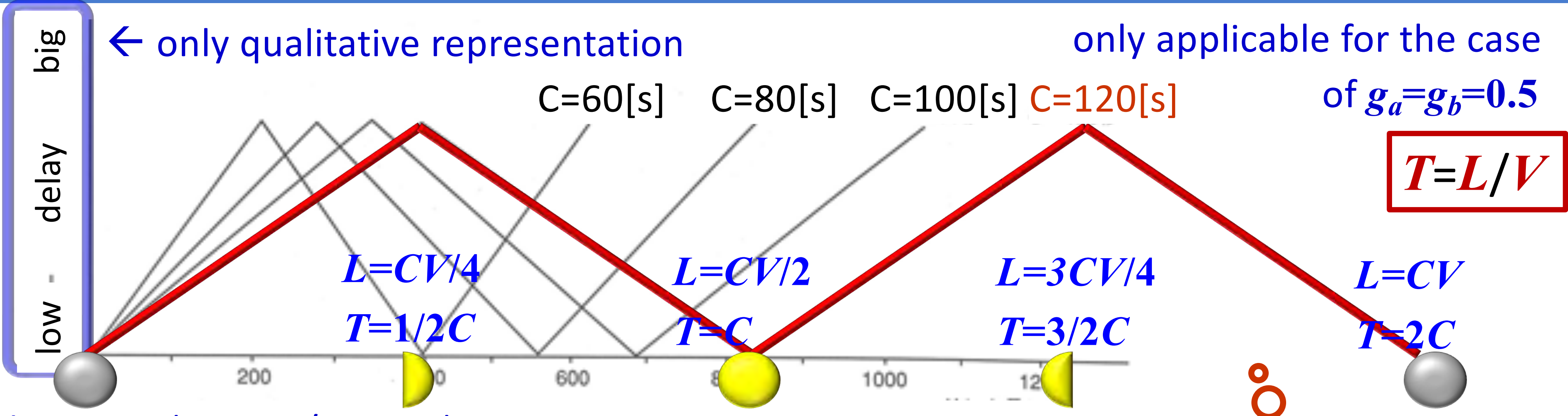
If link distance is long or cycle length is short, C become less than $2T$ and **coordination effect** can be fully achieved.

If traffic is heavy and a queue is formed at a bottleneck intersection, the **coordination effect** become small.

[original work] Koshi (1975) J. JSCE, in Japanese

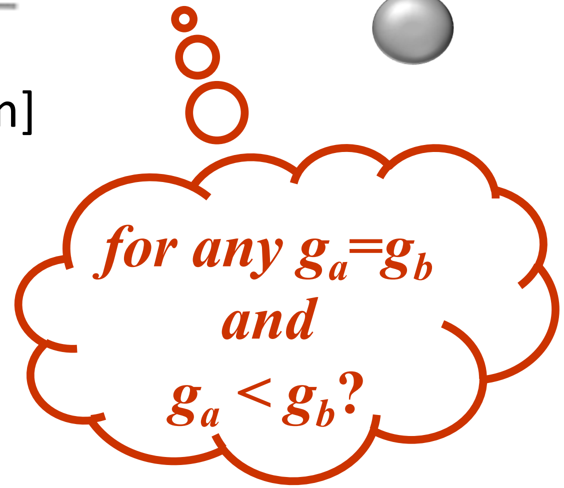
ref.) M. Koshi (1989): Cycle time optimization in traffic signal coordination. Transportation Research, 23A, 29-34

3. Signal coordination



Like moon (waxing/waning)

round-trip travel time T	coordi-nation effect	cycle [s]						
		60	70	80	90	100	110	120
$T=C/2$	small	208	243	278	312	347	383	417
$T=C$	large	417	486	556	625	694	764	833
$T=3C/2$	small	625	729	833	937	1042	1146	1250



[original concept] Koshi (1975) J. JSCE, in Japanese

ref.) "Traffic SIgnal Manual – Revised Version" (2016), JSTE, in Japanese

3. Signal coordination

Assume Demand=Capacity

*Source: H. Sakakibara and T. Oguchi (2016):
Study of offset control between 2 intersections.
JSTE Journal of Traffic Engineering, 2(6), 1-10 (in Japanese)

in the case of $g_a=g_b=0.5$,

➔ High coordination effect $L_h = (CV/2), CV, (3CV/2), 2CV, ...$

➔ Low coordination effect $L_l = (CV/4), (3CV/4), (5CV/4), (7CV/4), ...$

just middle point between adjacent two L_h

[M. Koshi (1975): The Optimal Control of Traffic Signal, IATSS Review, 1(1), 43-51 in Japanese]

in general case of the same green splits $g_a=g_b=g$,

set N: natural number, V: travel speed, g: green split

➔ High coordination effect link length $L_h = (CV/2)*N$

➔ Low coordination effect link length $L_l = (CV/2)*(g + N-1)$

[original findings]

3. Signal coordination

Assume Demand=Capacity

*Source: H. Sakakibara and T. Oguchi (2019):
Study of offset control between two intersections with different green time.
JSTE Journal of Traffic Engineering, 2(6), 1-10 (in Japanese)

in general case of the same green splits $g_a \leqq g_b$

set $\Delta g = (g_b - g_a)$, $g = (g_b + g_a)/2$

N: natural num., V: travel speed, g_a, g_b: green split

i) when $g_b - g_a \geqq 0.5$ then

delay can be zero with appropriate offset for any link length L

ii) when $g_b - g_a < 0.5$ then

➔ High coordination effect link length L_h has a range of

$$(CV/2)*N - \Delta g < L_h < (CV/2)*N + \Delta g$$

➔ Low coordination effect link length $L_l = (CV/2)*(g + N\text{-}1 + R)$

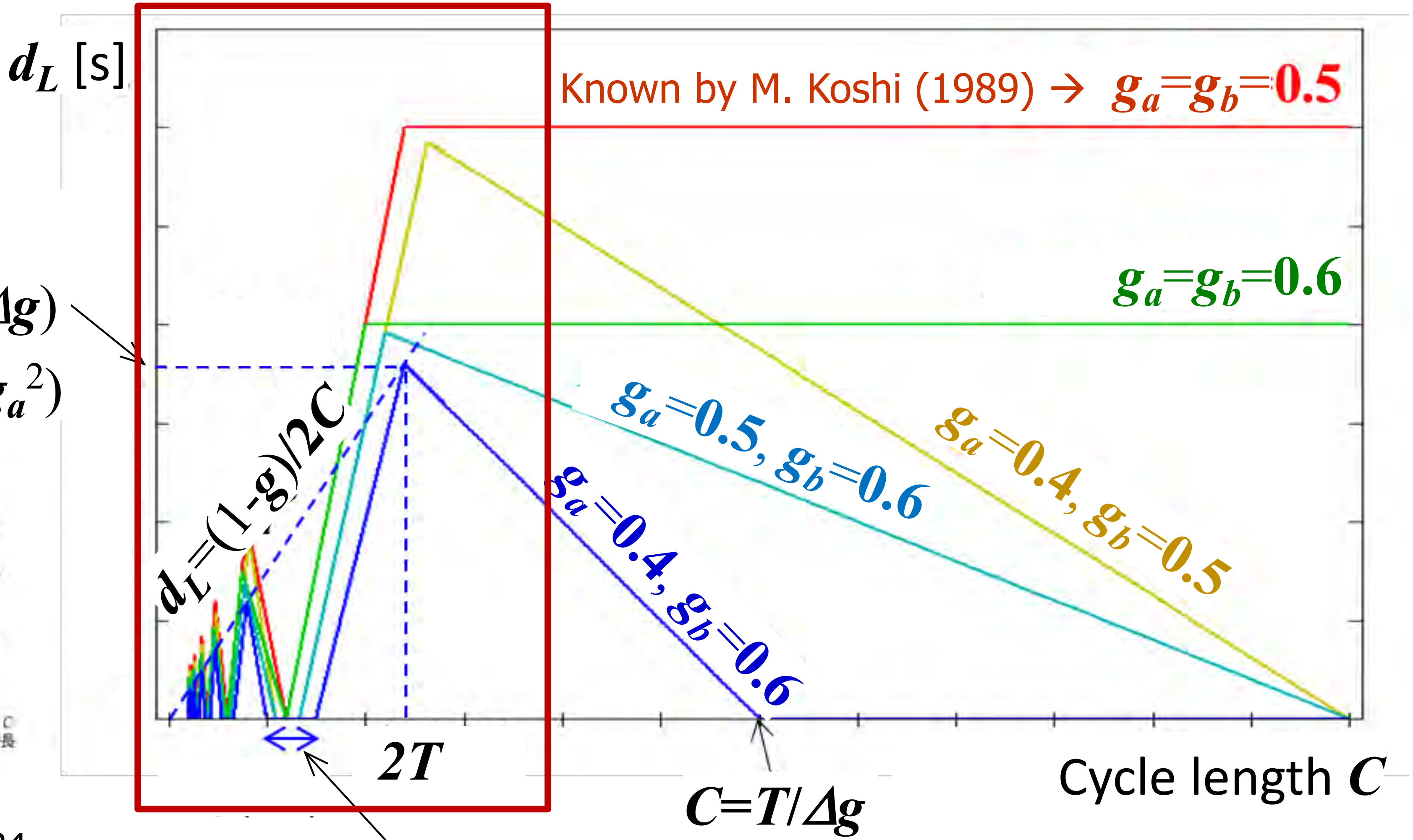
where $R = [\Delta g\,(1 - 2g)]/[2(1 - 2g)]$

[original findings]

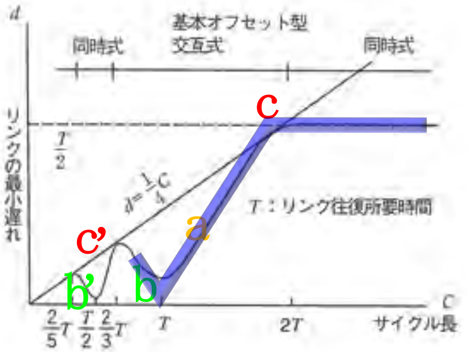
3. Signal coordination: Relationship C and average delay d_L

$T = L/V$

$$d_{Lopt} = T(1 - g_b)(1 - 2\Delta g) \div 2(g_b - (g_b^2 - g_a^2))$$

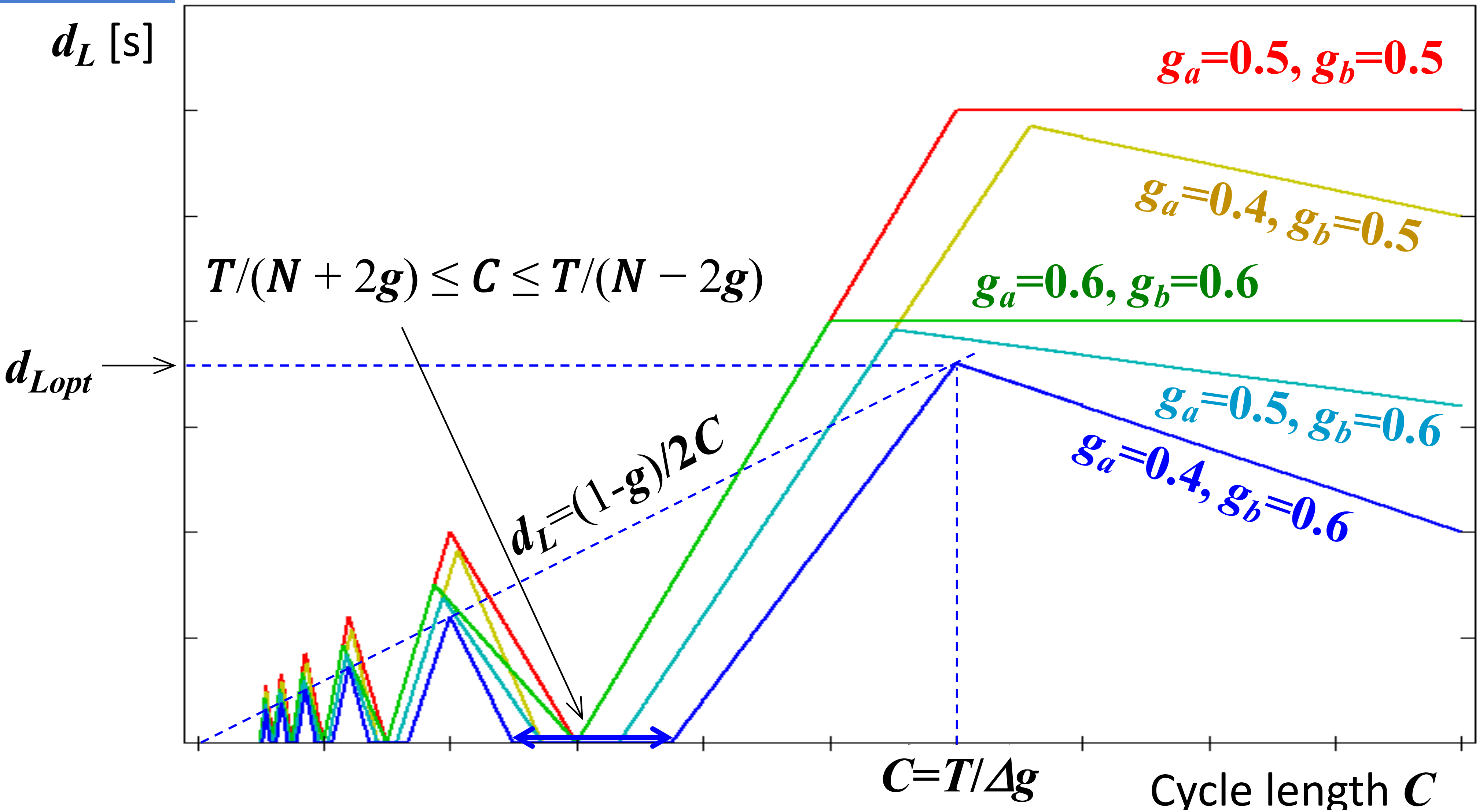


$$T/(N + 2g) \leq C \leq T/(N - 2g)$$



M. Koshi (1989): Transp. Res., 23A, 29-34

3. Signal coordination: Relationship C and average delay d_L



3. Signal coordination

Offset pattern selection method

- maximum change of 1/8 of cycle length for avoiding suddle large change

  positive change (0 – 50 %)

  negtive change (50 – 100 %)

- changing direction should be carefully determined for adjacent links to avoid "reverse offset pair"

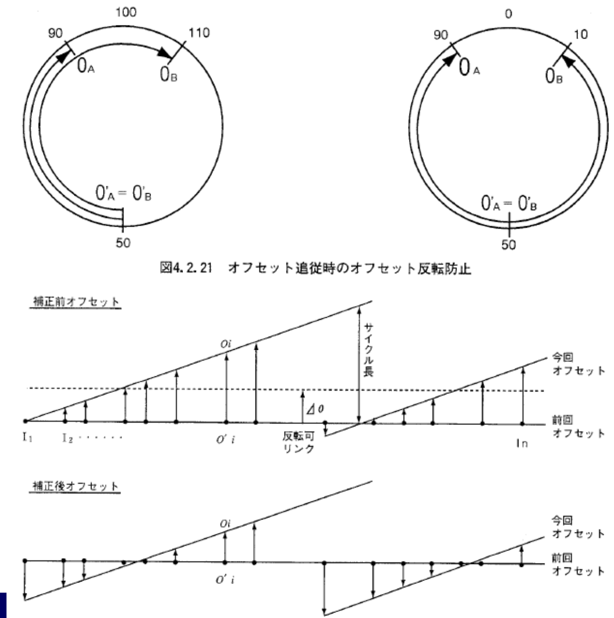
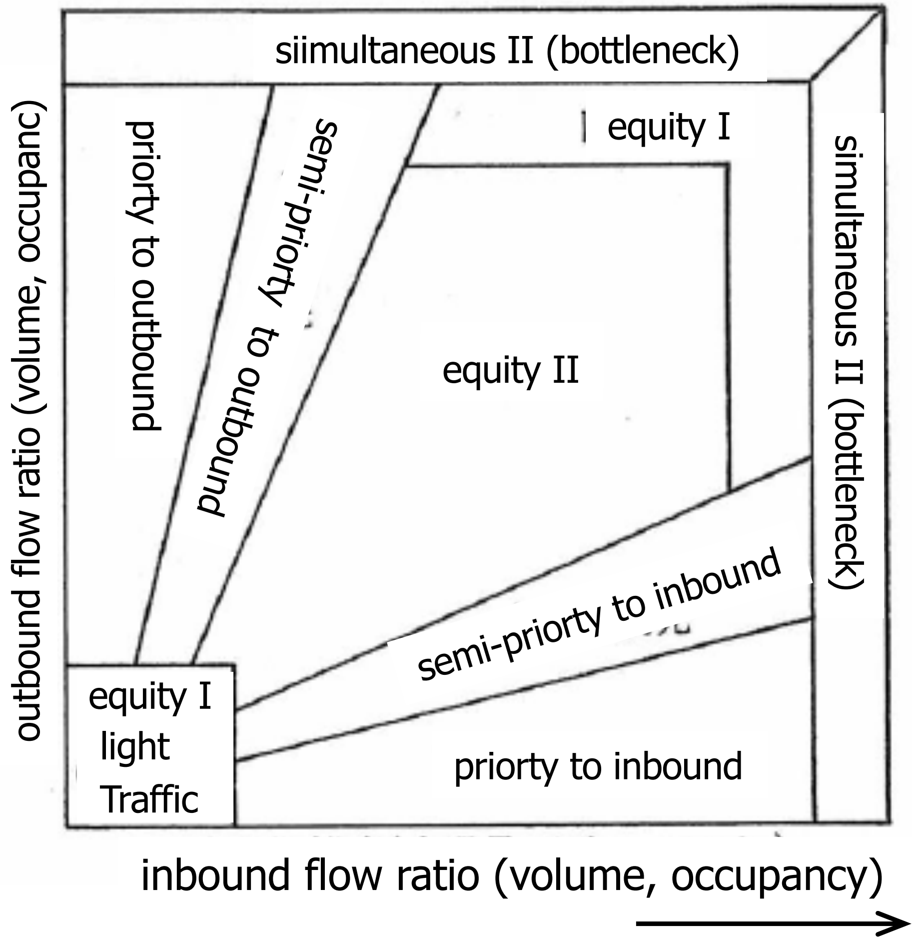


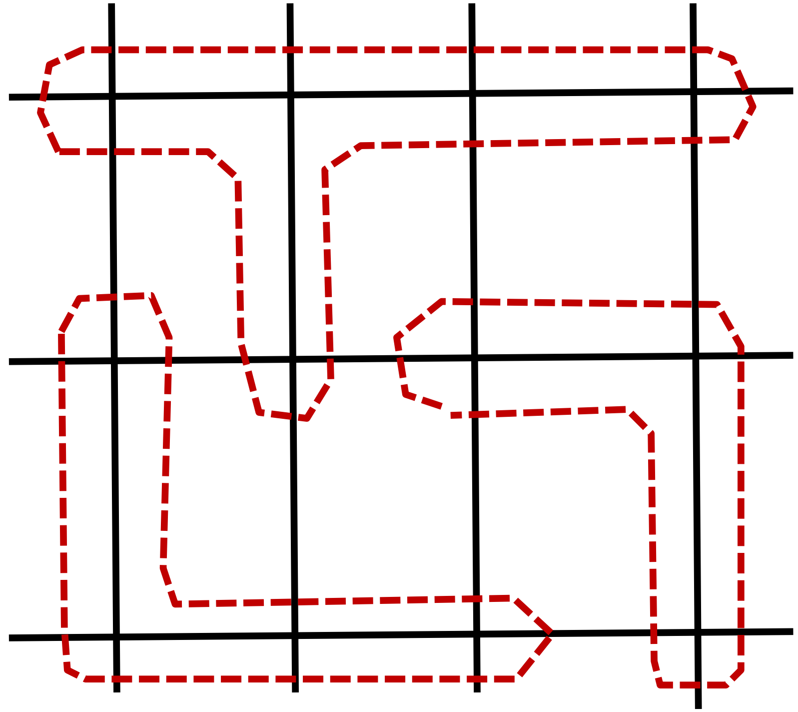
図4. 2. 21　オフセット追従時のオフセット反転防止



3. Signal coordination

Area-wide control:

- Strategy: no-loop formation
  to avoid "**offset annexation**"
  ➔ creation of "**subnetworks**"
  to let any subnetwork form
  a **tree structure** (w/o loop)



Each subnetwork has unique common cycle time C, and define green splits and offsets for intersections in the subnetwork.

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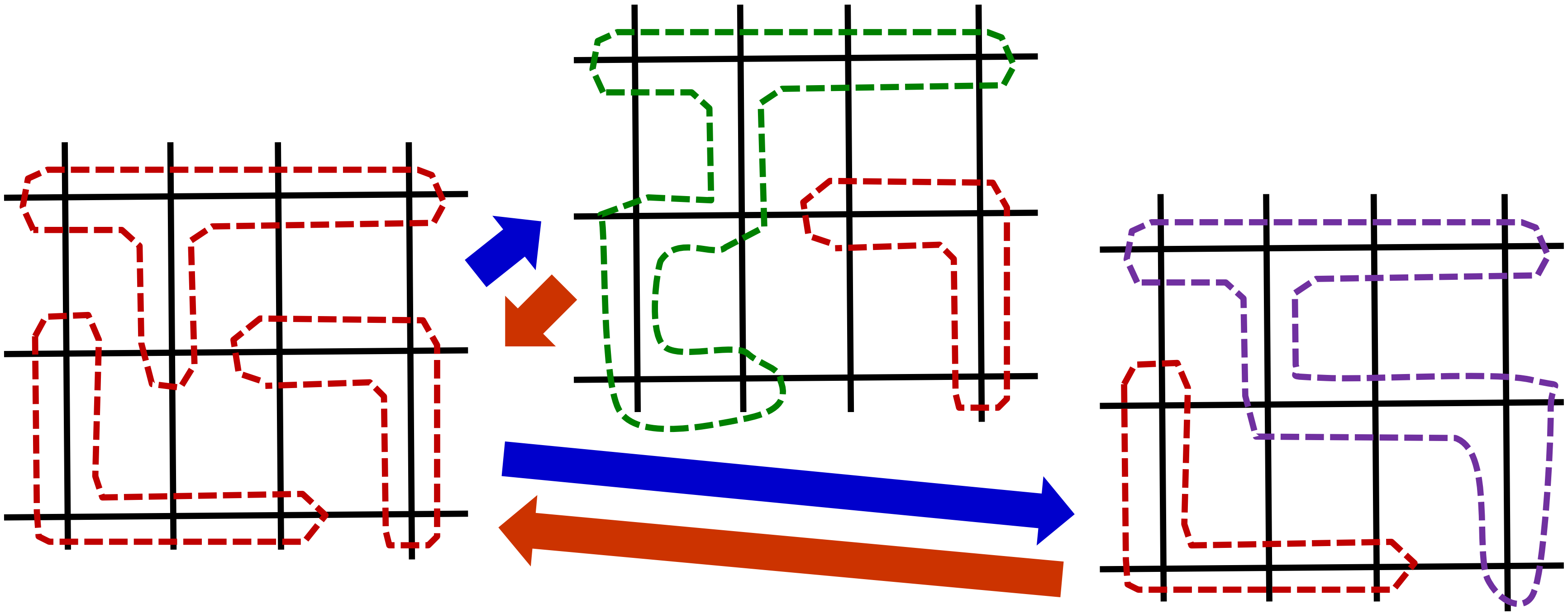
Oguchi LAB Traffic ENGINEERING GROUP

3. Signal coordination and area-wide control in Japan

Area-wide control:

- "**connection**/**disconnection** of adjoining subnetworks"
  become another upper level optimization problem.
  → basically add-hoc/rule-of-thumb ...

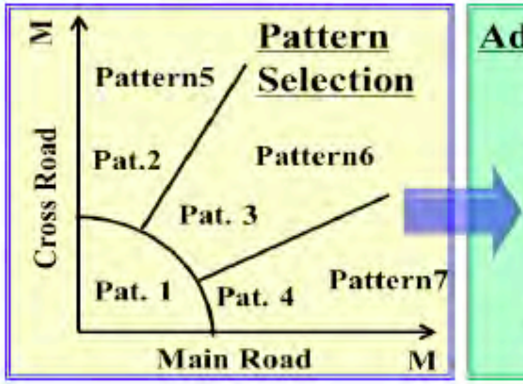
<u>No comprehensive optimization problem are not defined yet.</u>



4. Traffic responsive coordination control

Development of **TCC** by Tokyo Metropolitan Police Department (MPD)

Year	Split Calculation	Split	Cycle Length	Offset
Before 1995	Every 300sec.	Pattern Selection	Pattern Selection	Pattern Selection
1995	Every 150sec.	Adaptive	Adaptive	
2007	Every 50sec.	Algorithm Development		Real Time Simulation
2009		Traffic Demand Prediction		



Adaptive : calculated by formulas or simulations

Load Ratio (Lri) = Max{Lri1, Lri2}

Split(phase i) (SPi) = Lri / Σ (Lri)

Cycle Length(Cy) = 1.5 · Loss / {1.0 − Σ(Lri)}

Loss : Loss Time

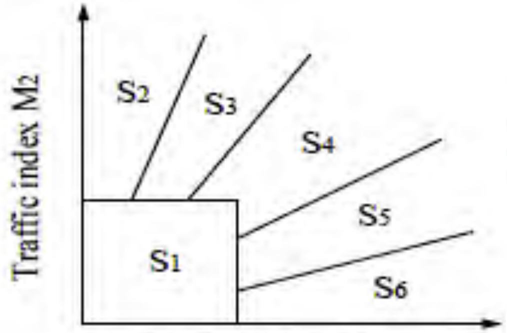
Offset : Real Time Simulation

ref.) K. Takahashi, H. Sakakibara, M. Naruse (2013): Effects and future plans for sophisticated MPD traffic control system / signal control, Proc. of 20th ITS World Congress 2013.

4. Traffic responsive coordination control

STREAM (**ST**rategic **REA**ltime control for **M**egalopolis-traffic)

- A system in Tokyo Metropolitan Police Department (MPD) started 1995
- Pattern selection control (cycle, split, offset) with Load Ratio (ρ); applicable in the case of over-saturation



Traffic index M_1

S_K: Split pattern number

$M_{ij} = \alpha \cdot Q + \beta \cdot O$

$M_i = \mathrm{Max}(M_{i1}, M_{i2})$

i = Road, j = Approach

$$\rho = (Q_{in} + r \cdot k \cdot E) / s \quad (2$$

Where

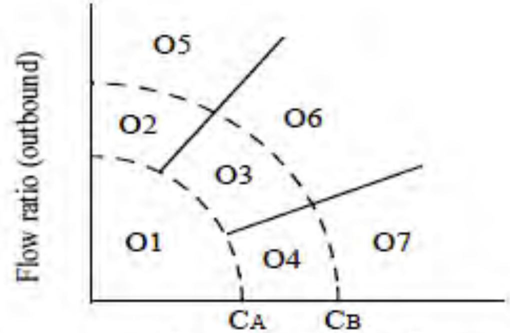
Q_{in} : Inflow [veh/2.5 min]

E : Vehicles in queue [veh]

s : Saturation flow [veh/2.5 min]

k : Usage ratio of E ($0 < k \leqq 1$) [1/2.5 min]

r : Usage ratio of E when vehicles are queued ahead ($0 \leqq r \leqq 1$)



Flow ratio (inbound)

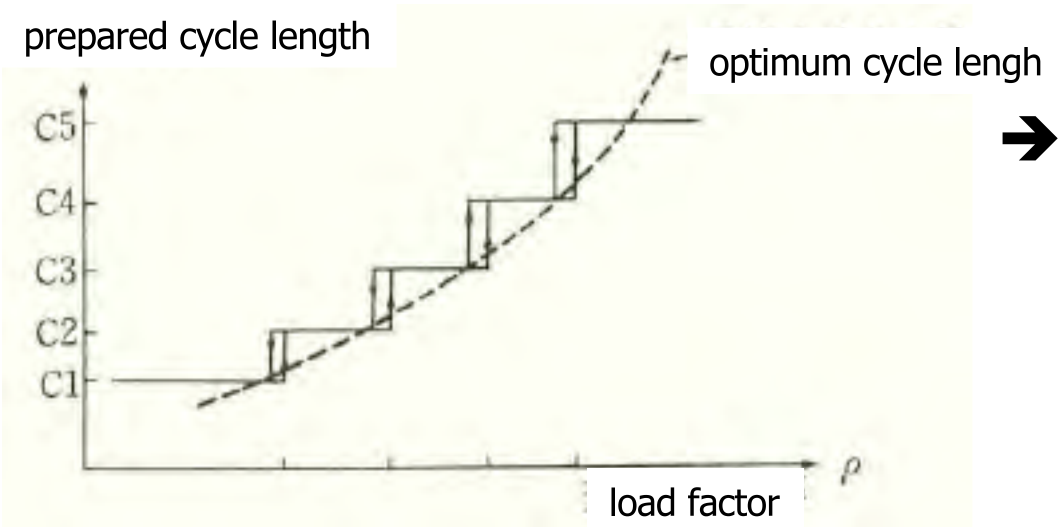
C_A, C_B: Sub-area cycle length

O_i: Offset pattern number

ref.) S. Miyake, M. Noda, T. Usami (1995): STREAM (Strategic Realtime Control for Megalopolis-Traffic) Advanced Traffic Control System of Tokyo Metropolitan Police Department, Proc. of 2nd ITS World Congress 1995.

MODERATO (**M**anagement by **O**rigin-**DE**stination **R**elated **A**daptation for **T**raffic **O**ptimization)

- Firstly introduced in Tokyo MPD **TCC**, adaptive generation of cycle/split, and realtime simulation/pattern selection of offset
  - "Load Ratio": $\rho = (Q_{\mathrm{in}} + E)/s$ Q_{in}: demand, E: # of veh. in queue, s: saturation flow rate



$\Delta Q_{\mathrm{in}} \fallingdotseq \Delta Q_{\mathrm{out}} + E(t+\Delta) - E(t)$

➔ ρ should be replaced with "flow ratio"

- Green split
- Cycle: $C_{gen} = \dfrac{a_1 L + a_2}{1 - a_3 \rho}$
- Offset [under sat.] realtime simulation

  [over sat.] pattern selection

ref.) H. Sakakibara et., al. (1999): MODERATO (Management by Origin-DEstination Related Adaptation for Traffic Optimization), Proc. of 6th ITS World Congress 1999.

4. Traffic responsive coordination control

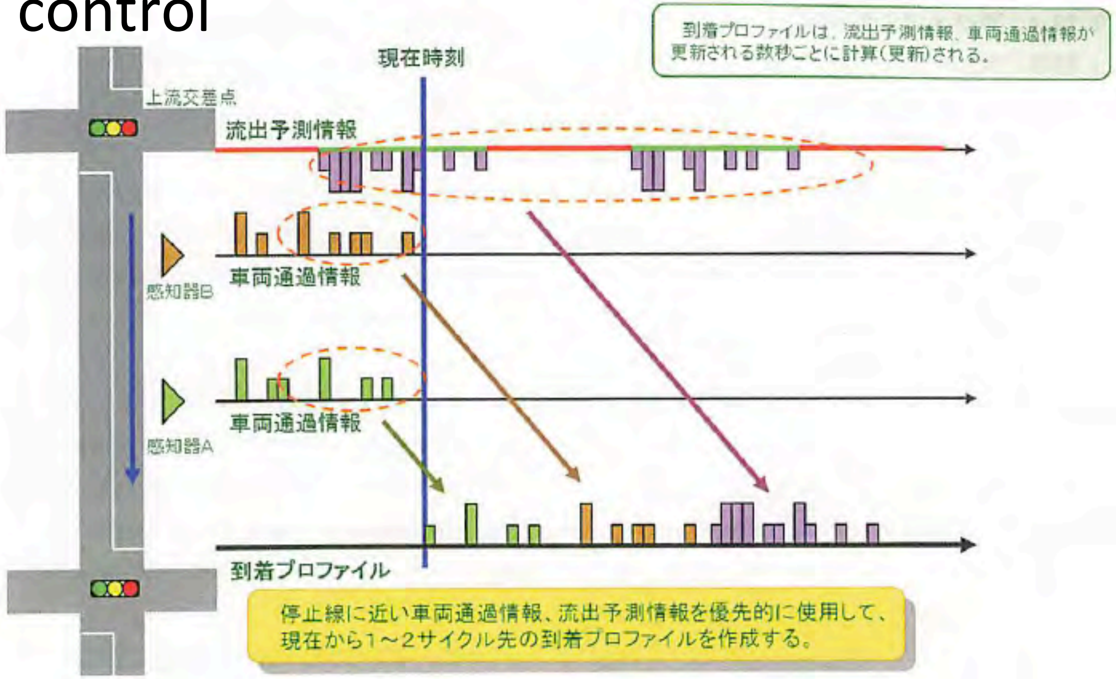
Automatic Offset Generation in STREAM (Tokyo MPD system) in 2007

- application of realtime simulation framework including congested flow

ref.) S. Kurosaki, S. Kawano, N. Kimura (2008): Introduction of automatic offset generation method considering safty and smooth, Proc. of 15th ITS World Congress 2008.

Arrival flow pattern prediction-based control

- tested at "Aichi World Exposition 2005" with 34 intersections
- update arrival flow pattern every several seconds.



Thank you