Implementation of Park-and-Rides to Reduce Road Emissions and Traffic Congestion: a Queuing Theory Approach

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Outline

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  - Results
- Emissions Model
  - Results
- Cost Comparison
  - Convenience vs. Environmental
- Conclusions

Introduction

ENERGY, SOLUTIONS

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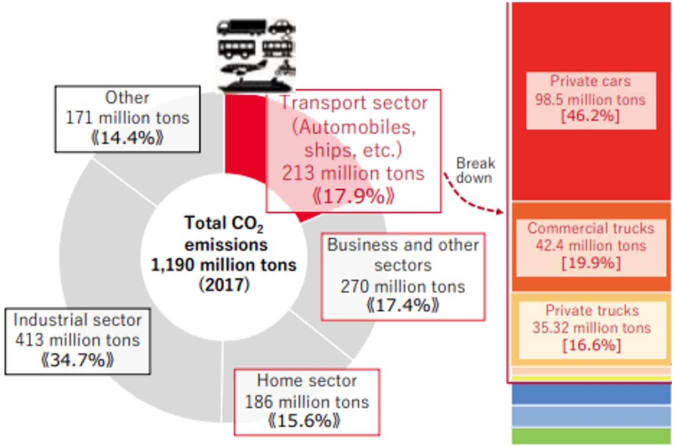

TOYOTA ENVIRONMENTAL CHALLENGE 2050

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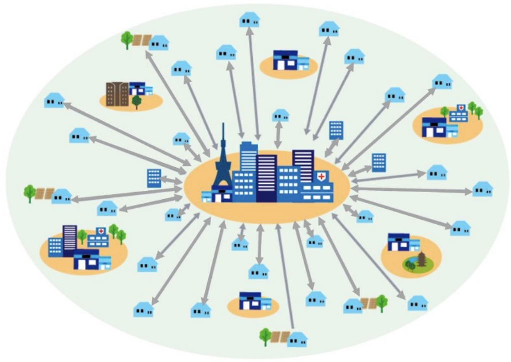
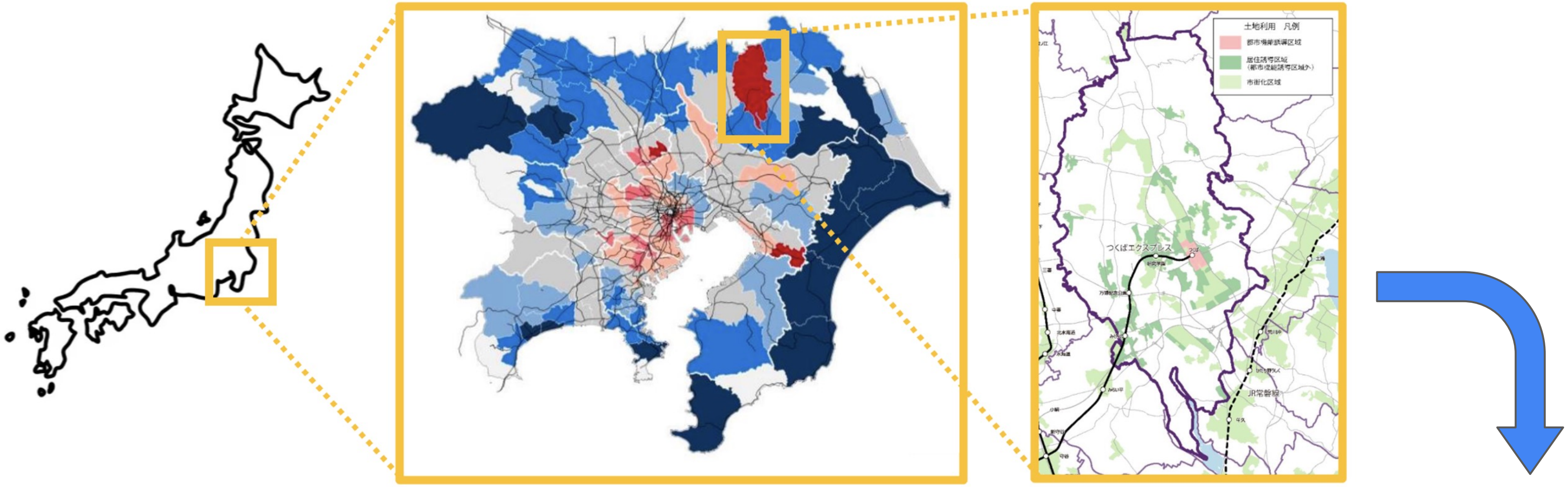
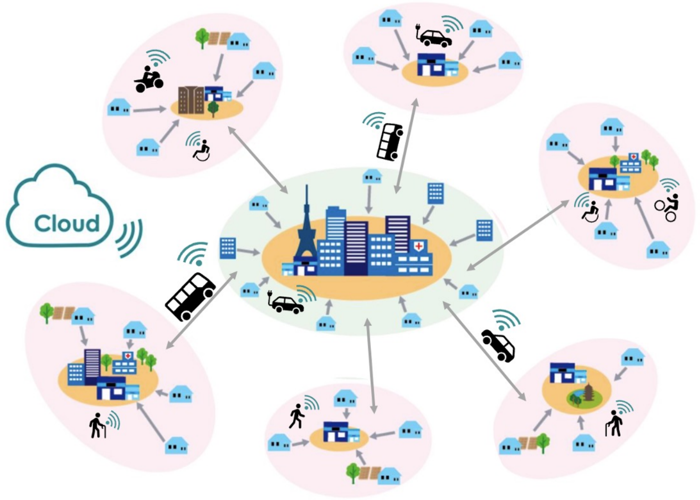


How can Tsukuba provide convenient, accessible, *and* sustainable public transportation?



Future trajectory:

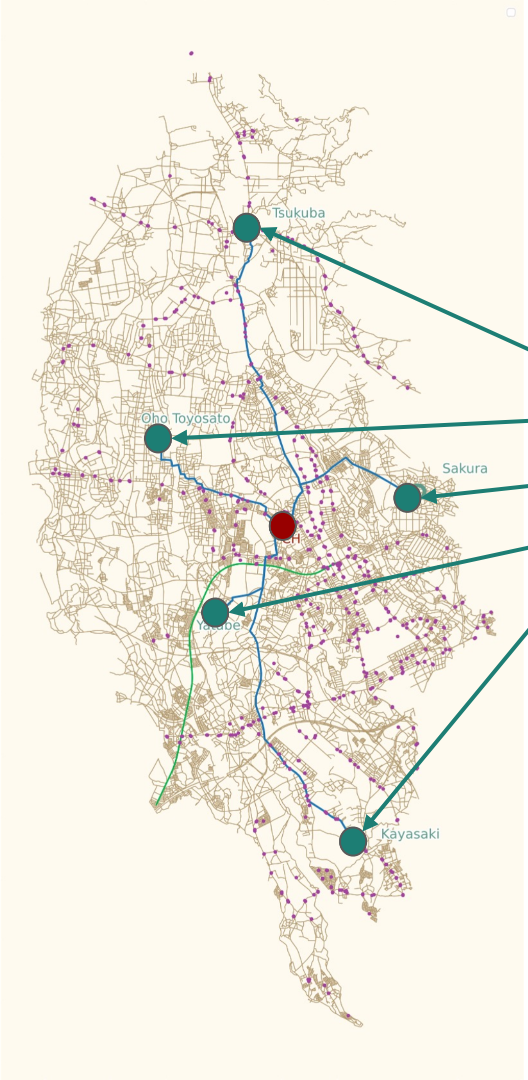
1. Smaller spheres of living
2. Local infrastructure
3. Fewer individual trips



Proposed Park-and-Ride

- Cost Comparison:
  - Convenience via Queueing Model
  - Environment via Emissions Model

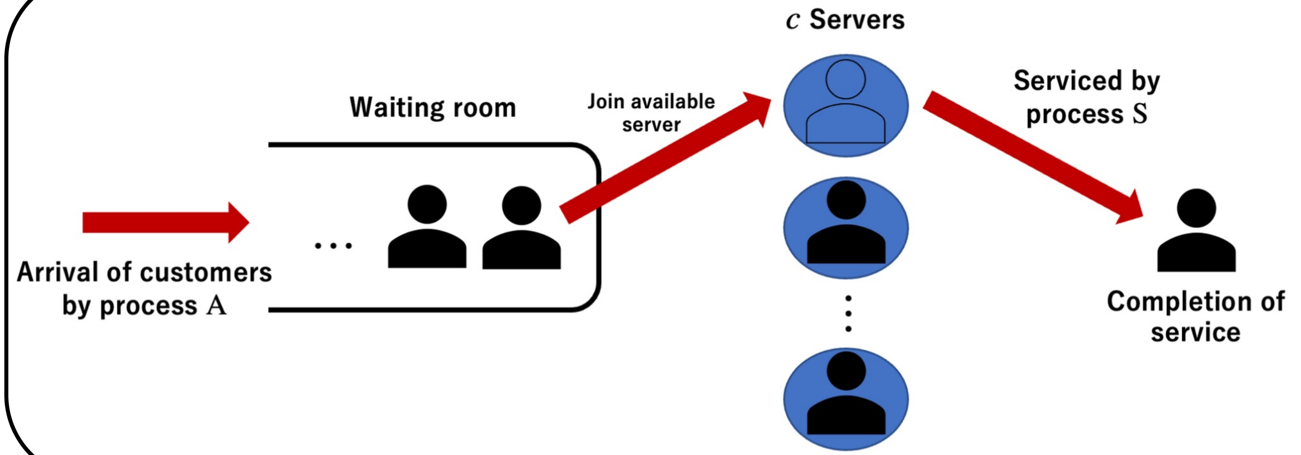
- Available Datasets:
  - Person Trip Survey
  - Bus Location



1. Mt. Tsukuba
2. Oho Toyosato
3. Sakura
4. Yatabe
5. Kayasaki

● Central Hub

Queueing analysis: A/S/ c queuing model



Examples of Kendall's notation

M : **Memoryless or Markovian**

D : **Deterministic (fixed)**

G : **General**

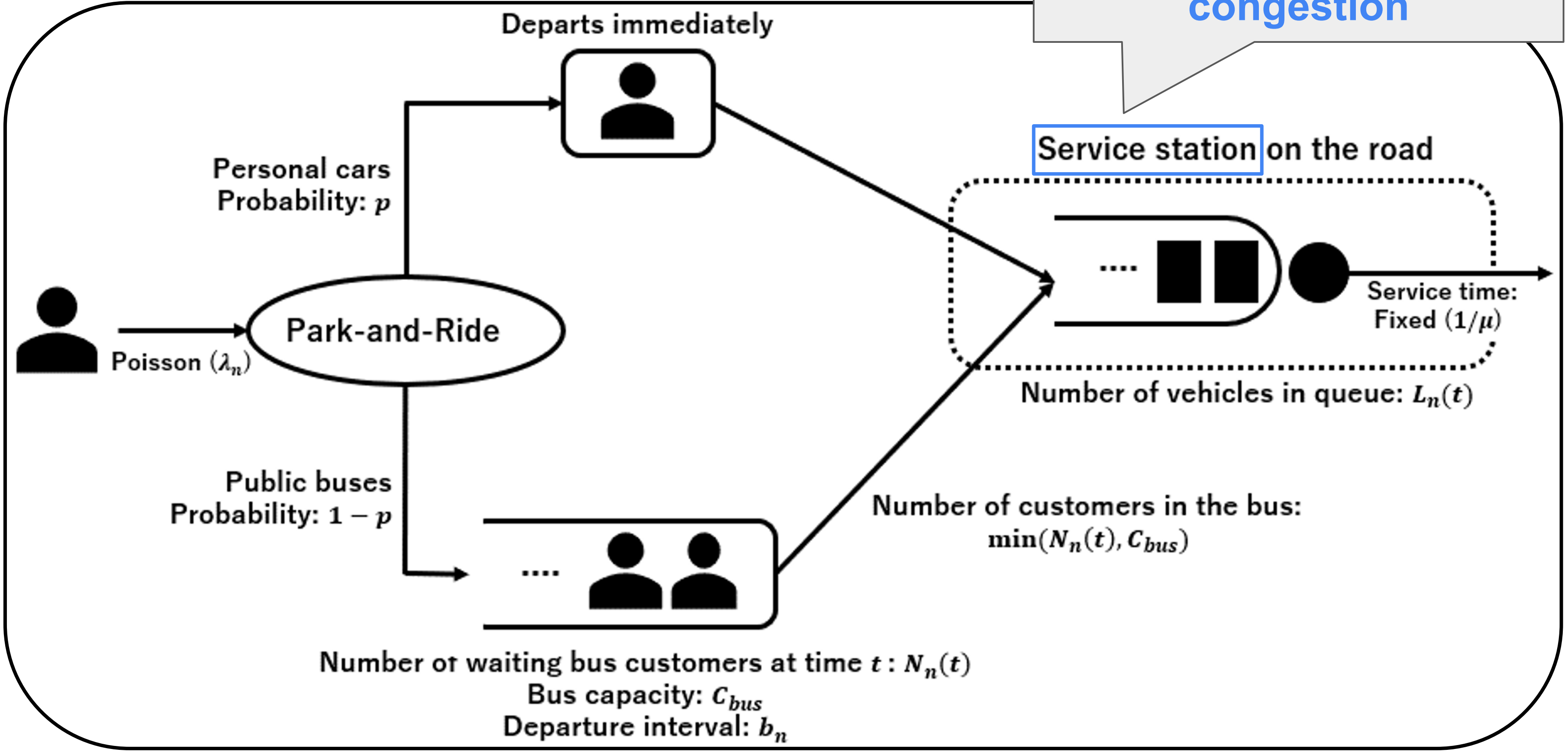
Modelling & Analysis

Performance measures (output):

Waiting time, Total time, Number of waiting customers, …

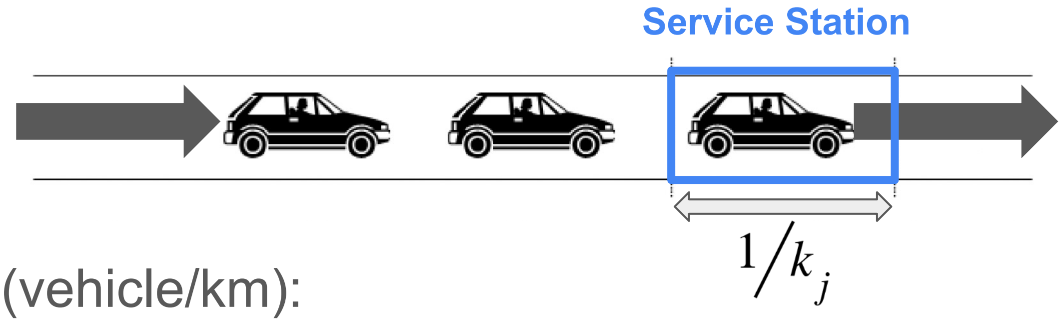
Queueing model for Park-and-Ride
(from Suburb n to the city center)

Virtual queueing model to express the traffic congestion



Traffic congestion model

(Van Woensel, 2007)



- Maximum traffic density k_j (vehicle/km):
  - Maximum number of vehicles on per unit road
  - → physical size of the service station = $1/k_j$
- Service station = **G/D/1** queue
  - **G**eneral arrival process
    - Convolution of arrival processes of cars and buses (numerically obtained)
  - **D**eterministic (fixed) service time = $1/\mu$
  - μ (veh/h) = v_{NS} (Nominal speed) (km/h) × k_j (vehicle/km)
  - T_n (h) = k_j × d_n (distance) (km) × R_n (sojourn time) (h/vehicle)

(main output:) Traveling time on road

Analysis of Park-and-Ride queueing model

- Under two **stability conditions** (for the number of customers in a queue does not diverge to infinity):

(1) $\lambda_n(1-p) < \frac{C_{bus}}{b_n},$ (2) $\lambda_n p + \frac{1}{b_n} < \mu,$

(for the queue of bus customers) **(for the queue of vehicles in the service station)**

- Letting $L_n(t)$ and $N_n(t)$ denote the numbers of vehicles in the service station and the waiting bus customers, $\{(L_n(t), N_n(t)); t \geqq 0\}$ becomes a multidimensional continuous time stochastic process under the set space $S = \{(i,j); i = 0, 1, \ldots, j = 0, 1, \ldots\}.$

→ obtain the steady state probability numerically:

$$\pi_{i,j} = \lim_{t \to \infty} \mathrm{P}(L_n(t) = i, N_n(t) = j)$$

Performance measures (output)

By a simulation, we obtain

v : Speed of a car (km/hr)

R_n : Sojourn time of a car in the service station (hr)

W_n : Waiting time for a bus customer (hr)

T_n : Traveling time for a vehicle on the road (hr)

$$TotalTrip_n = T_n + (1-p)W_n$$

: Total trip time for a customer (hr)

Assumptions for simulation (1)

— estimation of **a maximum traffic density** k_j (vehicle/km)

Approximation: the service station on **the current road** is an **M**/D/1 queue

(original assumption: G/D/1 queue)

Almost all of the vehicles are private cars (Poisson arrivals represented by **M**)

Procedure

From real data
(Expected traveling time)

relationship
(Van Woensel, 2007)

From real data

Our goal !!

Analytical result of expected sojourn time for M/D/1 queue (=Service station) (Medhi, 2002)
※parameters: from real data

$$\mathrm{E}[T_{current}] = d_n k_j \mathrm{E}[R_{current}]$$

Assumptions for simulation (1)

— estimation of **a maximum traffic density** k_j (vehicle/km)

Solution of the last equation:

※ $\lambda^{all}_{current}$: Current arrival rate of all the vehicles **(From real data)**

$$k_j := \begin{cases} \dfrac{\lambda^{all}_{current}(2\mathrm{E}[T_{current}]v_{NS} - d_n)}{2v_{NS}(\mathrm{E}[T_{current}]v_{NS} - d_n)}, & \mathrm{E}[T_{current}]v_{NS} - d_n > 0, \\ \dfrac{\lambda^{all}_{current}}{v_{NS}}, & \mathrm{E}[T_{current}]v_{NS} - d_n \leqq 0. \end{cases}$$

Simple assumption:
Every driver travels at the nominal speed v_{NS}

Exception: Drivers in the real world sometimes do not keep the nominal speed…

Assumptions for simulation (2)
— introduction of **bus policy coefficier** $r \in (0, 1)$

To satisfy the stability condition (1) for the bus customers, i.e.,

$$\lambda_n(1-p) < \frac{C_{bus}}{b_n},$$

We assume that the bus departure interval is as follows:

$$b_n := \frac{C_{bus}}{\lambda_n(1-p)} \times r$$

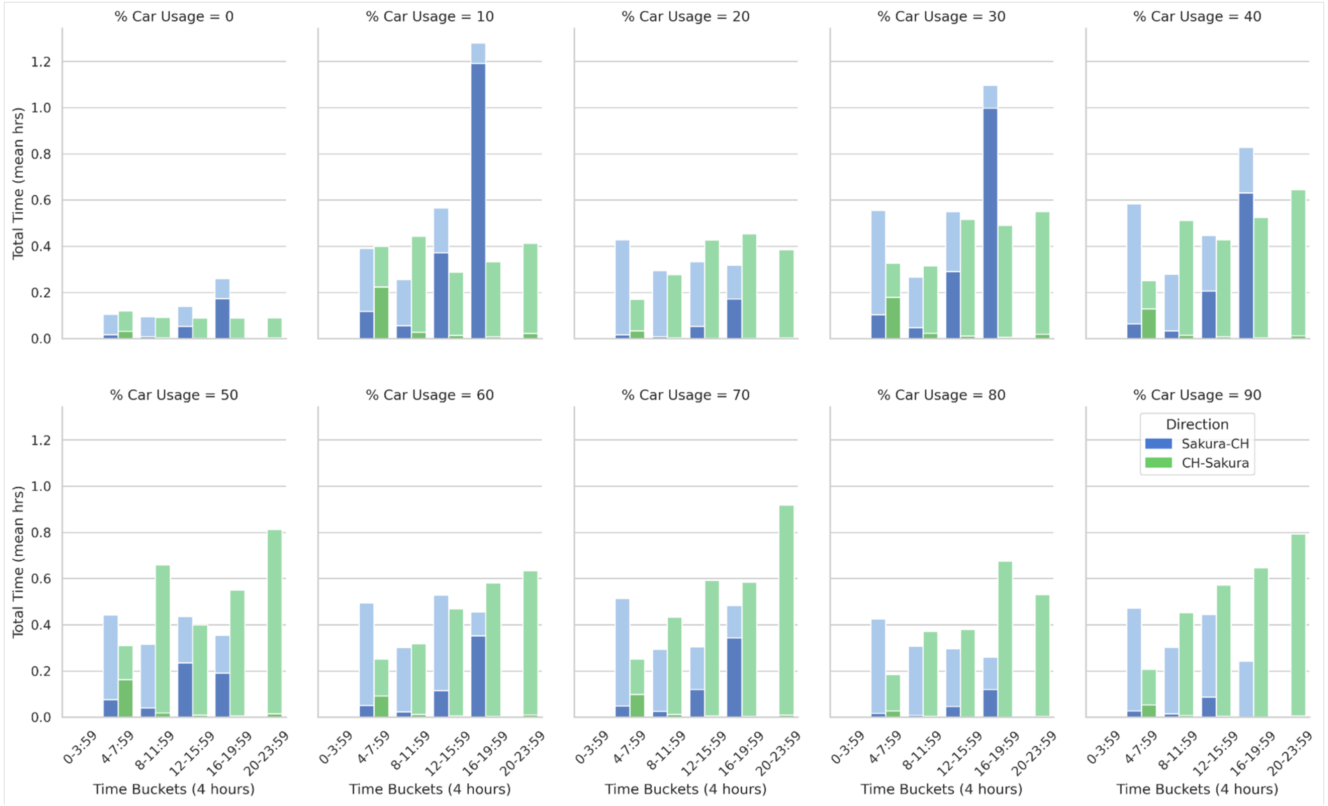
※ C_{bus} : Capacity of a bus

Queueing Model Parameters: Implementation

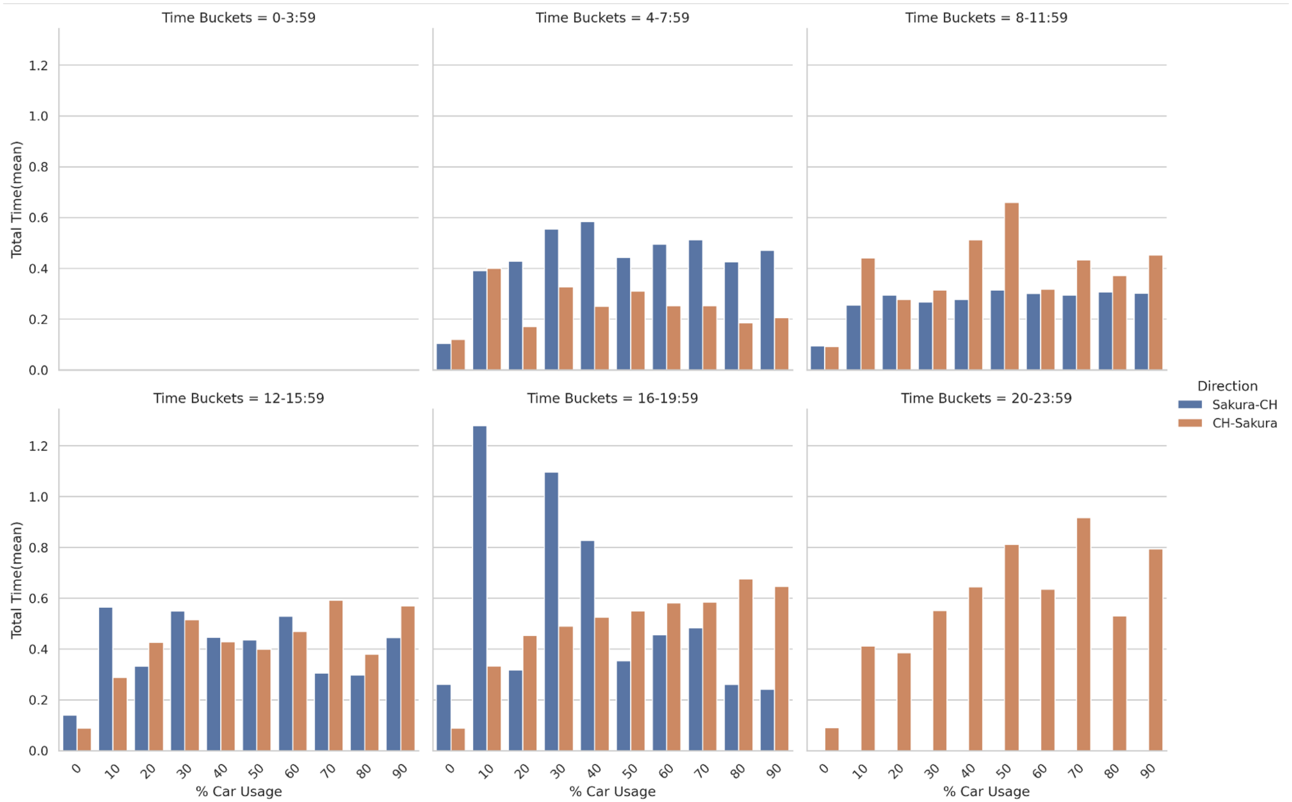
- Clean person-trip survey dataset provided arrival rates for customers and vehicles, as well as initial travel times
- Bus capacity was fixed at 80 (number of customers) for all scenarios
- Nominal speed was fixed at 80 km/hr for all scenarios
- % car usage ranged from 0-90% and results were computed for every 10%
- Bus policy coefficient (*r*) was obtained for each % car use, for each hub, via a brute force search in the linear space [0,1) for the minimizer of total trip time:

We will look at some results for one hub - Sakura district in more detail

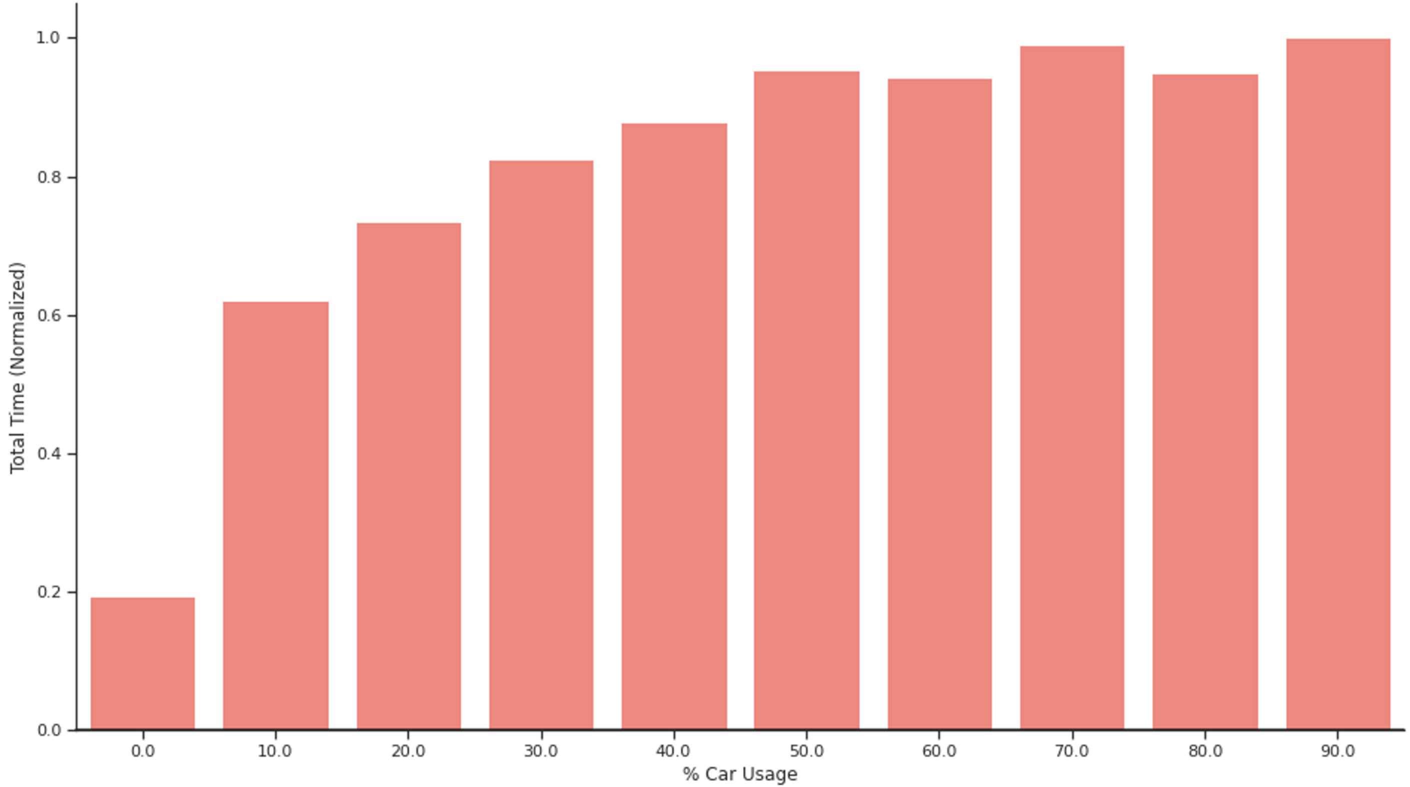
Queueing Results: Average Trip Times



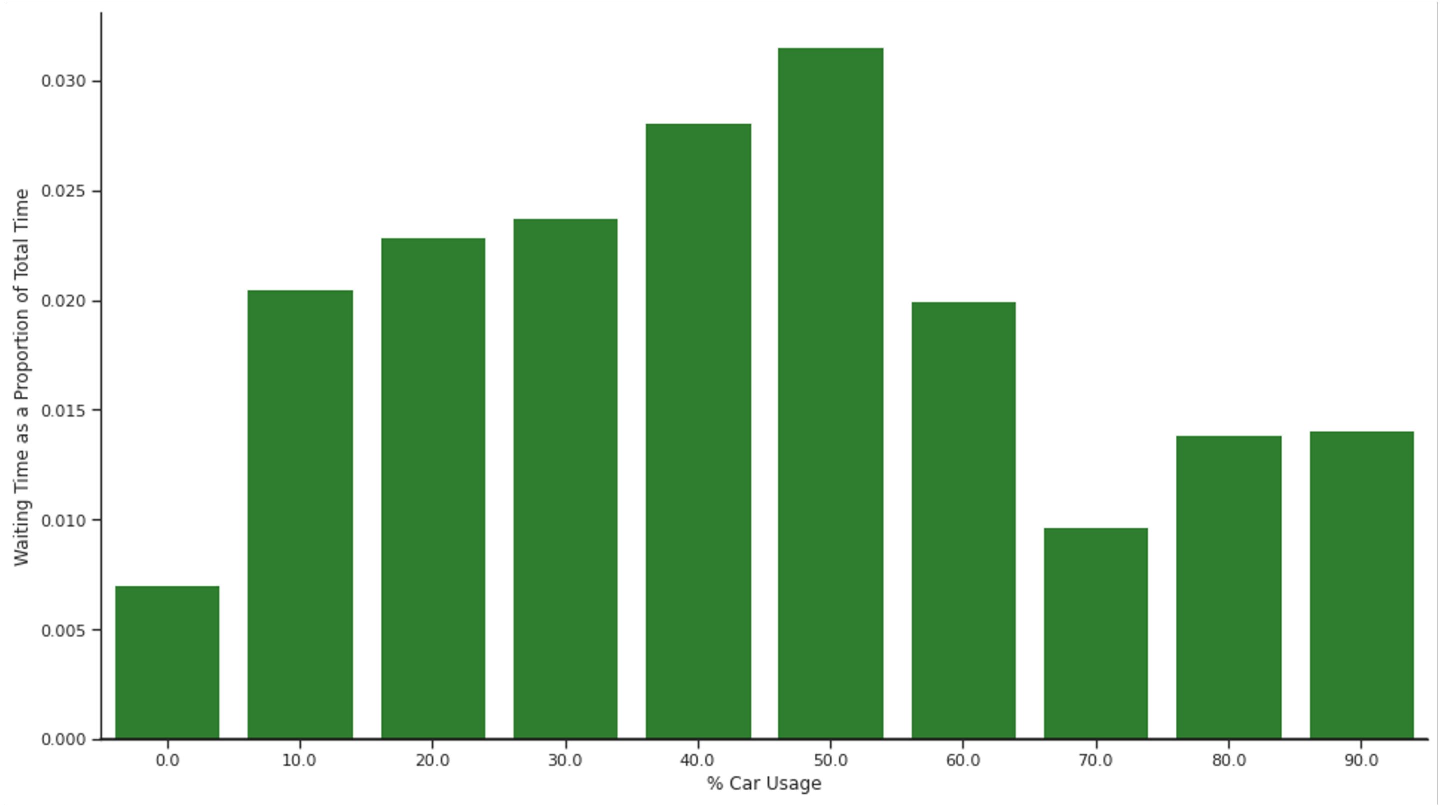
Queueing Results: Time of Day Effects



Queueing Results: Trip Time Trend for % car use



Queueing Results: Waiting Time Trend for % car use



Emission Estimations

- Evaluating environmental impact of new and conventional traffic system
- Focus on the emission product
- Two types of mathematical emission model.

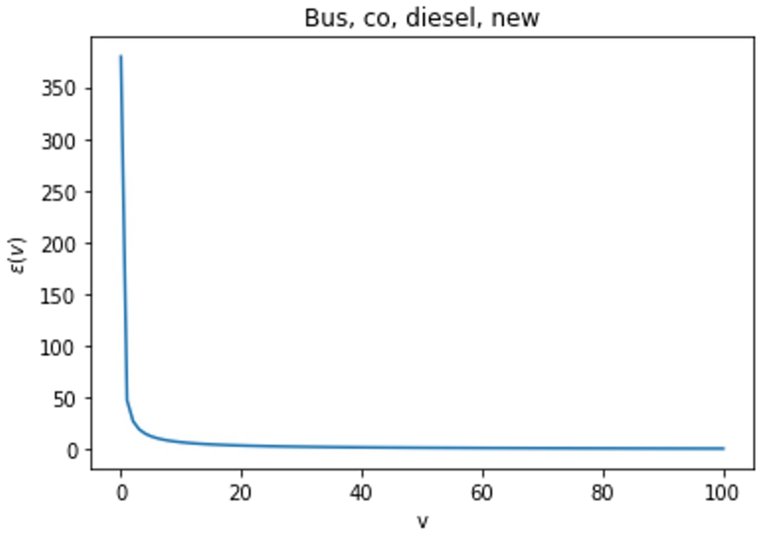
  1. Dynamic model → instantaneous

  2. Static model → average

- Use static model [1]

[1]: Jo, H.; Kim, H. Developing a Traffic Model to Estimate Vehicle Emissions: An Application in Seoul, Korea. Sustainability 2021, 13, 9761. https://doi.org/10.3390/su13179761

Emission Function



- Numerous emission functions depending on the parameters
- The argument of the function is the average speed.
- No CO_2 function in this paper, so we used national emission factor data.

emission product	fuel type	age	$\mathcal{E}(v)$	v_t	$\mathcal{E}(v)$ for $v \geq v_t$
CO	diesel	new	$52.136v^{-0.8618}$		

Algorithm

$$T\mathcal{E}_{i,j,k,l,m} = \sum_{i,j,k,l,m} VKT_{i,j,k,l,m} * \mathcal{E}(v)_{i,j,k,l,m}$$

i vehicle type, j fuel, k vehicle age, l emission product, and m vehicle displacement.
VKT the vehicle kilometers traveled

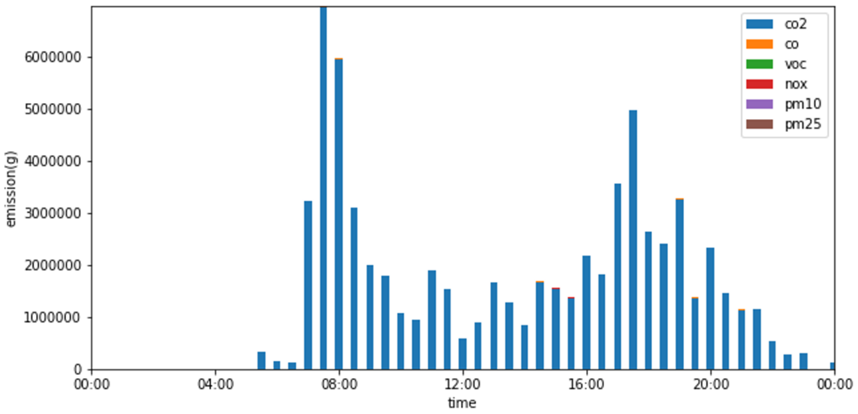
- The unit of emission function is g/km
- Emissions are calculated by the product of the emission function and the distance.
- By calculating the sum, one can calculate the total emission of the emission product.

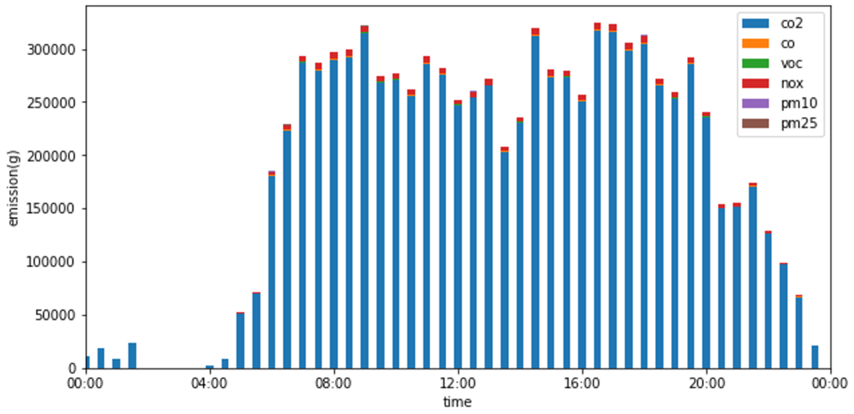
Output from Real Data

Calculating Emission from Person Trip and Bus Location data.

(above: Private Car, below: Bus)

- Determine parameter from National Data (eg. the number of car by fuel)
- The emission of Private Car is much bigger than Bus.
- The emission of Private Car is high in rush hour time
- Bus emission is constant during the day
- CO2 is major emission product





Queueing Model → Emission Model

- Combine emission model with Queueing Model
- Velocity and distance is required for emission model.
- Distance and sojourn time in the service station are outputs from Queueing model
- Velocity are obtained by equation from Queueing Model

Outputs

$\boldsymbol{d_n}$, $\boldsymbol{R_n}$

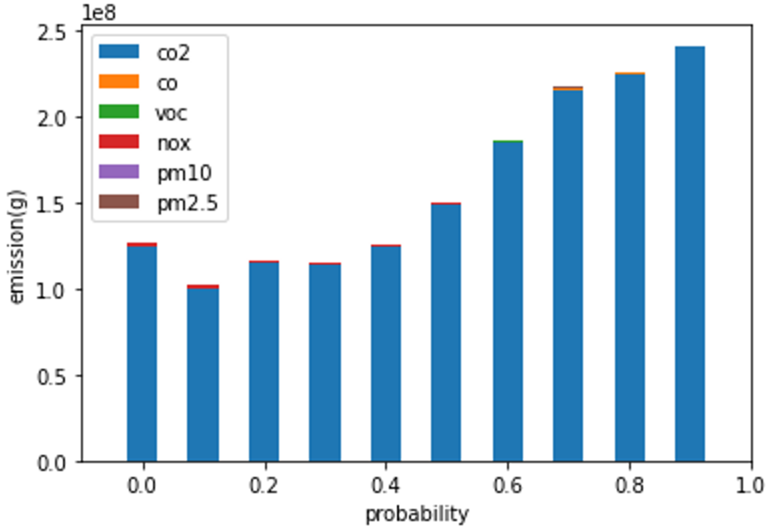
$$v = \frac{1}{k_j R_n}$$

$$\boldsymbol{emission} = \boldsymbol{d_n} \times \boldsymbol{\varepsilon(v)}$$

Emission from Queueing Model

Plot emission for each probability(Car Usage)

- Almost monotonically increasing with respect to probability
- It is thought to be due to capacity of the vehicle (Bus: 80, Private Car: 1)
- CO2 emission is proportional to distance and the number of vehicle in the road
- As bus user increases, the number of vehicles on the road decreases.

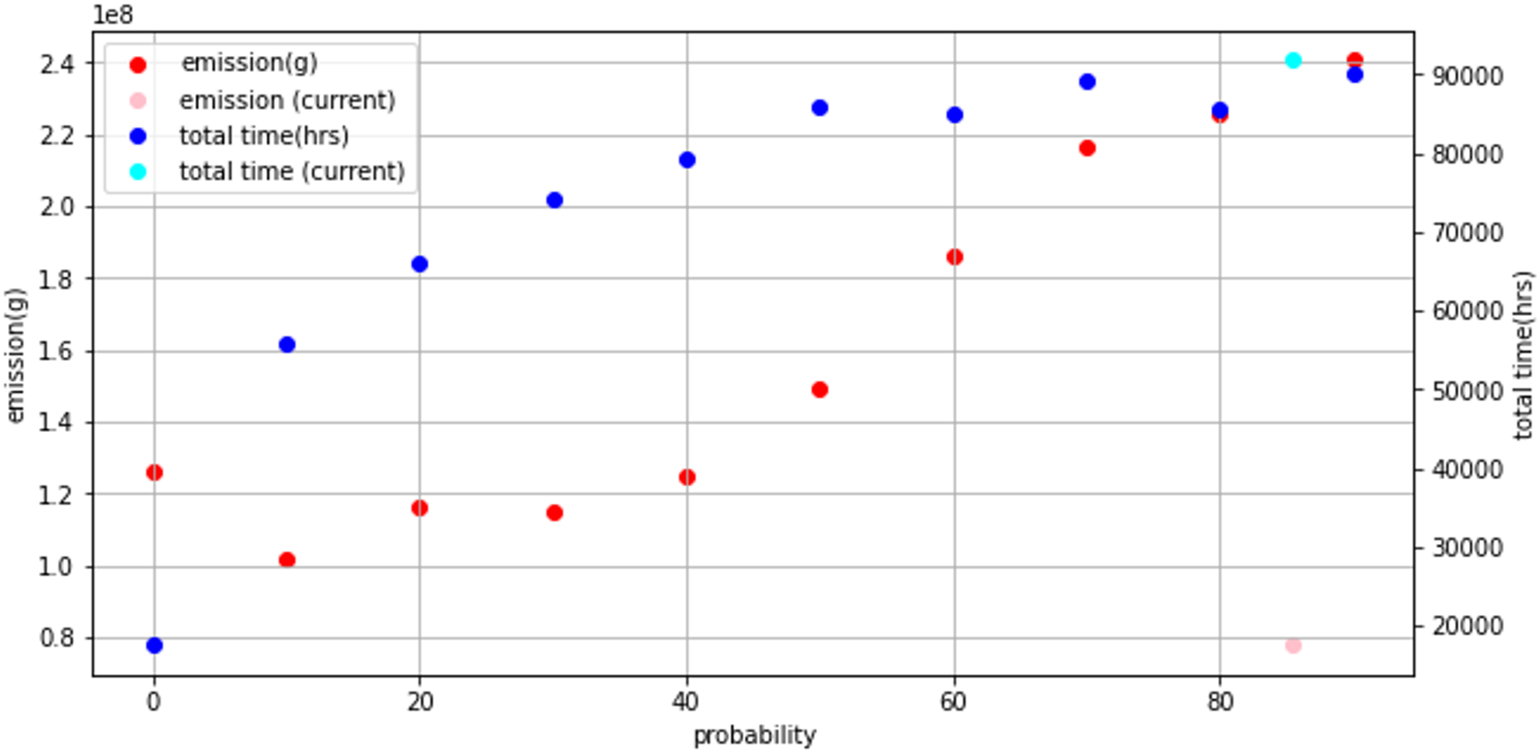


Convenience Cost vs. Environmental Cost

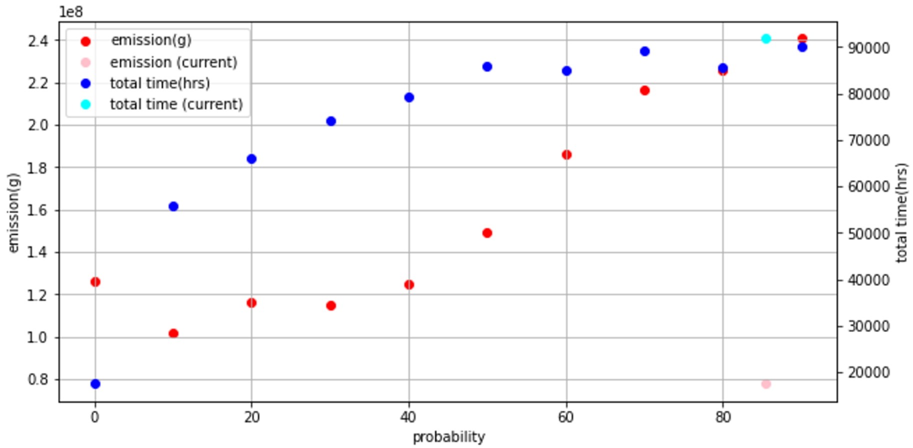
Scenario	$p(\%)$	total traveling time (hrs)	total emissions (kg)
PnR	0	17489.26	126055.03
	10	55892.46	101588.77
	20	66059.75	116335.91
	30	74170.65	114737.08
	40	79146.82	124880.05
	50	85860.41	149157.89
	60	84871.50	185969.05
	70	89153.13	216539.00
	80	85546.84	225431.32
	90	90025.94	240680.46
Current	$\sim 85.5 \sim$	91806.167	77838.63

As *p* increases, so does the number of private cars.

Convenience Cost vs. Environmental Cost



Convenience Cost vs. Environmental Cost



- Bus location data only has data for one bus company

- Slow speed contributions

- Choice of *r* optimal for total traveling time.

- Does the current public transport in Tsukuba only serve 15% of the population?

Does a PnR system make a significant difference?

Conclusions:

- Queueing good method to model traffic behavior under various scenarios
- Emissions need to be quantified to align with future goals
- Results imply current public transport in Tsukuba only optimal for current usage

Future Directions:

1. Queueing:
   a. Other service process and more servers
   b. Decision between private car and public transport
   c. Choice of parameter *r*
   d. ‘Strategic’ queueing model
2. Emissions:
   a. Static vs. Dynamic model
   b. Consider hybrids and electric vehicles
3. Input parameters:
   a. Consider particular populations
   b. Finer time scales
   c. Other modes of transport, more data
   d. Machine learning to select policy parameters

Thank you!

Questions are welcome

☺

Relevant References:

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