Global System Metrics（closed）：

Average Cycle Time (W):

- Definition: The Average Cycle Time (ACT) measures the average time a vehicle spends within the system from the moment it is assigned a task until the completion of that task. This includes both the active task execution time and any waiting time at the starting point. ACT is a key indicator of operational efficiency, reflecting how quickly tasks are being completed.
- Calculation: ACT is calculated by summing the total time spent by each vehicle from task assignment to task completion and dividing this sum by the total number of vehicles that have completed tasks during the observation period.

Average Number of Vehicles (L):

- Definition: The Average Number of Vehicles (ANV) indicates the average number of vehicles actively engaged in tasks within the system at any given moment. This metric provides insights into resource utilization and the level of activity within the system.
- Calculation: ANV is computed by recording the number of vehicles that are actively engaged in tasks at various intervals, summing these numbers, and then dividing by the total number of

observations.

Arrival Rate (λ):

- Definition: The Arrival Rate (λ) represents the rate at which vehicles are assigned tasks within the system. It is a critical measure of task inflow and operational demand, indicating the frequency at which vehicles are put to work.
- Calculation: To calculate λ, count the total number of task assignments to vehicles over the entire observation period. Then, divide this total by the overall duration of the observation period to obtain the average rate at which tasks are assigned to vehicles.

Prerequisite Variables:

Vehicle State Storage Structure

This structure is a dictionary (vehicles), designed to manage and store state information for various vehicles efficiently. Each vehicle is uniquely identified by its Vehicle ID, and the data associated with each vehicle is encapsulated within a list. Each list contains multiple dictionaries, with each dictionary recording a timestamp of the vehicle's state change.

- Structure Description

Key: Each key in the dictionary is a string representing the unique Vehicle ID (e.g., "V001", "V002", "V003", etc.).

Value: The value corresponding to each key is a list. This list consists of dictionaries, each documenting a specific point in time when the vehicle's state changes.

- Fields in Each State Change Dictionary

Time: A string, formatted as "HH:MM", indicating the exact time of the vehicle's state change.

State: A string that specifies the current state of the vehicle. The possible states include "active", "passive", and "pending".

- Example:

For instance, the entry:

```
vehicles = {
    "V001": [
        {"Time": "08:00", "State": "active"},
        {"Time": "12:00", "State": "passive"},
    ],
    "V002": [
```

{"Time": "09:00", "State": "active"},
{"Time": "10:30", "State": "passive"},
]
}

indicates that:

- Vehicle V001 starts in an active state at 08:00 and transitions to a passive state at 12:00.
- Vehicle V002 starts in an active state at 09:00 and transitions to a passive state at 10:30.

Path Data Structure Description

The designed data structure primarily accumulates the total duration of different vehicle states (active, passive, pending) on each road, significantly reducing storage requirements and simplifying data handling.

Structure Components

- Road Dictionary (path_stats): This top-level dictionary has road IDs as keys and another dictionary as values. The latter records the total duration for each vehicle state on that road.
- State Duration Dictionary: For each road, this dictionary contains keys such as active, passive, and pending, each associated with an

integer value representing the total duration of that state in minutes.

Collection and Extraction Methods

- Data Collection: When a vehicle's state changes, we calculate the duration of this change and add the time to the corresponding road and state's total duration. This process does not require recording specific timestamps for each state change, thus lowering space complexity.
- Data Extraction: To calculate the total duration of all vehicles in all roads for a certain state, we simply iterate through the path_stats dictionary, summing up the durations for each state. This method makes total time calculation straightforward and efficient.
- Example

Assuming we have two roads (Path1 and Path2) and wish to record and retrieve the total duration of vehicles in active, passive, and pending states on these roads, the data structure might look like this:

```
path_stats = {
    "Path1": {
        "active": 120,  # Total active state duration on Path1 is 120 minutes
```

```
        "passive": 60,  # Total passive state duration on Path1 is 60 minutes
        "pending": 30,  # Total pending state duration on Path1 is 30 minutes
    },
    "Path2": {
        "active": 90,
        "passive": 30,
        "pending": 15,
    },
}
```

Initial conditions

- PathActiveStartTime: The moment a vehicle begins moving on a specific path, reflecting the start time of the vehicle's active state on that road. This indicates the vehicle is in motion on the path, focusing solely on the vehicle's movement without relating to loading, unloading, or other activities.
- PathActiveEndTime: The moment a vehicle stops moving on the path, marking the end of the vehicle's active state. This means the vehicle has completed its movement on that path and has stopped.
- PathPassiveStartTime: The moment a vehicle enters a paused state

on the path, indicating the vehicle has temporarily stopped moving but has not left the path. This state may occur due to traffic control or while waiting for other conditions to be met.

- PathPassiveEndTime: The moment a vehicle leaves the paused state and is ready to resume movement on the path. This indicates the vehicle has ended its paused state, possibly because the conditions previously waited for have been fulfilled.
- PendingListLength: The length of pending list belongs to each path.
- VehicleActiveStartTime: The time point when a vehicle enters an active state, similar to PathActiveStartTime but more focused on the vehicle's overall active condition, not limited to movement on a single path.
- VehicleActiveEndTime: The time point when a vehicle exits its active state, signaling the vehicle has completed all its active tasks and may stop for further instructions.
- VehiclePassiveStartTime: The time point when a vehicle enters a passive state, during which the vehicle pauses all activities and may wait for external conditions to change.
- VehiclePassiveEndTime: The time point when a vehicle exits the passive state, ready to re-enter an active state for movement or other tasks.

- VehiclePendingStartTime: The start time when a vehicle requests to enter the next path segment, during which the vehicle waits for the "handshake" confirmation between paths, i.e., waiting for confirmation that there is an available spot in the next segment for it to enter.
- VehiclePendingEndTime: The moment a vehicle receives confirmation that there is an available spot in the next path segment, preparing to transition from the current state to moving towards the next path in an active state.
- Total Simulation Time: The total time of the entire simulation.

Calculation of Total Dwell Time:

- Formula: Total Dwell Time =

$$\sum_{\text{each vehicle}}\left(\sum_{\text{each path}}\left(\left(\text{PathActiveEndTime}-\text{PathActiveStartTime}\right)+\left(\text{PathPassiveEndTime}-\text{PathPassiveStartTime}\right)\right)\right)$$

$$=$$

$$\sum_{\text{each vehicle}}\left(\sum\left(\left(\text{VehicleActiveEndTime}-\text{VehicleActiveStartTime}\right)+\left(\text{VehiclePassiveEndTime}-\text{VehiclePassiveStartTime}\right)+\left(\text{VehiclePendingStartTime}-\text{VehiclePendingEndTime}\right)\right)\right)$$

- Method: For each vehicle, calculate the duration of time spent in

the active and passive states on each path. Sum these durations across all paths and all vehicles.

Calculation of Total Arrival Count:

- Formula: Total Arrival Count $= \sum_{\text{distinct vehicle}} \text{Vehicles}$
- Method: For the all Vehicles, calculate the length of the vehicles list.

Total Waiting Time:

- Calculation Method: For each vehicle, calculate the duration of time spent in the passive state in each queue, which is PassiveEndTime - PassiveStartTime. Sum up these waiting times across all vehicles and all queues.
- Formula: Total Waiting Time = $\sum_{\text{each vehicle}} (\text{VehiclePassiveEndTime} - \text{VehiclePassiveStartTime})$

Global System Metrics(open):

Average Cycle Time (W):

- Definition: ACT measures the average time a vehicle spends within the simulation boundaries from entry to exit. It is a key indicator of system efficiency and congestion levels.
- Calculation: $ACT = \frac{\text{Total Dwell Time}}{\text{Total Arrival Count}}$

Average Number of Vehicles (L):

- Definition: ANV reflects the average quantity of vehicles present in the simulation at any given moment, providing insights into traffic density and flow.
- Calculation: $ANV = \frac{\text{Total Dwell Time}}{\text{Total Simulation Time}}$

Arrival Rate (λ):

- Definition: Arrival Rate (λ) indicates the number of vehicles arriving at a specific segment or control point per unit of time. It is a critical measure of the traffic inflow into the system.
- Calculation: $\lambda = \frac{\text{Total Arrival Count}}{\text{Total Simulation Time}}$

Global Queue Average Waiting Time (W):

- Definition: The average waiting time of vehicles across all queues in the simulation.
- Calculation Method:

$W = \frac{\text{Total Waiting Time}}{\text{Total Arrival Count}}$

Global Queue Average Number of Vehicles (L):

- Definition: The average number of vehicles present at any given moment across all queues in the simulation.

- Calculation Method:

$$L=\frac{\text{Total Waiting Time}}{\text{Total Simulation Time}}$$

Global Queue Arrival Rate (λ):

- Definition: The average rate at which vehicles enter all queues in the entire simulation.
- Calculation Method:

$$\lambda=\frac{\text{Total Arrival Count}}{\text{Total Simulation Time}}$$

Segment-Specific Metrics:

Segment Average Number of Vehicles (Segment L):

- Definition: SANV measures the average number of vehicles present on a specific road segment at any given time, offering a perspective on traffic density and flow on that segment.
- Calculation:

$$\sum_{\text{each vehicle}}((\text{PathActiveEndTime}-\text{PathActiveStartTime})+(\text{PathPassiveEndTime}-\text{PathPassiveStartTime}))/\text{Total Simulation Time}$$

Segment Arrival Rate (Segment λ):

- Definition: Segment Arrival Rate represents the rate at which

vehicles arrive at a specific segment within a unit of time.

- Calculation: VehicleListLength/ Total Simulation Time

Segment Cycle Time (Segment W):

- Definition: SCT calculates the average time vehicles spend traveling through a specific segment from entry to exit of that segment.
- Calculation:

$\sum_{\text{each vehicle}}$((PathActiveEndTime− PathActiveStartTime)+(PathPassiveEndTime−PathPassiveStartTime))/ VehicleListLength

Local Queue Average Waiting Time (Segment W):

- Definition: The average waiting time of vehicles in a specific queue.
- Calculation:

$\sum_{\text{each vehicle}}$(PathPassiveEndTime−PathPassiveStartTime))/ VehicleListLength

Local Queue Average Number of Vehicles (Segment L):

- Definition: The average number of vehicles present at any given moment in a specific queue during the simulation.
- Calculation Method:

(PathPassiveEndTime−PathPassiveStartTime))/ Total Simulation Time

Local Queue Arrival Rate (Segment λ):

- Definition: The average rate at which vehicles arrive at a specific queue.
- Calculation： PendingListLength/ Total Simulation Time

Others:

Congestion Index:

- Definition: An indicator that reflects the level of congestion on a specific road segment or on the entire network.
- Calculation method: $\frac{\text{ActiveEndTime}-\text{ActiveStartTime}}{\text{PassiveEndTime}-\text{PassiveStartTime}}$

Segment Load Factor:

- Definition: The ratio of vehicle occupancy on a segment over a given time, reflecting the utilization of the segment.
- Calculation: **Segment L / Segment capacity**

Vehicle Trip Efficiency:

- Definition: The ratio of the time taken by a vehicle to complete its scheduled trip to the time it would take under ideal conditions (no congestion, no waiting).
- Calculation: **Total Dwell Time / Total Ideal Time**

Time Variability (as a proxy for Speed Variability):

- Definition: Since the distance of each segment is constant, time variability can be used as an indicator of speed variability.
- Calculation:

(Standard Deviation)∂ （Average Cycle Time or Segment Cycle Time）

Gini Coefficient = (Sum over all pairs of segments |x_i - x_j|) / (2 * n^2 * mean(x))

Traffic Balance (Using Gini Coefficient):

- Traffic Balance assesses the uniformity of traffic flow distribution across different road segments in the entire network.
- Calculation:

Gini Coefficient = (Sum over all pairs of segments |x_i - x_j|) / (2 * n^2 * mean(x))

in:

x_i and x_j respectively represents the vehicle flow on different road sections.

n is the total number of road segments.

mean(x) is the average value of vehicle flow in all road segments.