A New Paradigm to Model Aircraft Operations at Airports: The Virginia Tech Airport SIMulation Model (VTASIM)

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Agenda

1. Background and Purpose of the Model
2. VTASIM is Hybrid-type of Simulation Model
3. Components of VTASIM
    - Entities and State Variables
    - State Diagrams: represent time dependent behavior of each entity
    - Algorithms: define detailed sequences of actions
    - Data structures
    - Flowcharts
4. Output of VTASIM
5. Findings and Further Research

Introductory Remarks

- Existing microscopic simulation models for airport studies:
  - SIMMOD, TAAM: Deal with aircraft both in the airfield and the airspace.
  - HERMES, The Airport Machine: Mainly for airfield analysis
  - RAMS: Mainly for airspace analysis

- We provide a new *microscopic, hybrid type of* simulation model called VTASIM
  - Capable of describing *communication process* between flights and controllers.
  - Simulates aircraft operations *on the airfield area* including gates, taxiways, and runways.

VTASIM is a Hybrid Simulation Model

- Discrete-events simulation model
  - represents a system by changing the system status at the moments when an event occurs.
  - has benefit from a computational perspective.
- A discrete-time simulation model
  - represents a system checking and changing the system status at every step *dt*.
  - is able to describe behaviors of entities in great detail.
    eamples: runway exiting process, vehicle following behavior, etc.
- VTASIM: *Hybrid-type* of simulation model.
  - Communication: represented by *discrete-event* modeling principles.
  - Movement: represented by *discrete-time* simulation principles.

Components of VTASIM

- Entities and State Variables
- State Diagrams: represent time dependent behavior of each entity
- Algorithms: define detailed sequences of actions
- Data structures
- Flowcharts

Entities and State Variables

- Entities in VTASIM are

  1) two types of controllers (i.e., local and ground controllers),

  2) two types of flights (i.e., departing and arriving flights), and

  3) facilities including gates, taxiways, runways, etc.

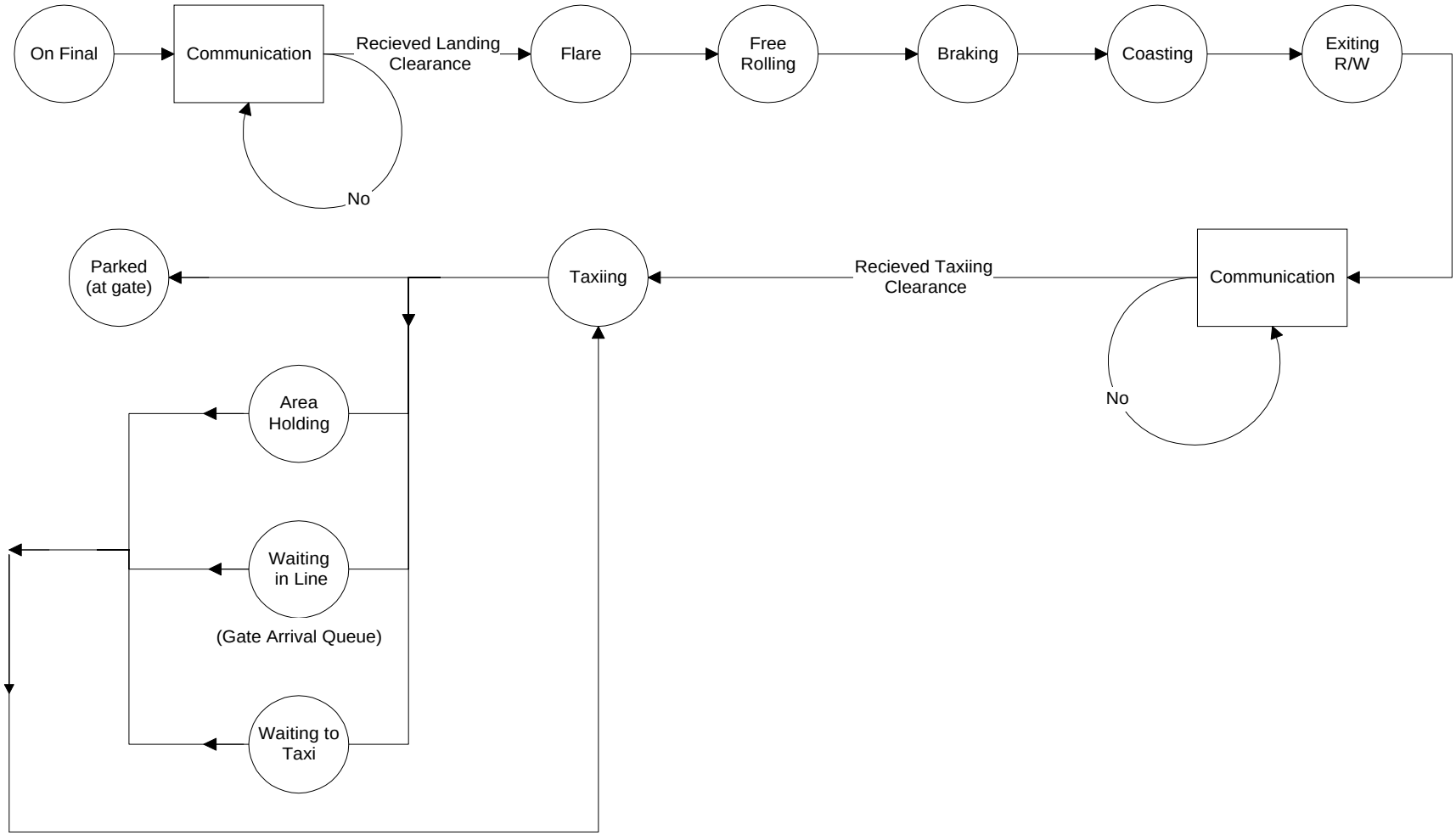
- State Variables for each entity include

  1) for controllers: controlling state, next communication time,

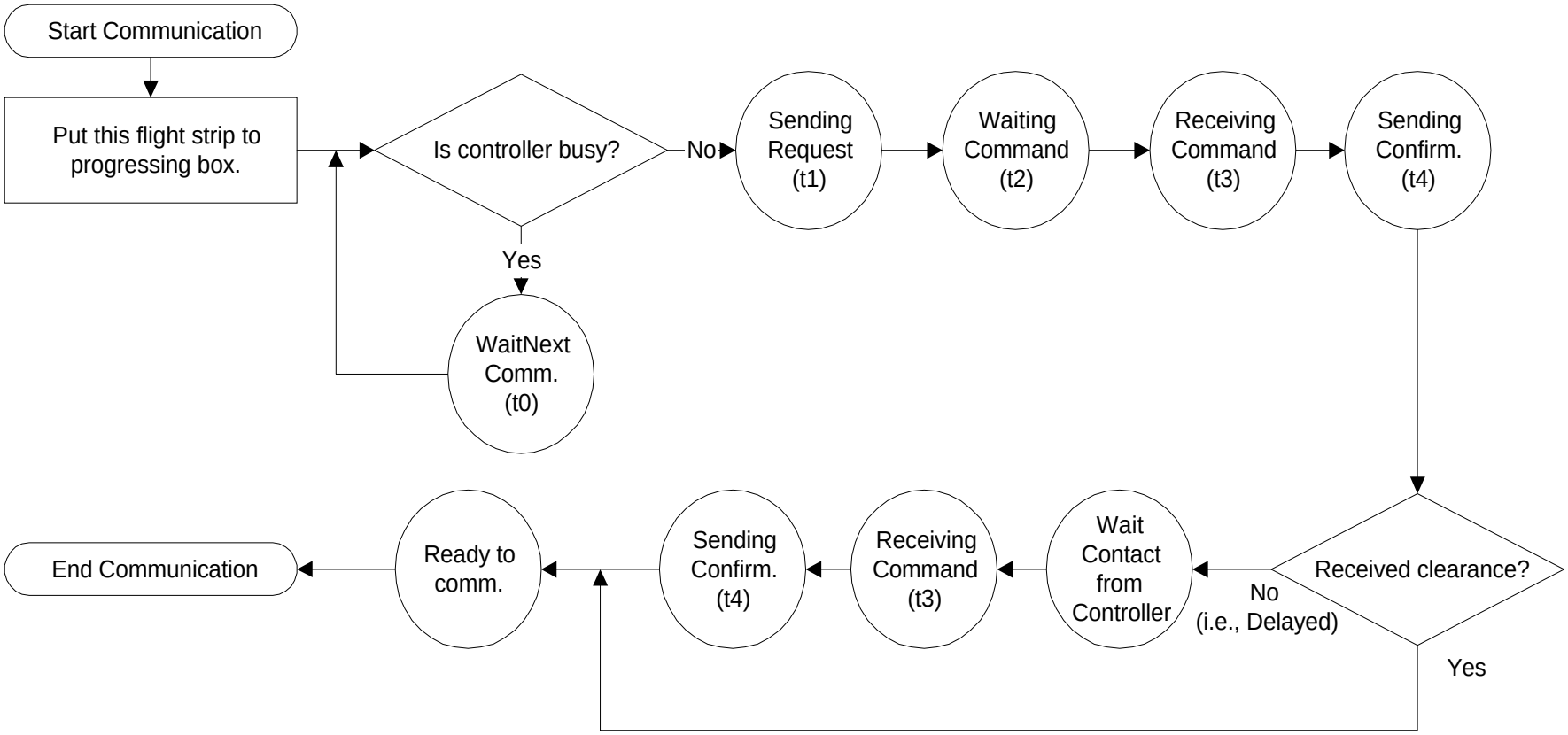
  2) for flights: communication state, next communication time, movement state, next movement time, speed, acceleration, position, etc.,

  3) for gates, taxiways, runways: current flight(s).

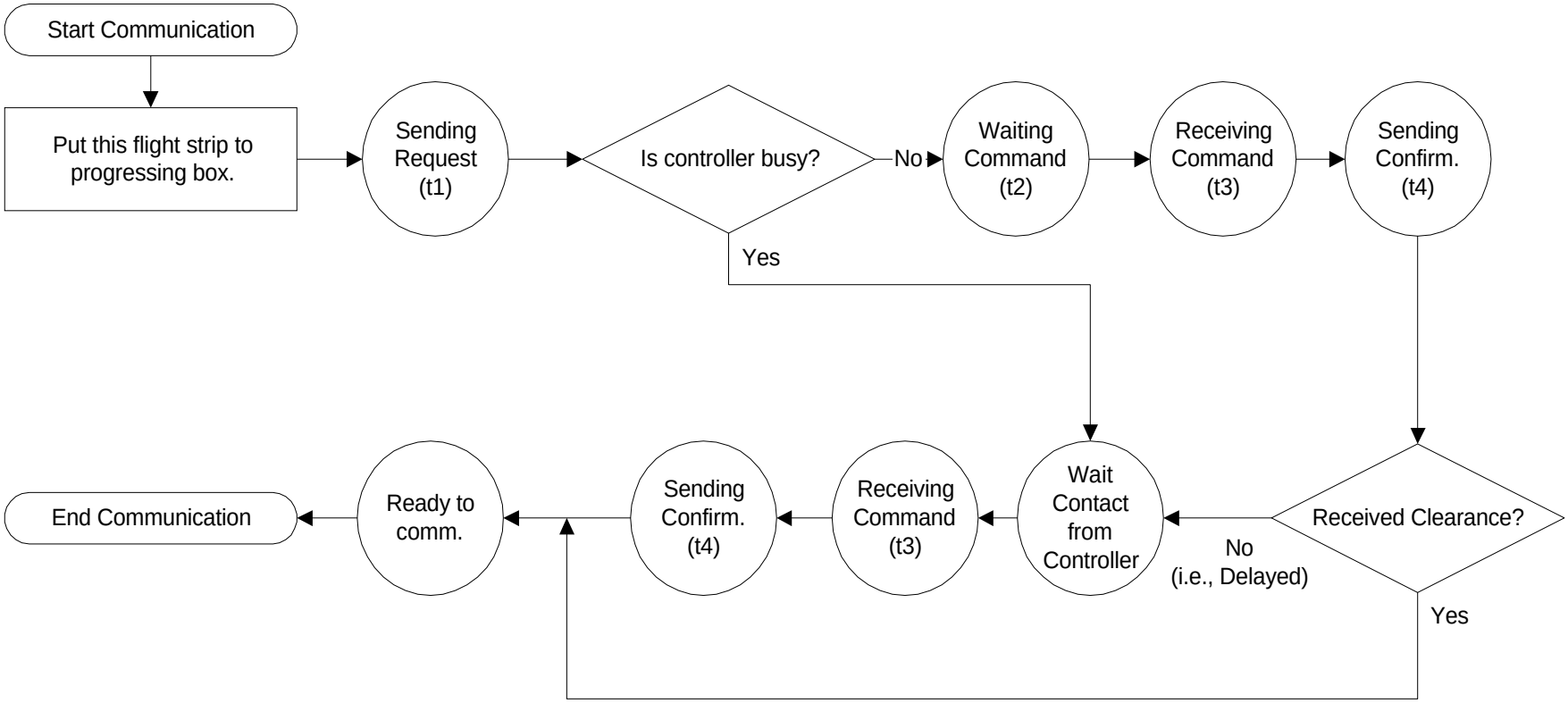
State Diagram: Arriving Aircraft Movement



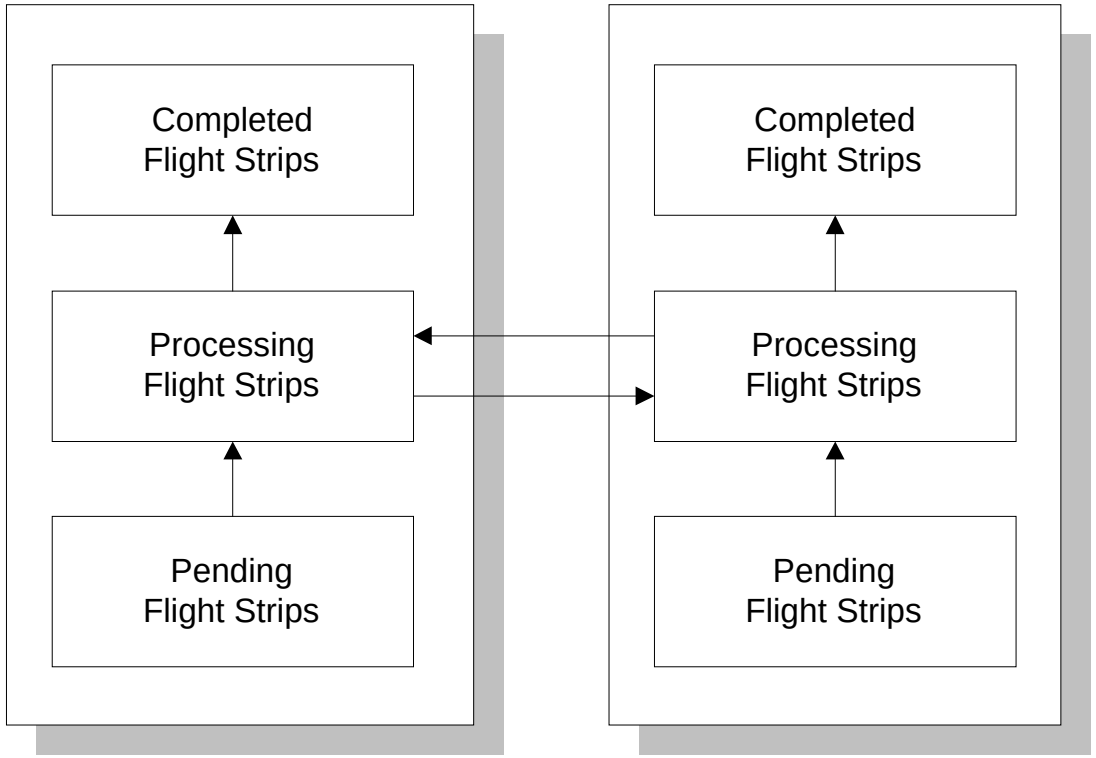
State Diagram: Communication (Voice Channel)



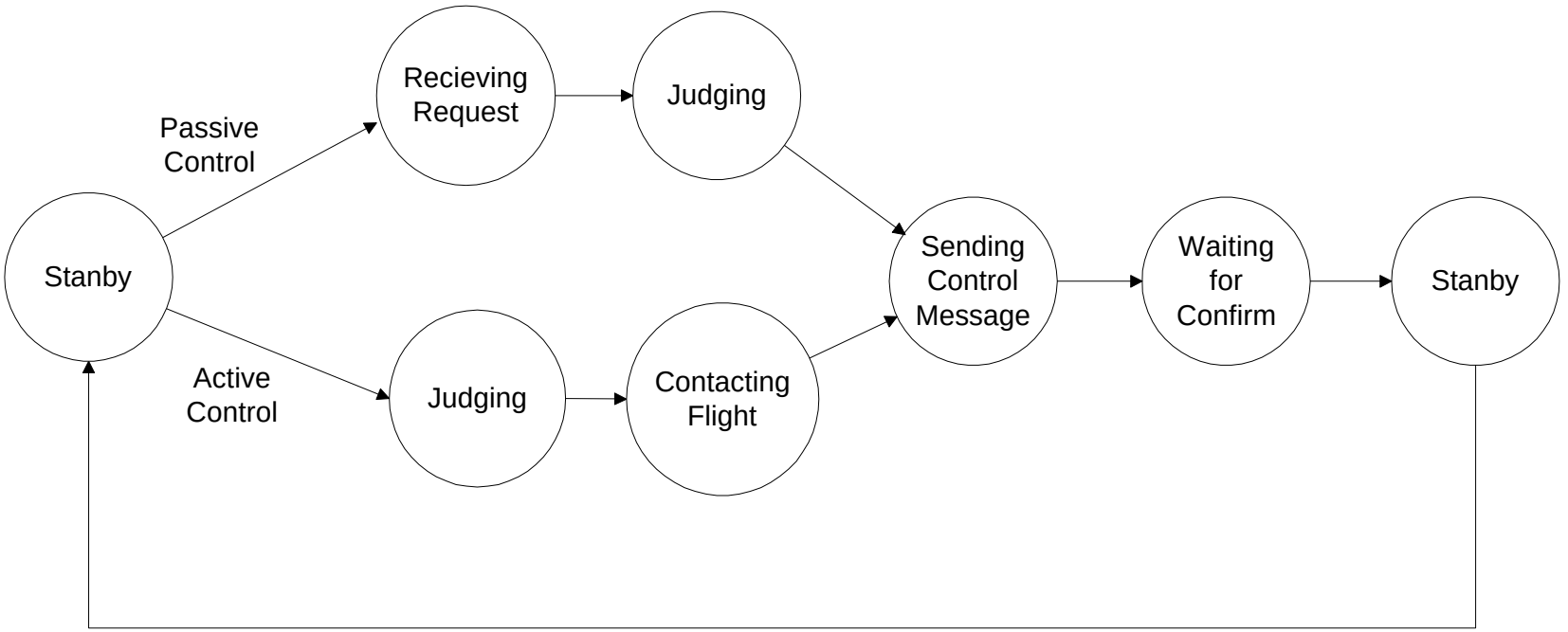
State Diagram: Communication (Data Link)



State Diagram: Controller's Flight Strips

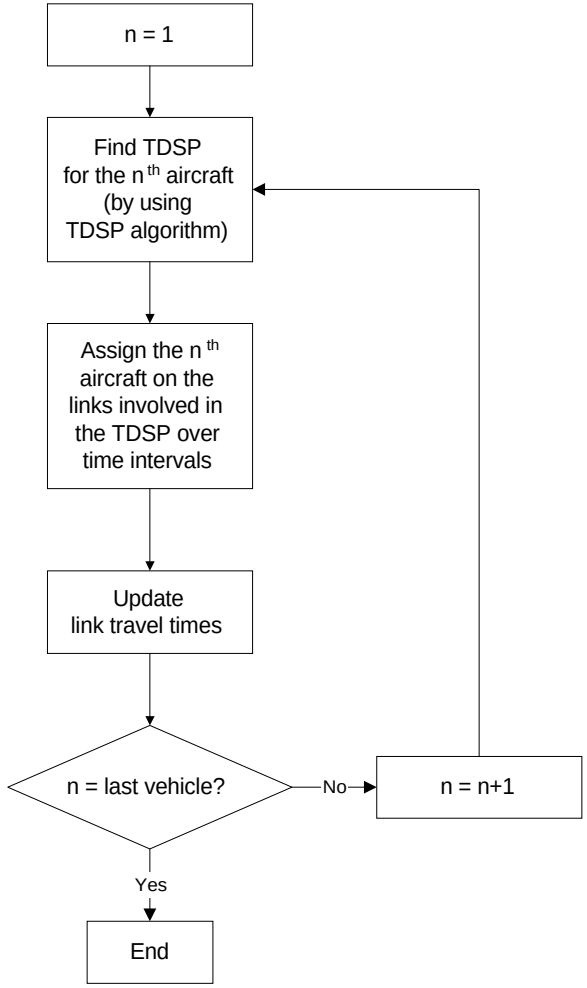


State Diagram: Communication (Controller point of view)



Algorithm: Taxiing Route Plan

- Considers time-dependent network loading.
- Employs an incremental time-dependent network assignment strategy
  - based on *time-dependent shortest path* algorithm.



Algorithm: Taxiing Route Plan

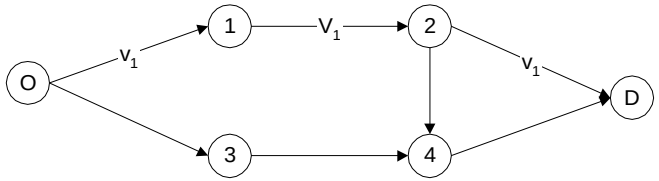


Figure 1: Example of QTDNA.

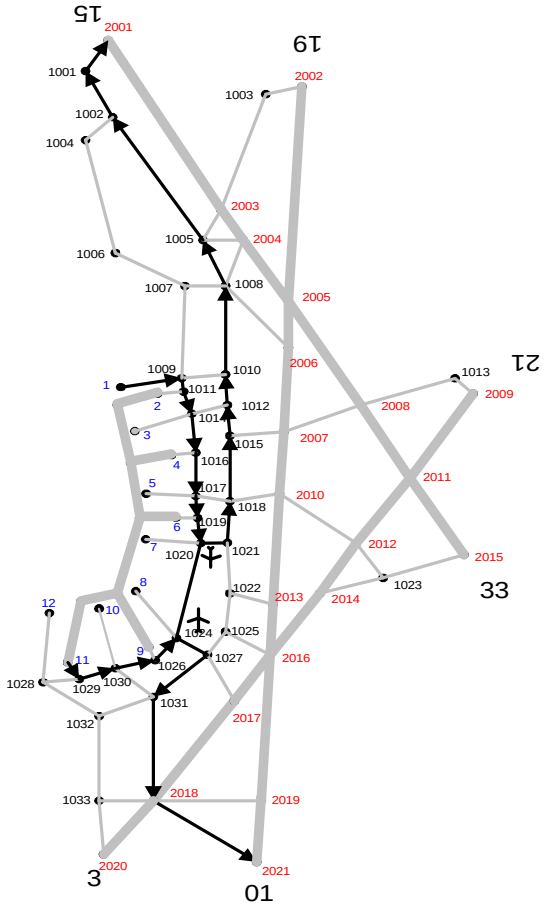
Table 1: Time-dependent Vehicle Flow

Links / Time slices	L_{O1}	L_{1O}	L_{O3}	L_{3O}	L_{12}	L_{21}	L_{34}	L_{43}	L_{24}	L_{42}	L_{2D}	L_{D2}	L_{4D}	L_{D4}
1	v_1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	v_1	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	v_1	-	-	-

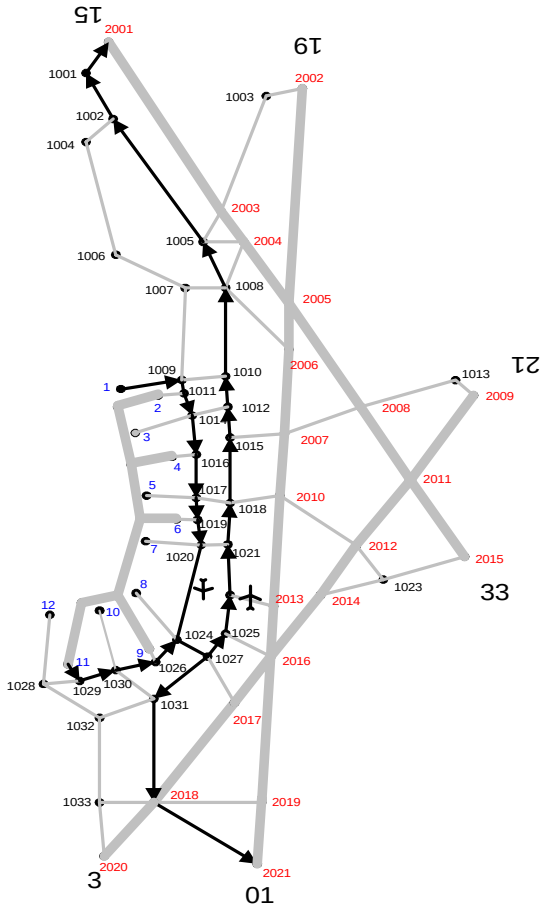
Table 2. Time-dependent Link Travel Times

Links / Time slices	L_{O1}	L_{1O}	L_{O3}	L_{3O}	L_{12}	L_{21}	L_{34}	L_{43}	L_{24}	L_{42}	L_{2D}	L_{D2}	L_{4D}	L_{D4}
1	t_{O1}^{1}	∞	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	t_{12}^{2}	∞	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	t_{2D}^{3}	∞	-	-

Algorithm: Taxiing Route Plan



(a) Statically assigned path.



(b) Time-dependent assigned path.

Algorithm: Aircraft Following Model

Step 1: Decide the desired speed for the following aircraft.

$$v_{t+\Delta t}^{d} = v^{f}(1 - \frac{H_j}{H_t}).$$

Where, $v_{t+\Delta t}^{d}$: following aircraft's desired speed at $t+\Delta t$,

v_f : free flow speed,

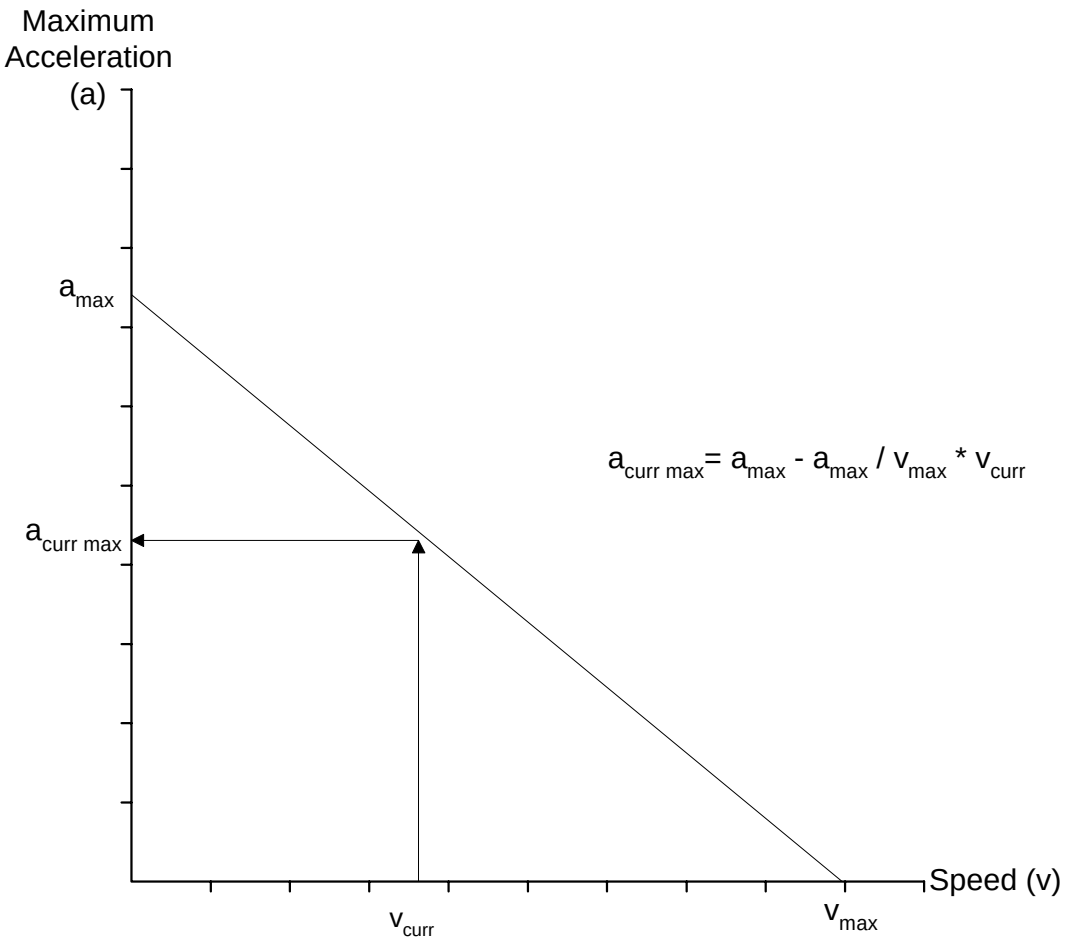
H_j : headway at jam density,

H_t : headway between the leading vehicle and the following vehicle at time t.

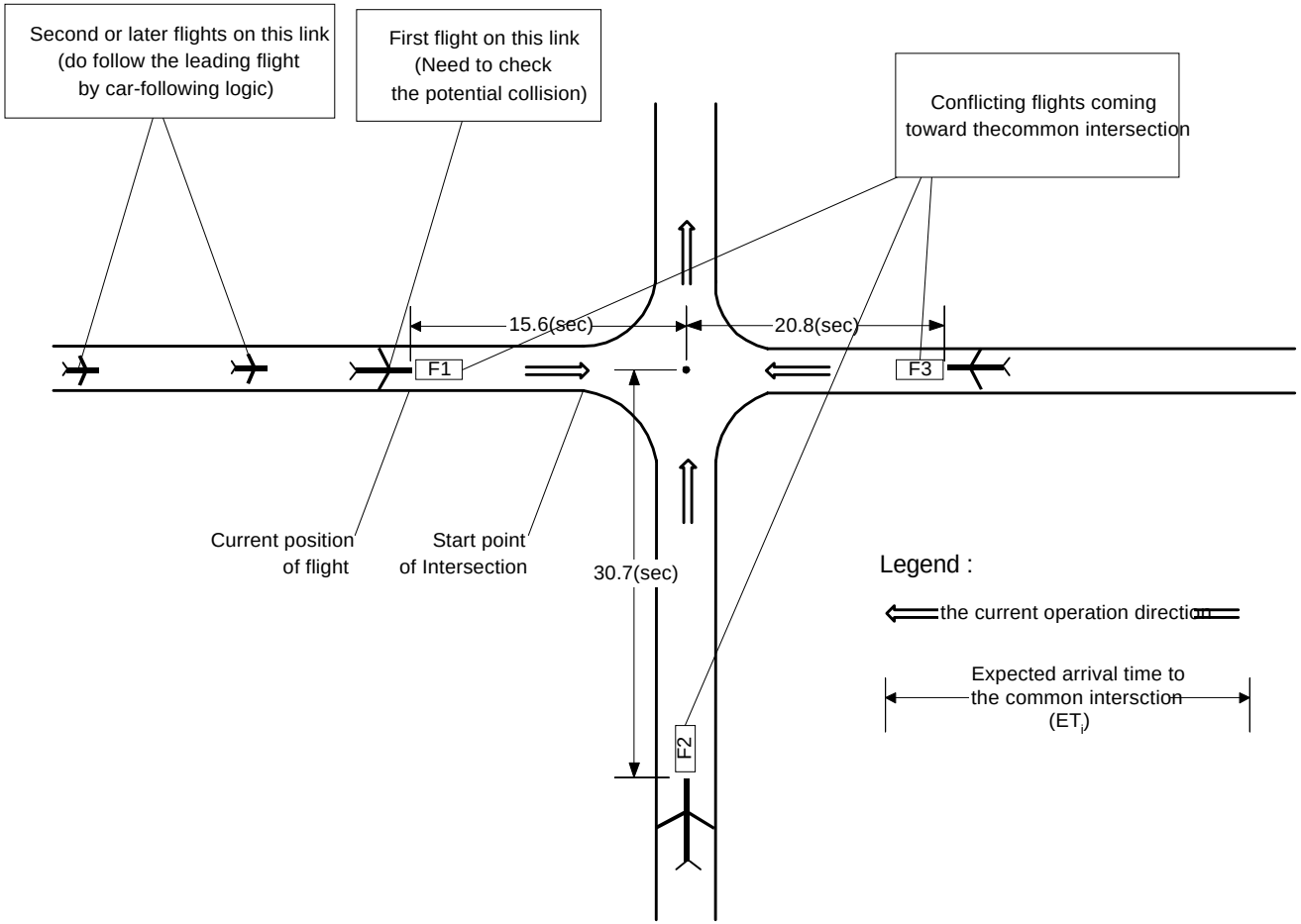
Step 2: Decide the following aircraft's acceleration.

$$a_{n+1}^{t+\Delta t} = (v_{t+1}^{d} - v_t)/\Delta t, \quad \text{if } a_{n+1}^{t+\Delta t} > a_{\max} \text{ then } a_{n+1}^{t+\Delta t} = a_{\max},$$
$$\text{if } a_{n+1}^{t+\Delta t} < a_{\min} \text{ then } a_{n+1}^{t+\Delta t} = a_{\min}.$$

Algorithm: Non-uniform Acceleration Model



Algorithm: Conflict Detection and Resolution Model

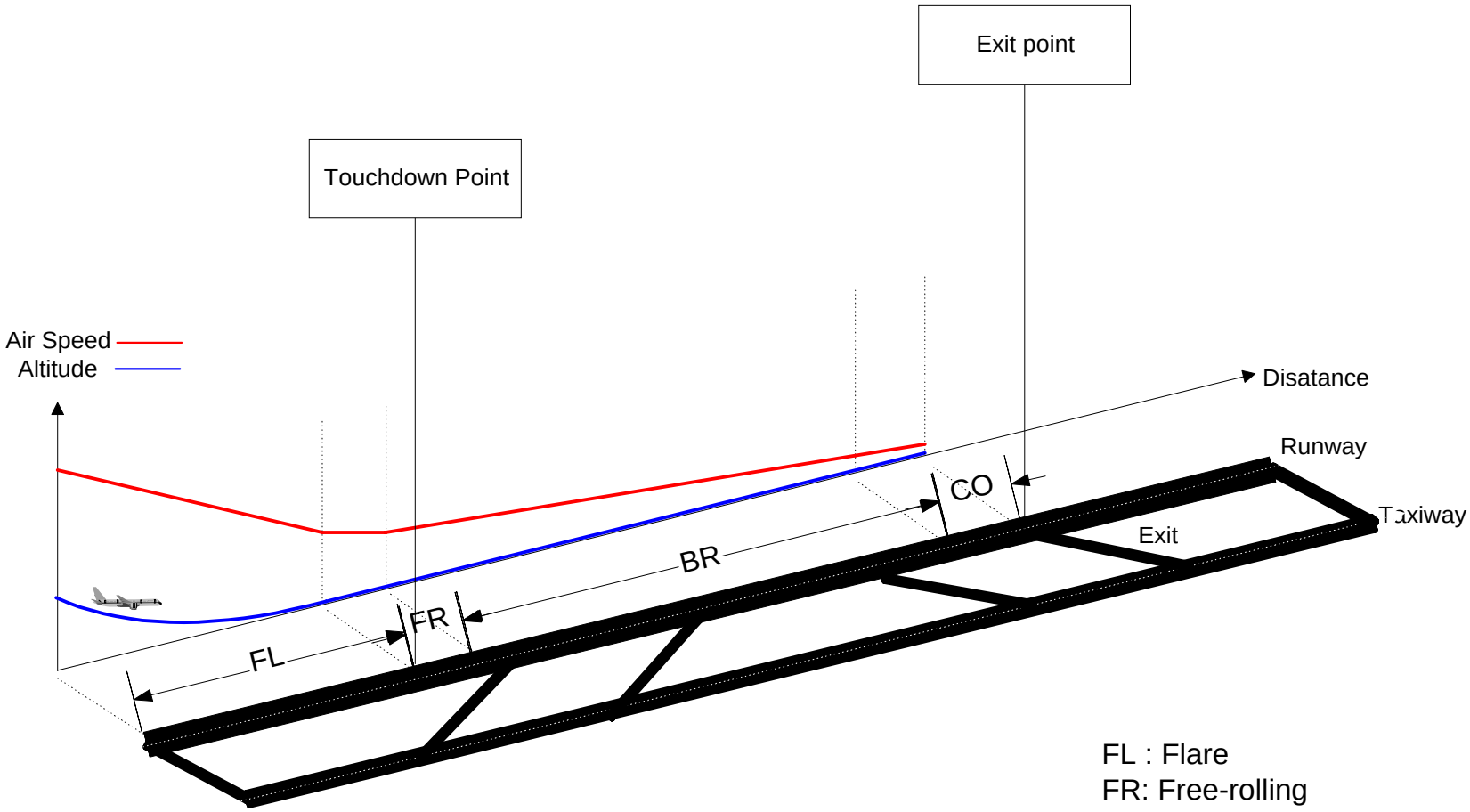


Algorithm: Others

- **Aircraft sequencing optimizer** for runway operations:
  - using the expected arrival and departure times and generate efficient sequence in runway operations
  - employs heuristic methods.

- **Aircraft behavior models** on Runways:
  - four phases to characterize the landing procedure: flare, free-rolling, braking, and coasting phases.
  - two phases to characterize the takeoff procedure: rolling and lift-off.

Algorithm: Four phases in landing procedure



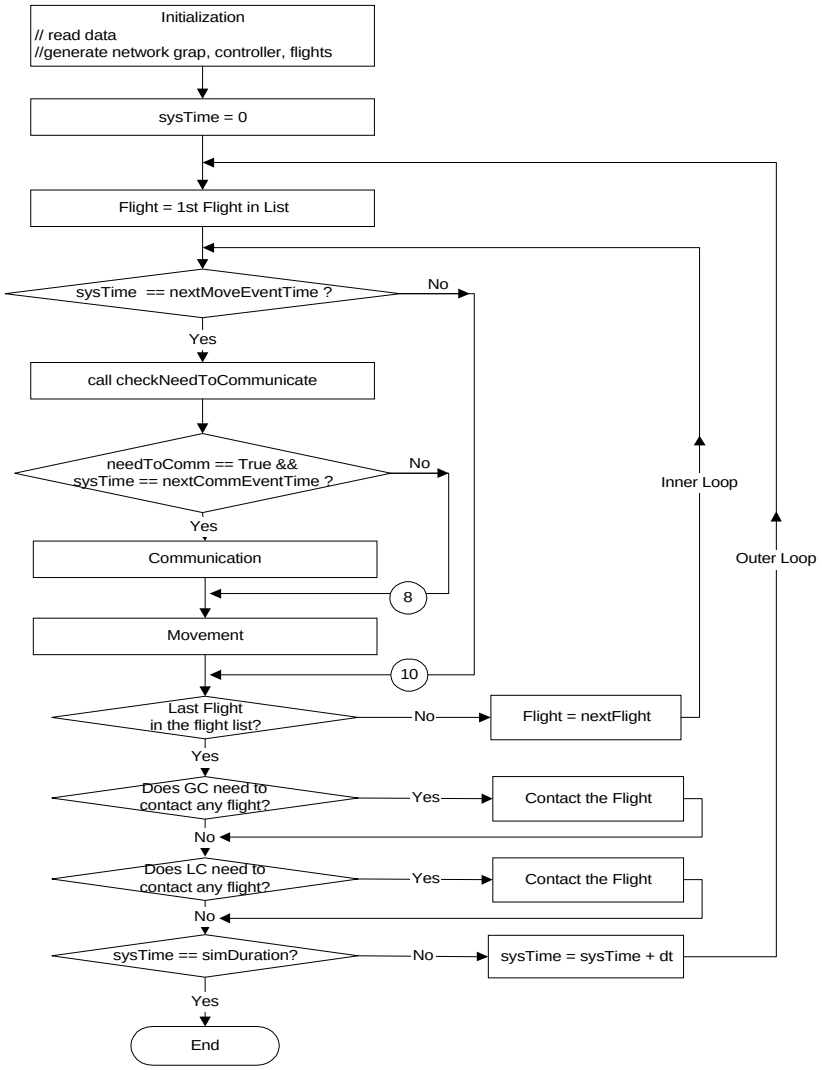
FL : Flare
FR: Free-rolling
BR: Braking
CO: Coasting

Data Structures

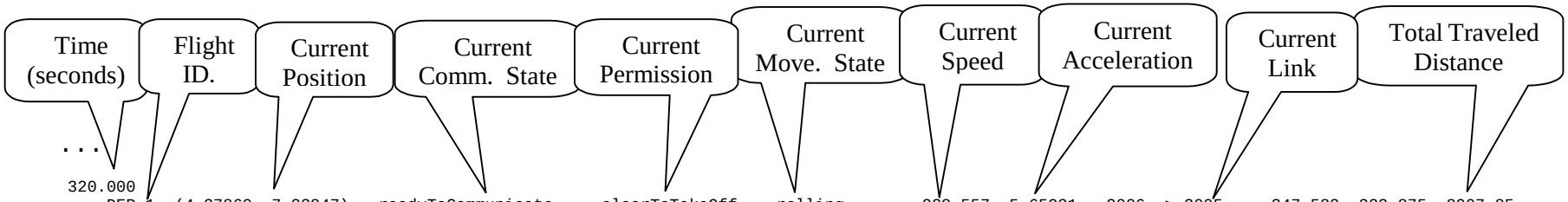
- Data structures play an important role in designing an efficient computer code.
- In VTASIM, two types of data structures are used: lists and queue.

Data structure type		Data
List	Array-based list	Node, Link
	Linked list	Flight schedule, Taxiing path
Array of linked list		Airport Network
Queue	FIFO queue	Aircraft on the link
	Sorted queue or Double-ended queue	Shortest path algorithms

Model Flowchart



Example of VTASIM Output: Log File

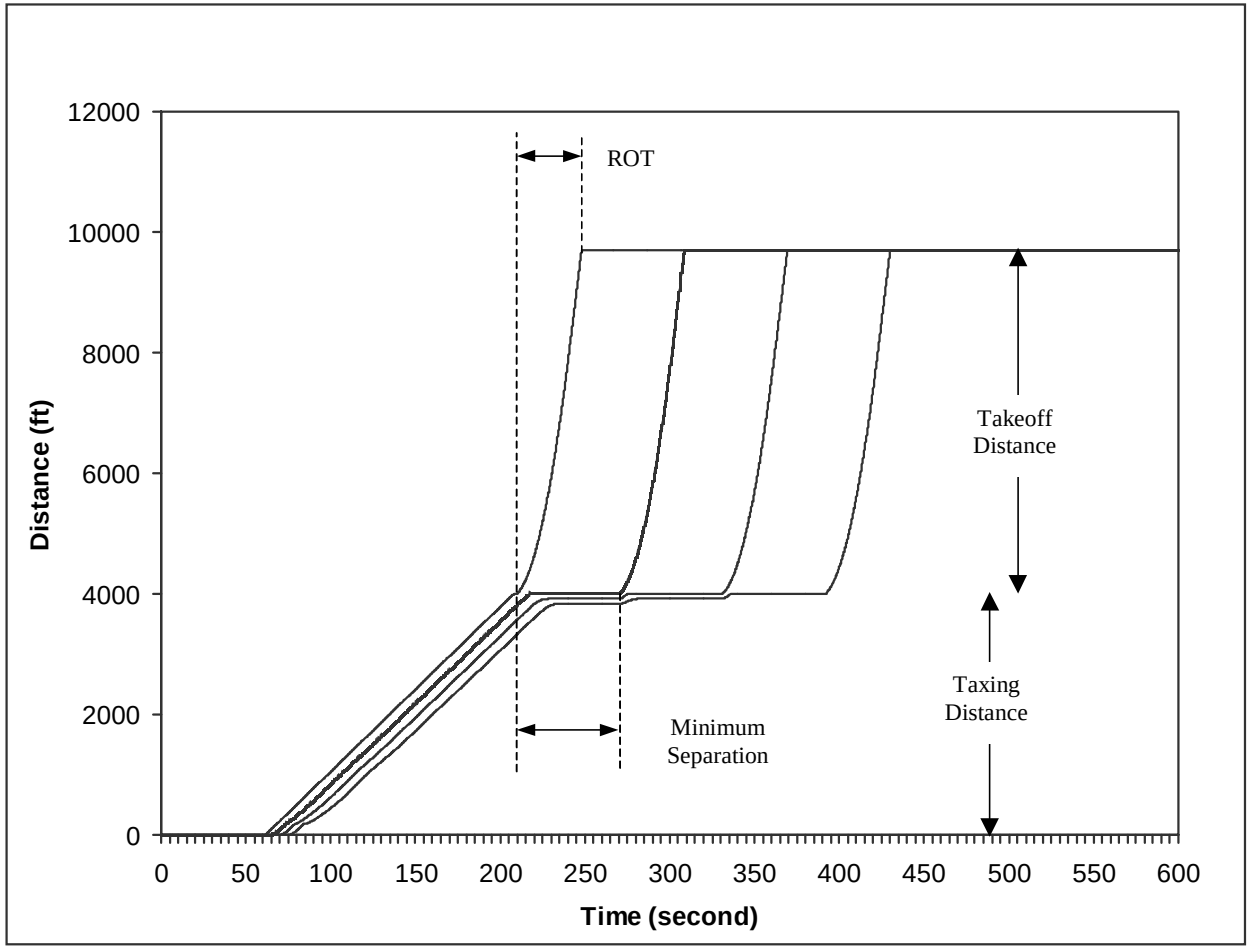



```
...
 320.000
     DEP_1  (4.27860, 7.23847)   readyToCommunicate     clearToTakeOff    rolling        228.557  5.65931   2006 -> 2005     347.582  322.875  8907.85
     DEP_2  (3.44770, 3.71363)   readyToCommunicate     clearToTaxi       taxiingToDepQue 27.3409  0.000000   1031 -> 2018     782.058  727.237  3832.22
     DEP_3  (3.65123, 6.51975)   readyToCommunicate     clearToTaxi       taxiingToDepQue 27.3409  0.000000   1011 -> 1014     185.988  107.714  608.929
     DEP_4  (3.24660, 6.64350)  waitControllerContact  waitThere         parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     DEP_5  (3.47540, 6.59730)  waitControllerContact  waitThere         parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     DEP_6  (3.47540, 6.59730)  waitControllerContact  waitThere         parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     DEP_7  (3.47540, 6.59730)  waitControllerContact  waitThere         parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     DEP_8  (3.47540, 6.59730)  readyToCommunicate     fileApproved      parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     DEP_9  (3.47540, 6.59730)  readyToCommunicate     fileApproved      parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
    DEP_10 (3.33330, 6.32750)  readyToCommunicate     fileApproved      parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     ARR_1  (2.80910, 5.01500)  readyToCommunicate     clearToTaxi       parking        0.000000  0.000000      0 -> 0          0  0.000000  0.000000
     ARR_2  (2.98857, 4.53792)   readyToCommunicate     clearToTaxi       taxiingToGate   27.3409  0.000000   1029 -> 1028     233.737  4.76052  6039.35
     ARR_3  (4.13276, 8.73577)   readyToCommunicate     clearToTaxi       taxiingToGate   16.3510  4.41148   1003 -> 2003     915.958  24.2862  6123.22
     ARR_4  (4.08470, 3.21800)   waitingCommand         waitThere         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
     ARR_5  (4.08470, 3.21800)   waitControllerContact  waitThere         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
     ARR_6  (4.08470, 3.21800)   waitControllerContact  waitThere         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
     ARR_7  (4.08470, 3.21800)   readyToCommunicate     unDecided         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
     ARR_8  (4.08470, 3.21800)   readyToCommunicate     unDecided         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
     ARR_9  (4.08470, 3.21800)   readyToCommunicate     unDecided         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
    ARR_10  (4.08470, 3.21800)   readyToCommunicate     unDecided         onFinal        0.000000  0.000000   2021 -> 2019     493.258  0.000000  0.000000
...
```

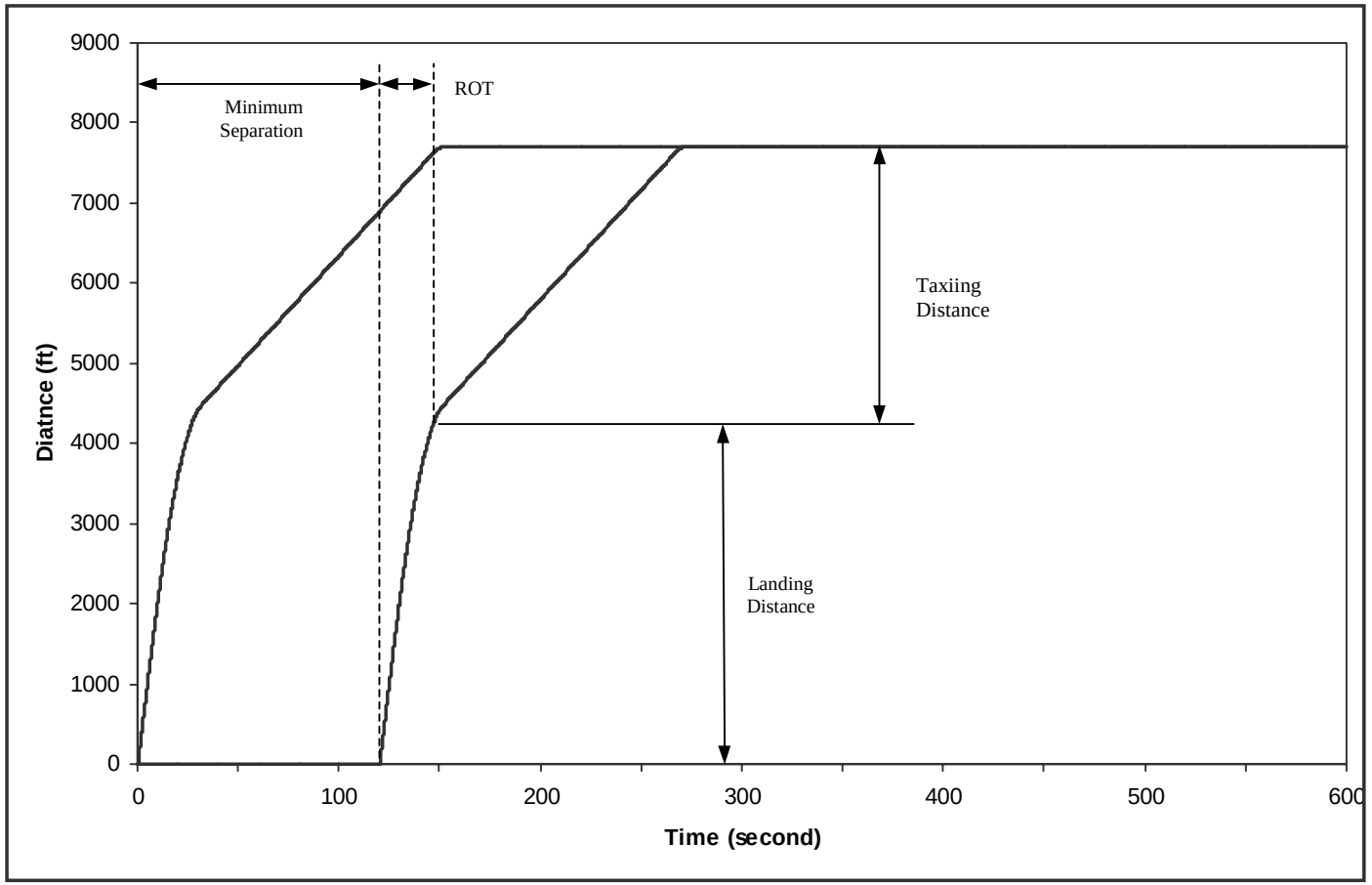
Example of Output: Summary File

```
< Simulation starts >
    system clock = 0 second
               At 1 sec, DEP_1 is removed from GC's PENDING list
               At 1 sec, DEP_1 is pushed back to GC's PROCESSING list
      ...
             At 17 sec., DEP_1 got "waitThere".
               this flight (ARR_1) is behind the schedule.
               -> scheduled time: 17   sysTime: 19
               At 19 sec., ARR_1 got "clearToLand".
      ...
    system clock = 7000 second
    system clock = 7200 second
< Simulation ends. >
------------------------------ SUMMARY -------------------------------
 Flight (Departure DEP_1, B727-100, Gate 1, Runway 36)
      Enters into the simulation at          : 1 sec.
      Taxiing Duration                       : 73 - 217
      Taxiing Delay                          : 2.22827
      Nominal Takeoff Time   (= NTOT)        : 186
      Sequenced Takeoff Time (= STOT)        : 268
      Actual Takeoff Time    (= ATOT)        : 289
      Runway Occupancy Time  (= ROT)         : 289 - 328
      Sequenced Delay        (= ATOT - STOT) : 21
      Runway Delay           (= ATOT - NTOT) : 103
...
   TotTaxiingDelay_sec = 47.9558
   TotRunwayDelay_sec = 6486
   TotDealy_sec       = 6533.96
   AvgTaxiingDelay_sec = 2.39779
   AvgRunwayDelay_sec = 324.3
   AvgDealy_sec       = 326.698
   Utilization factor (L/C) = totBusyTimeLC (=1234) / first 1 hour (= 3600) = 0.342778
   Utilization factor (G/C) = totBusyTimeGC (=1188) / first 1 hour (= 3600) = 0.33
```

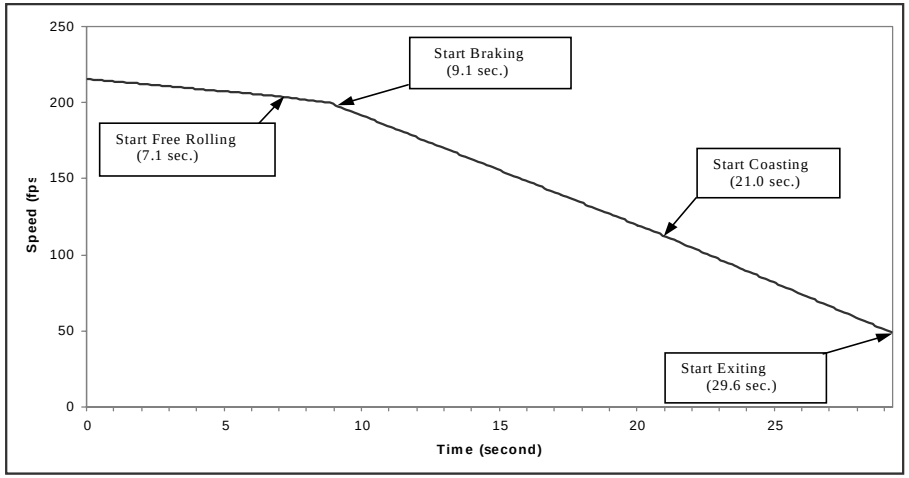
Example Output: Departure Profiles

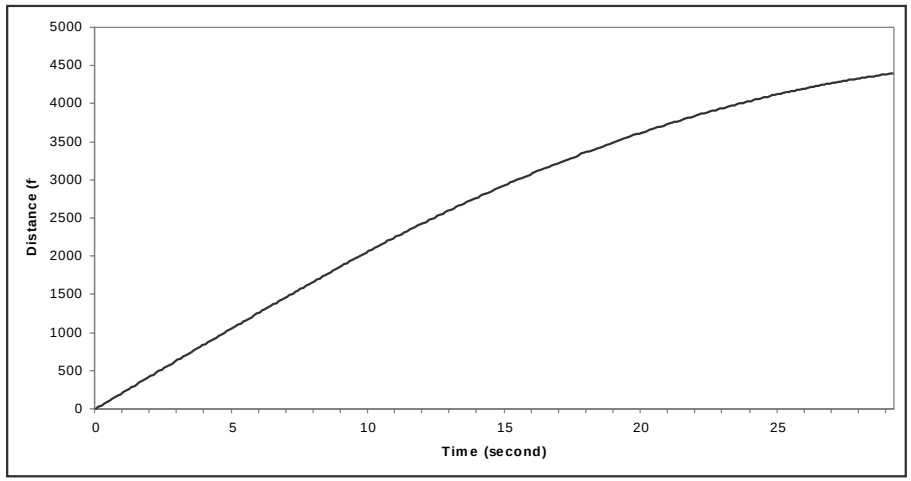


Example Output: Landing Profiles (1)

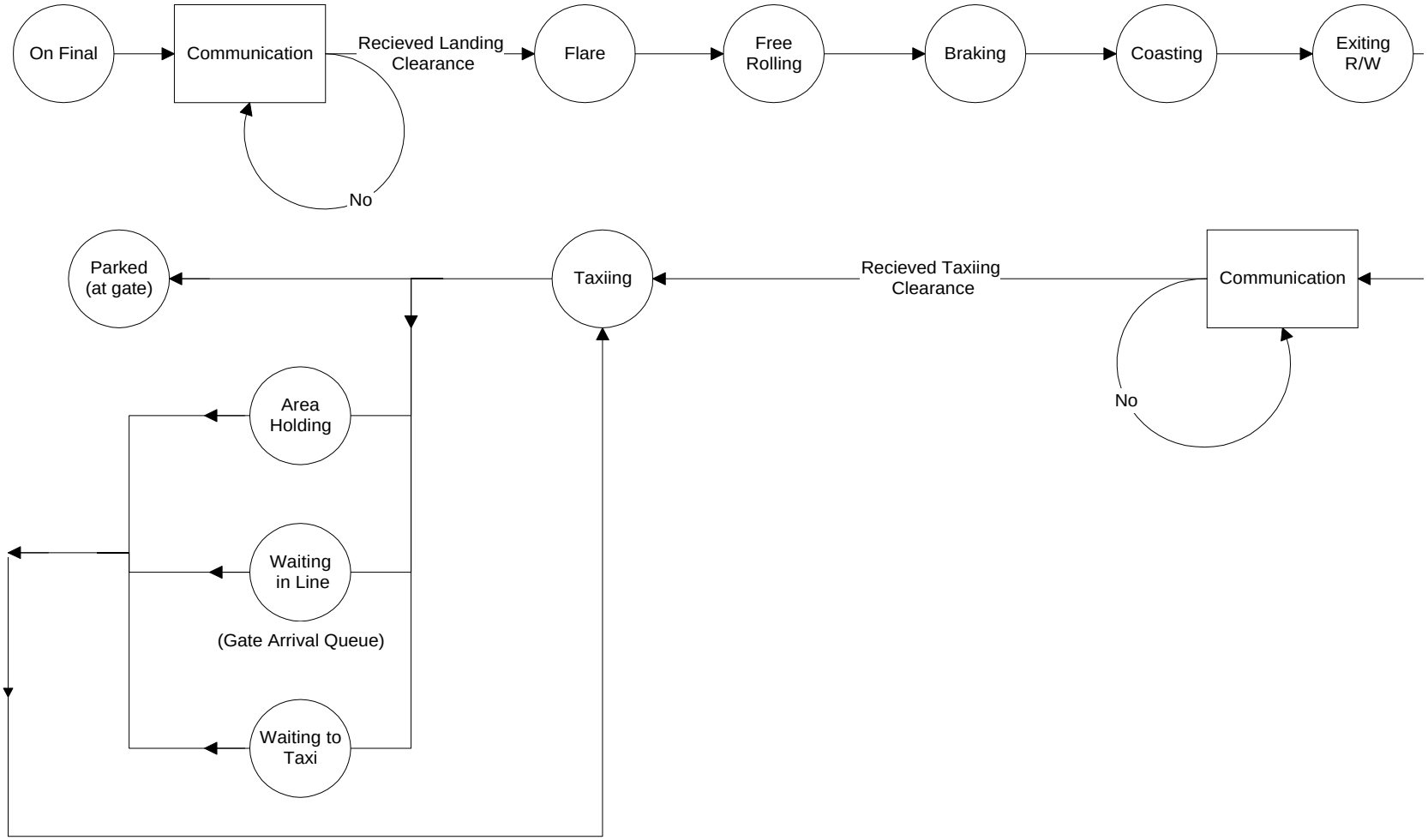


Example Output: Landing Profile (2)

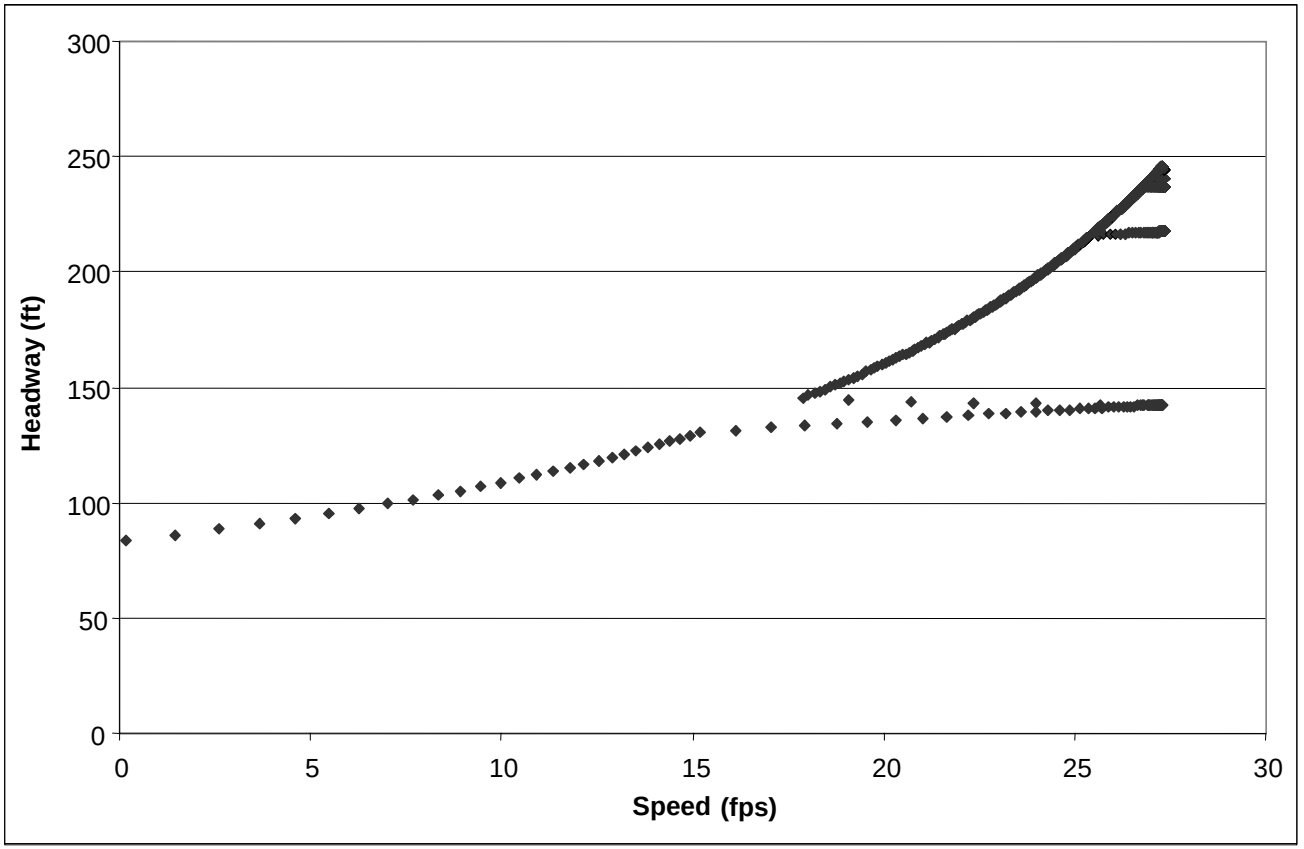




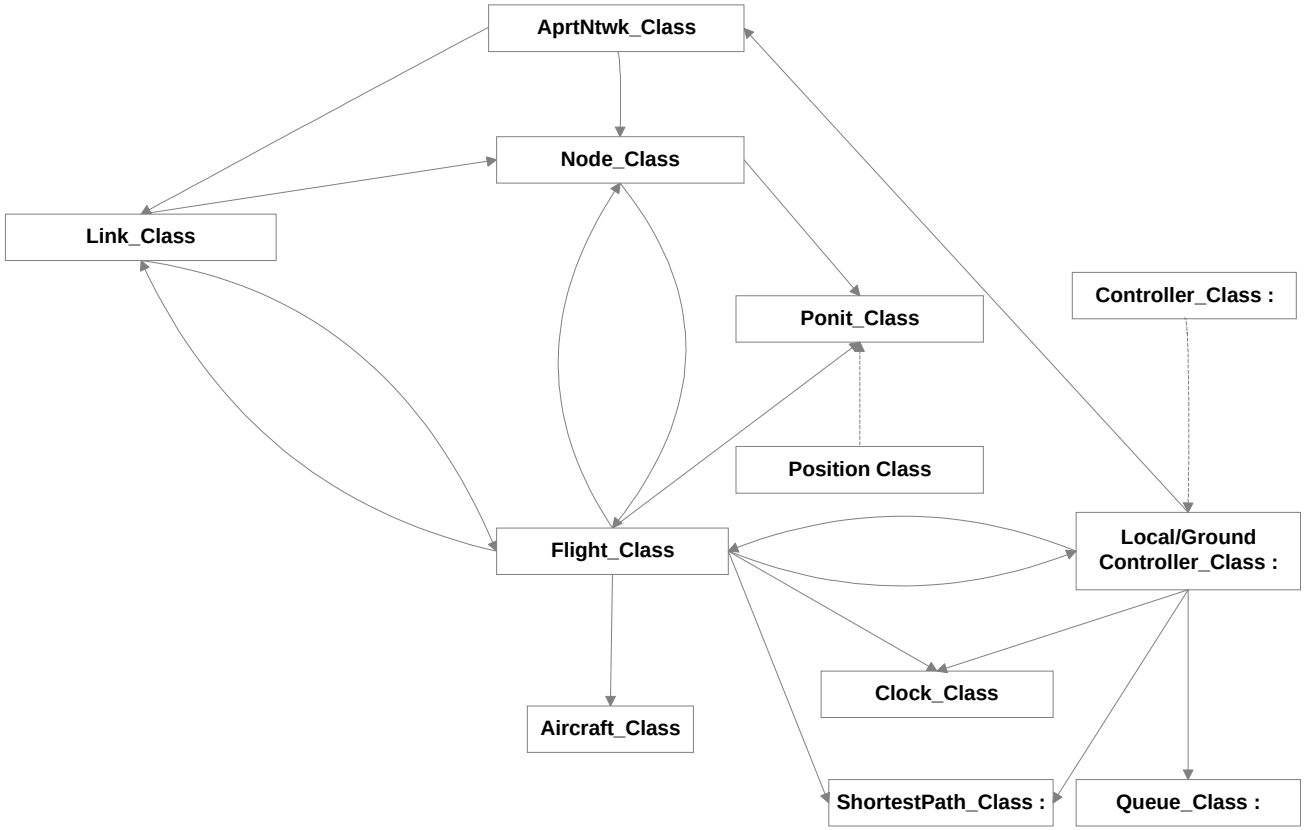
VTASM: Example of State Diagram (Arriving Aircraft)



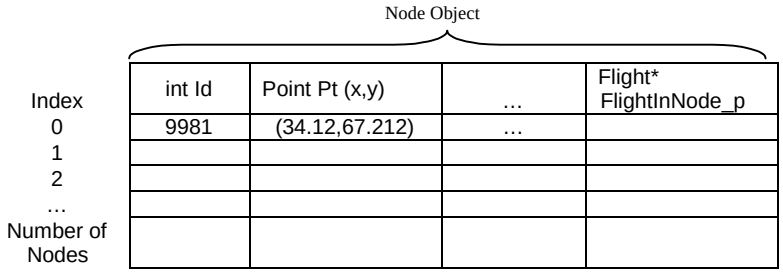
VTASM: Validation of Simulation Model (Aircraft-following Profile)



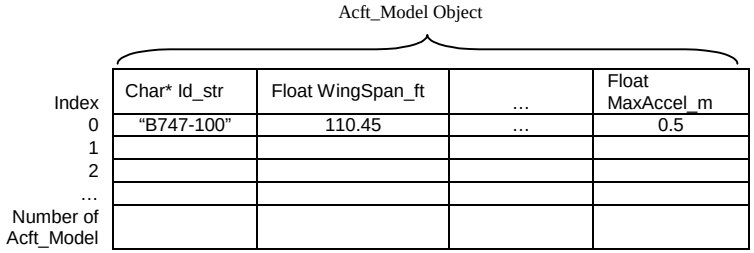
Object Diagram



Data Structures (1)

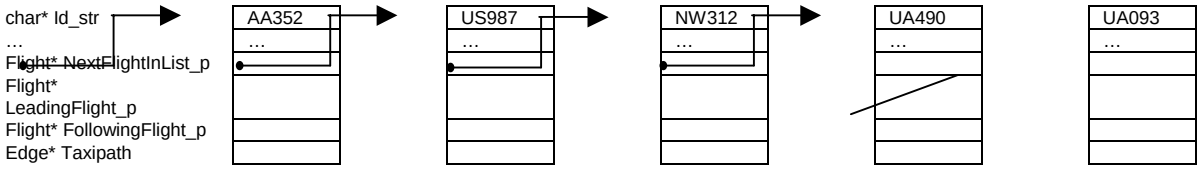


Array-based list for nodes

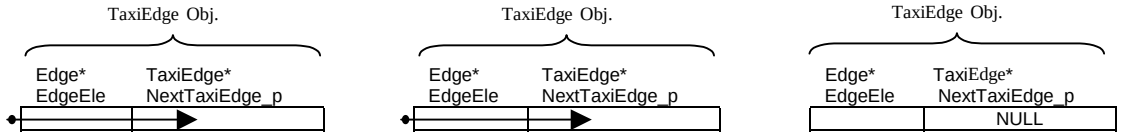


Array-based list for aircraft model

Data Structures (2)

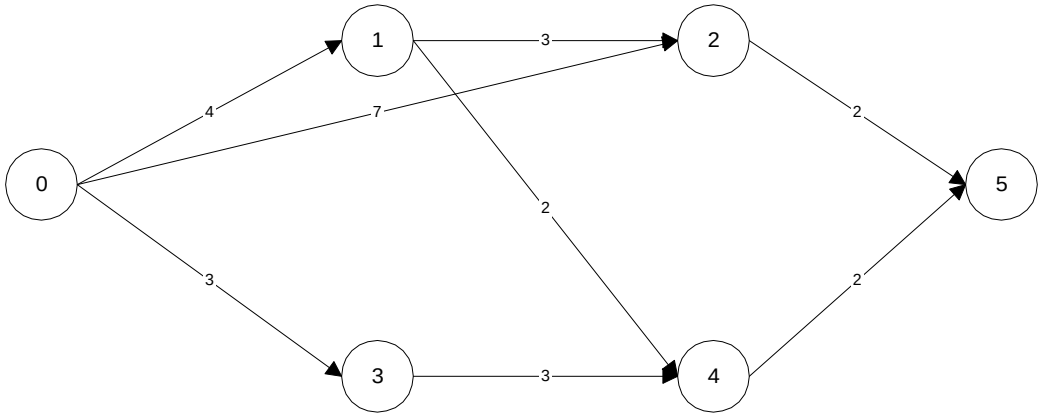


(Singly) linked list for edges

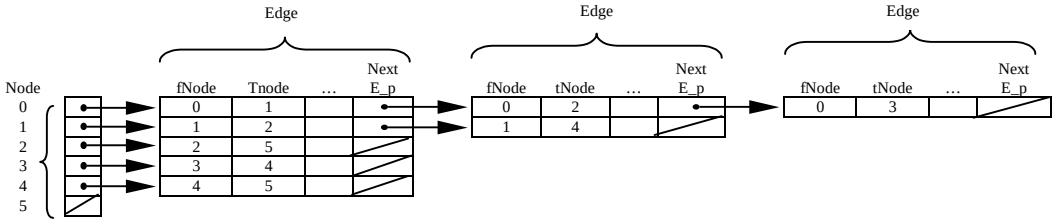


(Singly) linked list for taxiing path

Data Structures (3)



Sample network



Array of (singly) linked list for the sample network

Comparison of Voice-channel and Data-link (Total Delays)