# A Graph-Based Approach to Nominal Terminal Routing

Shannon Zelinski

NASA Ames Research Center

# Motivation

- Research and development in terminal airspace depends on routing
  - Terminal tactical conflict detection and resolution
  - Time-to-fly prediction for precision scheduling

- RNAV/RNP routing to the runway is expanding but not everywhere yet

# Motivation

## We spend a lot of time and effort developing routing models

- Fast-time concept benefit assessments
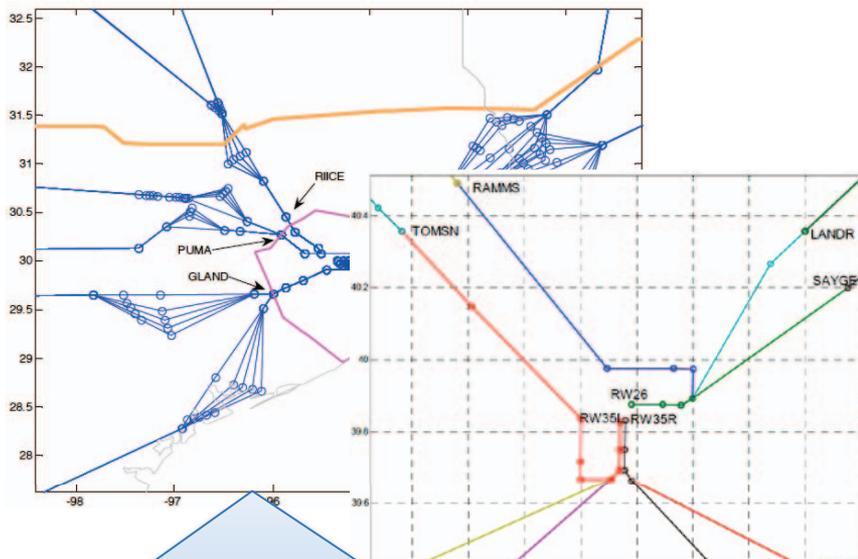


Houston (IAH) arrival routing model for use in the Trajectory Analysis and Modeling Environment

- Human-in-the-loop tools assessments
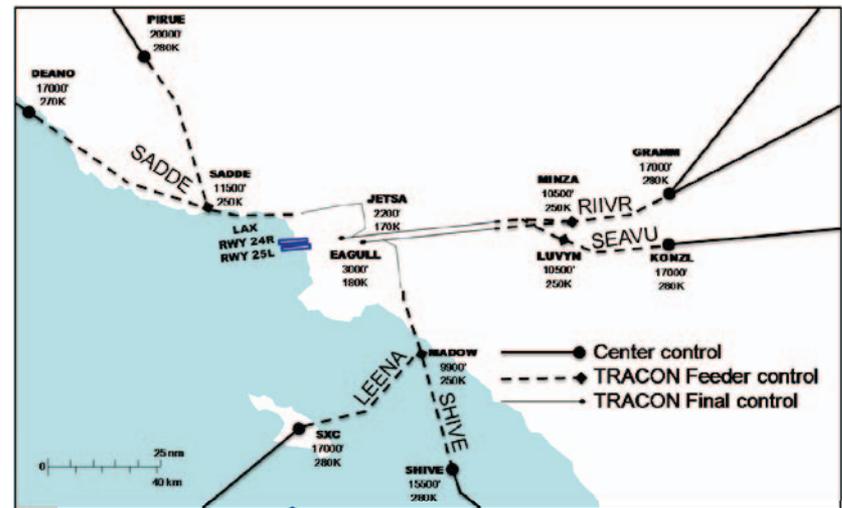


Los Angeles (LAX) arrival routing model for use in the Multi-Aircraft Control System

# Motivation



Published Routes

Flight Tracks

Routing Model
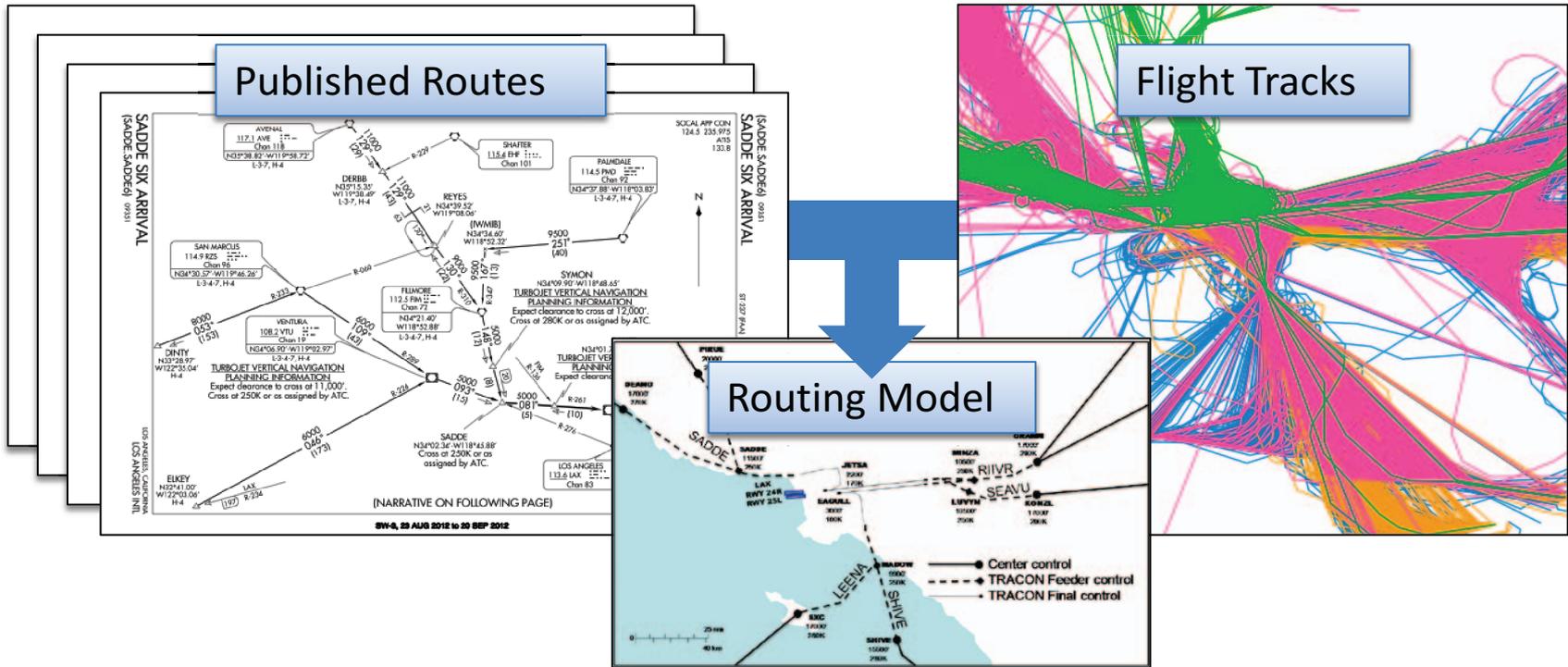
- Many of today's published routes do not contain details between the meter fixes and runways.

- Actual common paths may deviate from published routes.

- Visual analysis of flight tracks is time consuming and subjective.

# Motivation

## Need lower cost, faster methods to expand concept assessment scope
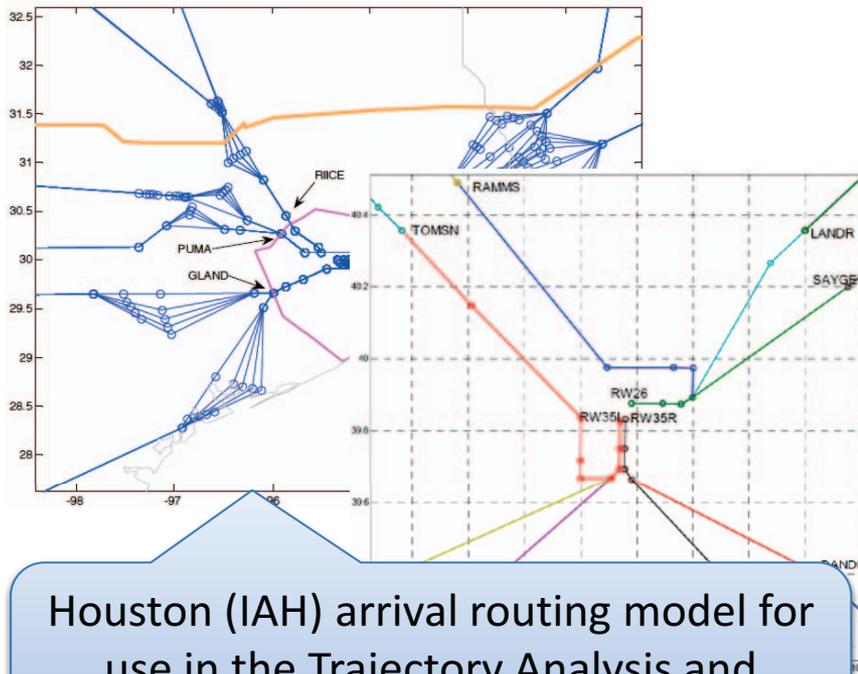


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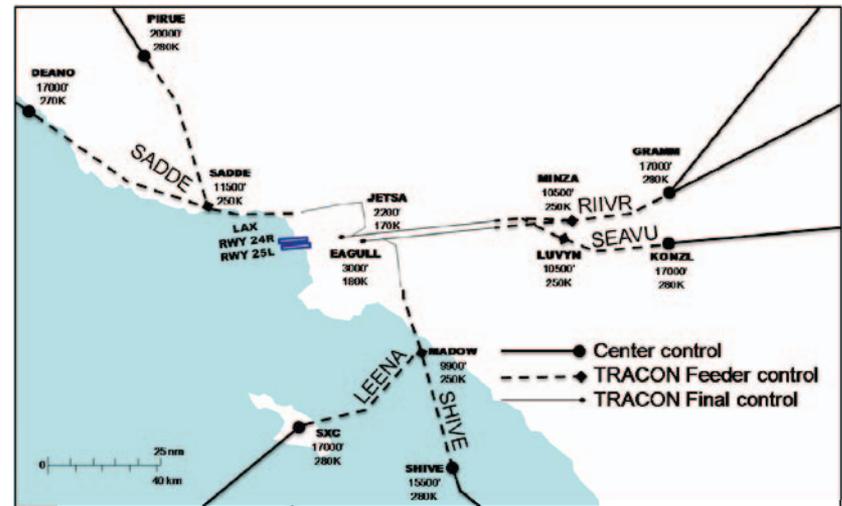


Los Angeles (LAX) arrival routing model for use in the Multi-Aircraft Control System

# Objective

Define nominal terminal routing all the way to the runway.

- Efficient
  - Low cost
  - Fast turn-around
- Realistic
  - Objective
  - Distinct dominant flows
  - Path options representing standard path control techniques

# Outline

- Graph-based method
- Results
  - Differences in graph-based routes
  - Comparison with other method characteristics
    - Manual (Timar et. al, 2011)
    - K-means-based (Leiden and Atkins, 2011)
- Graph-based path options
- Summary

# Graph-Based Method
## Overview

Given a set of two dimensional flight tracks to a shared endpoint

- Simplify flight tracks

- Generate graph

- Generate shortest path graph

- Refine shortest path graph

# Graph-Based Method
## Simplify Flight Tracks
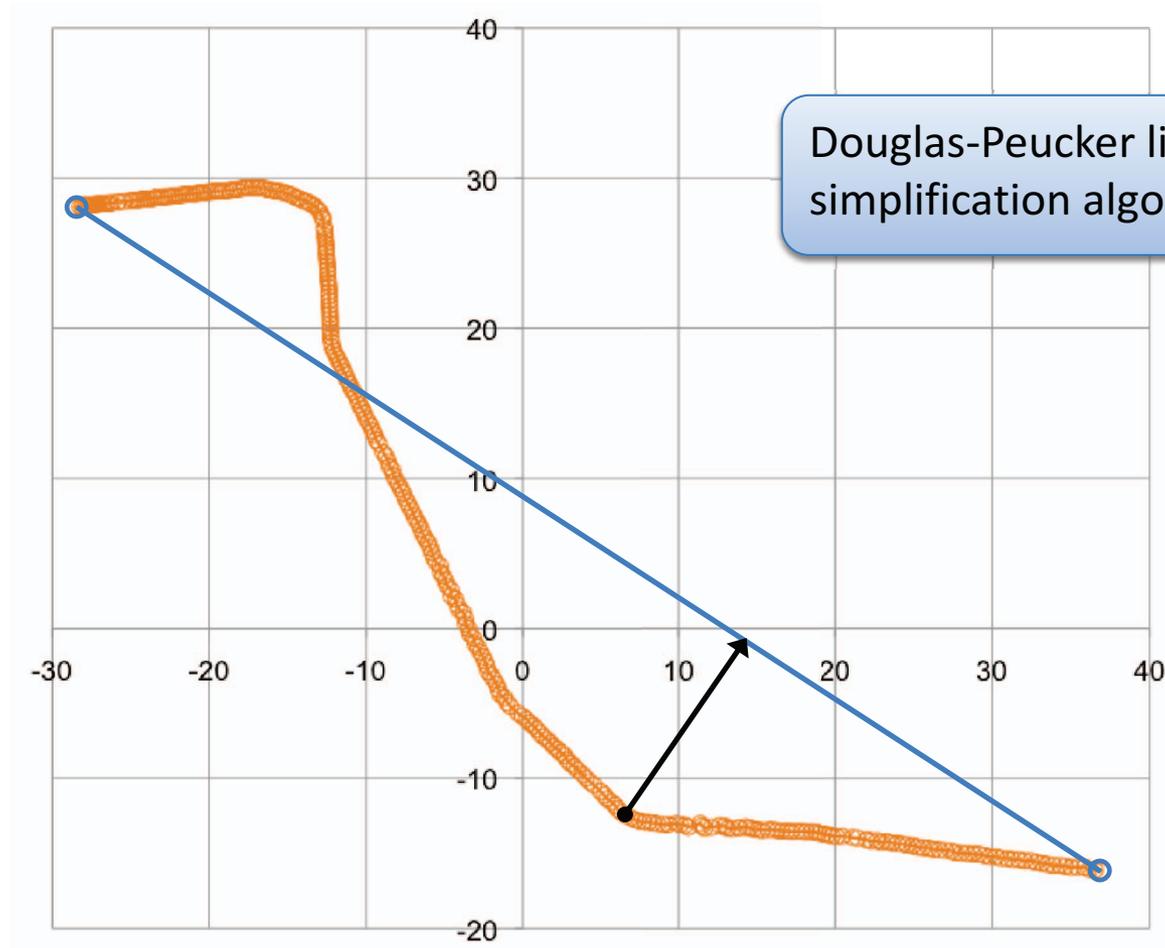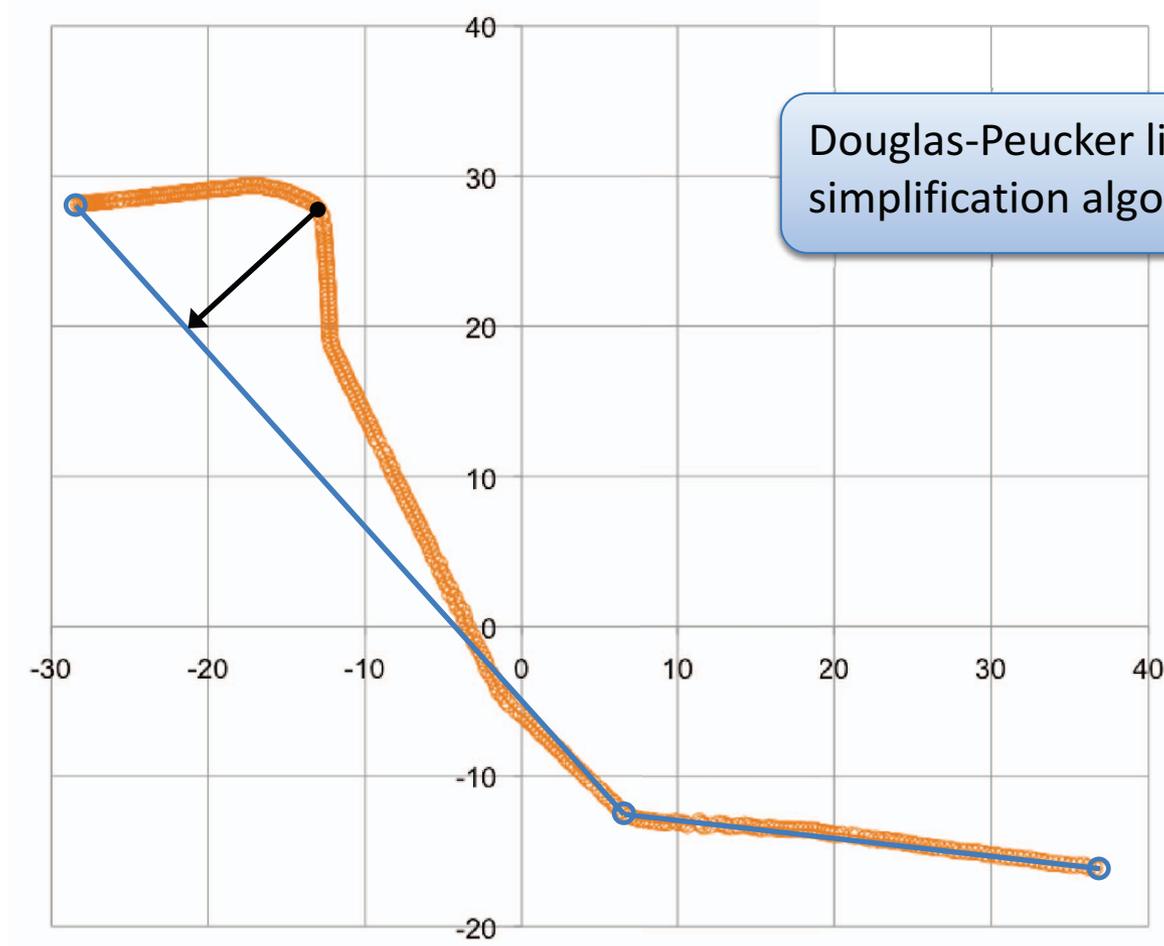


Douglas-Peucker line simplification algorithm

# Graph-Based Method
## Simplify Flight Tracks



Douglas-Peucker line simplification algorithm

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Douglas-Peucker line simplification algorithm
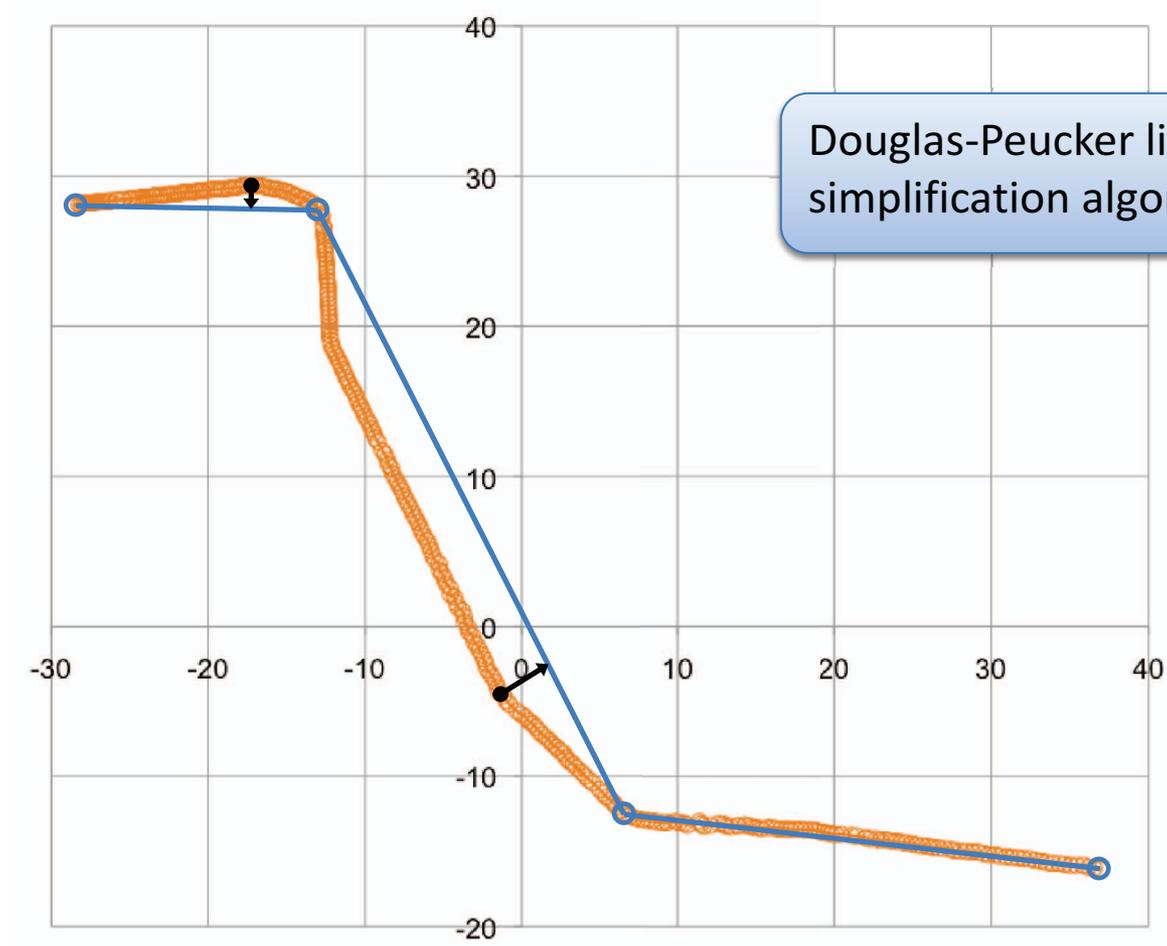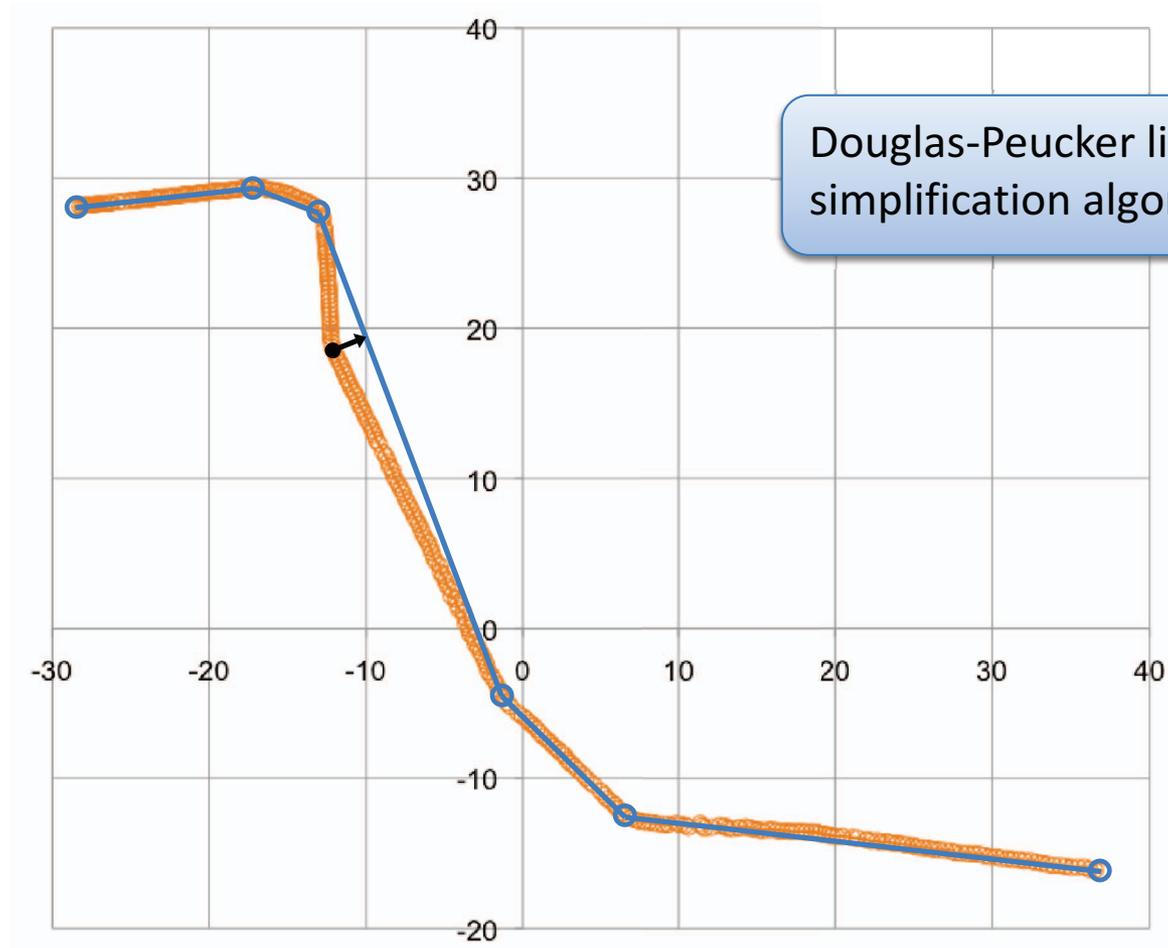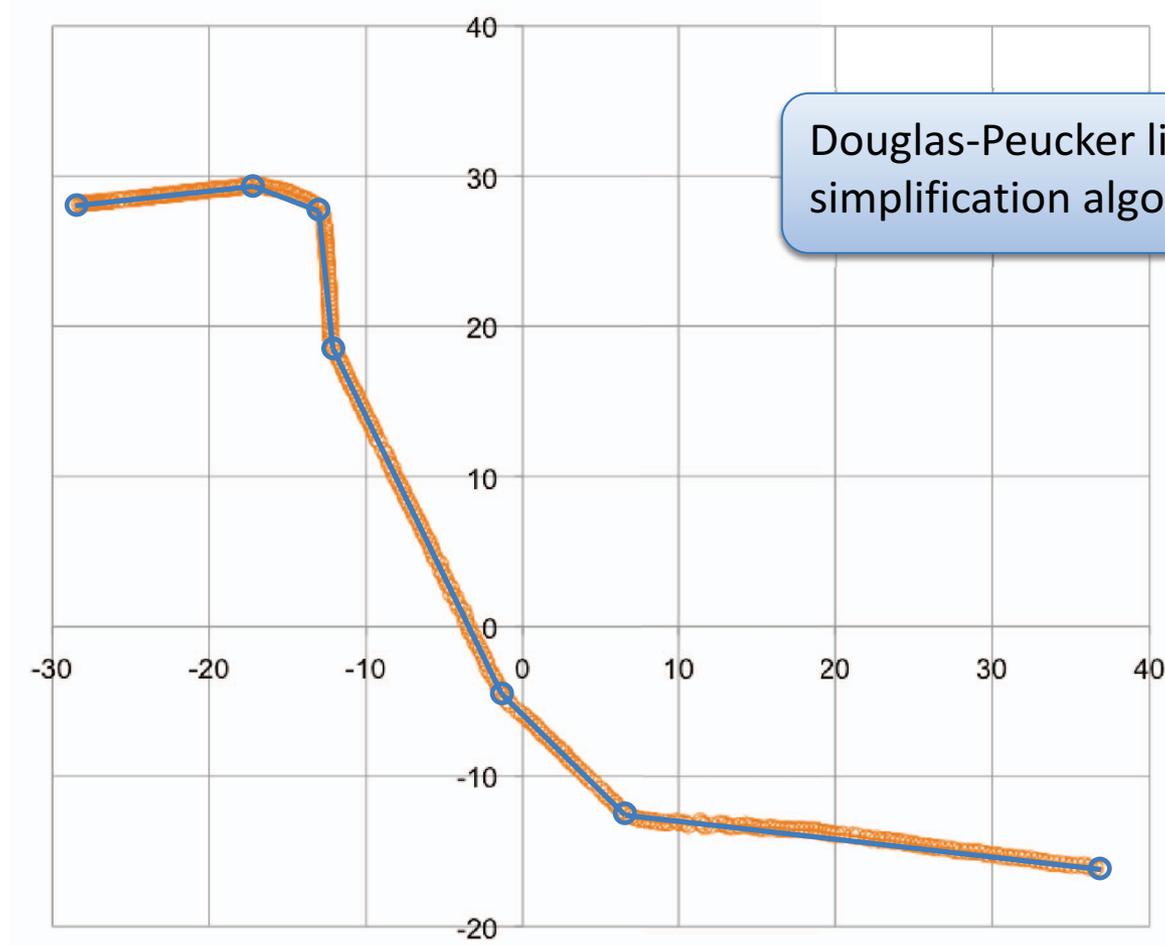
# Graph-Based Method
## Simplify Flight Tracks
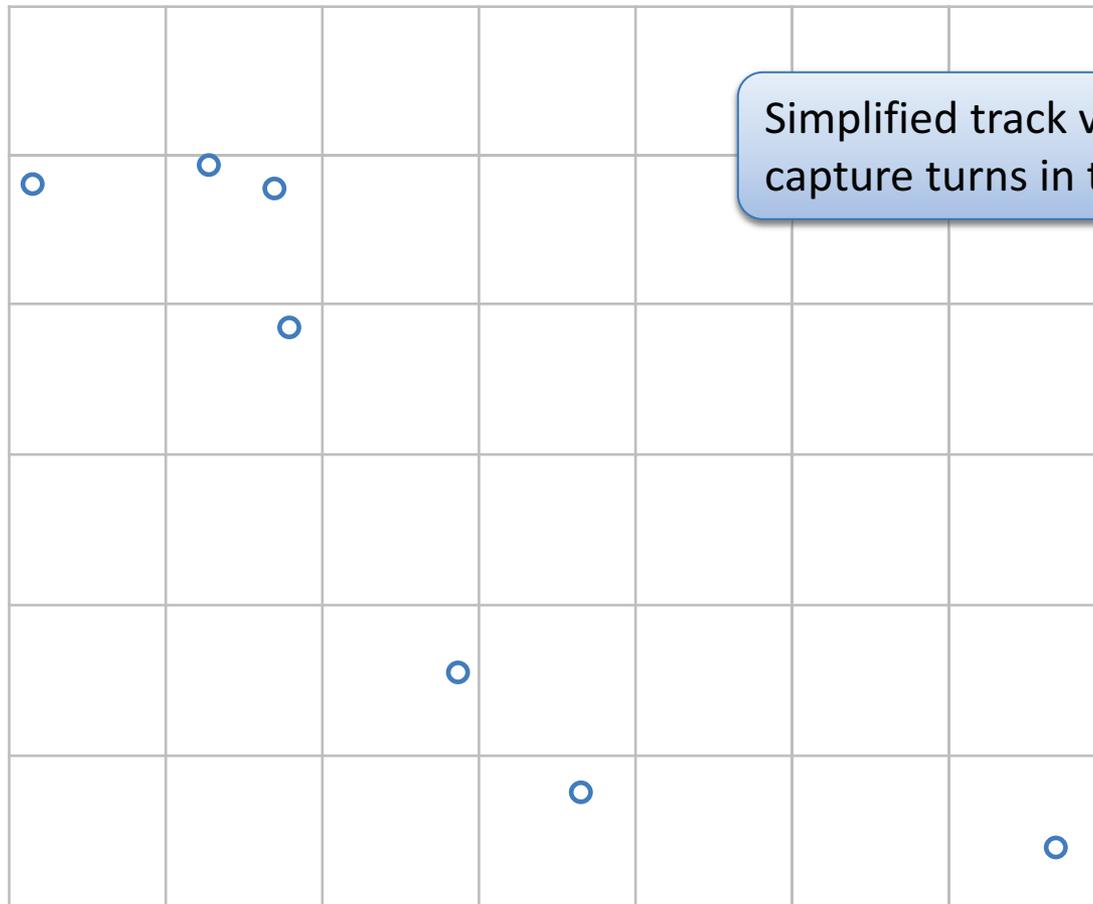


Simplified track vertices capture turns in the track

# Graph-Based Method
## Simplify Flight Tracks



Simplified track vertices for many flights
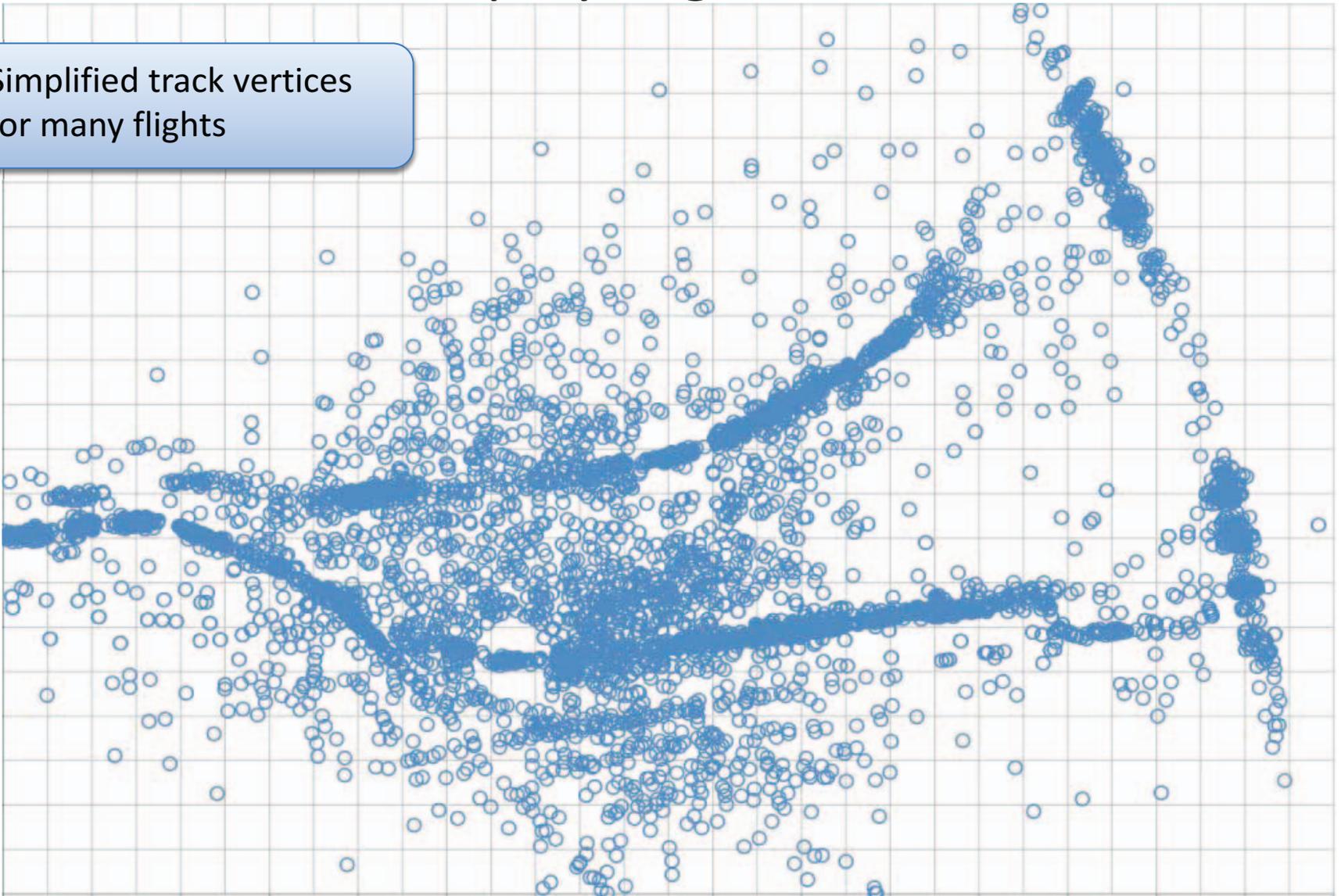
# Graph-Based Method
## Generate Graph

Cluster track vertices into weighted graph nodes

Node weight = number of flights represented by clustered vertices

< 1.5 nmi
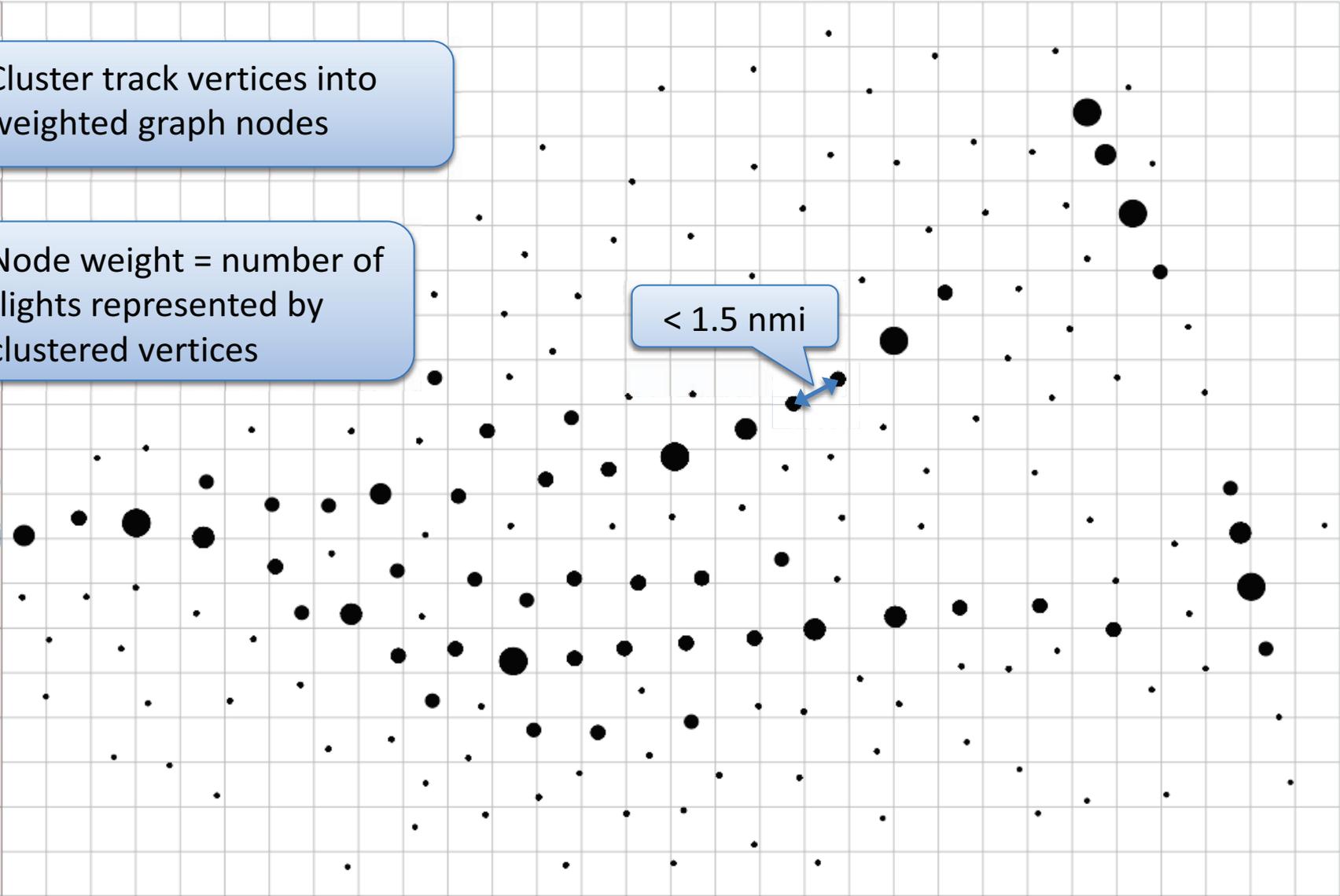
# Graph-Based Method
## Generate Graph



Place weighted links between nodes.

Link weight = number of flights travelling the link
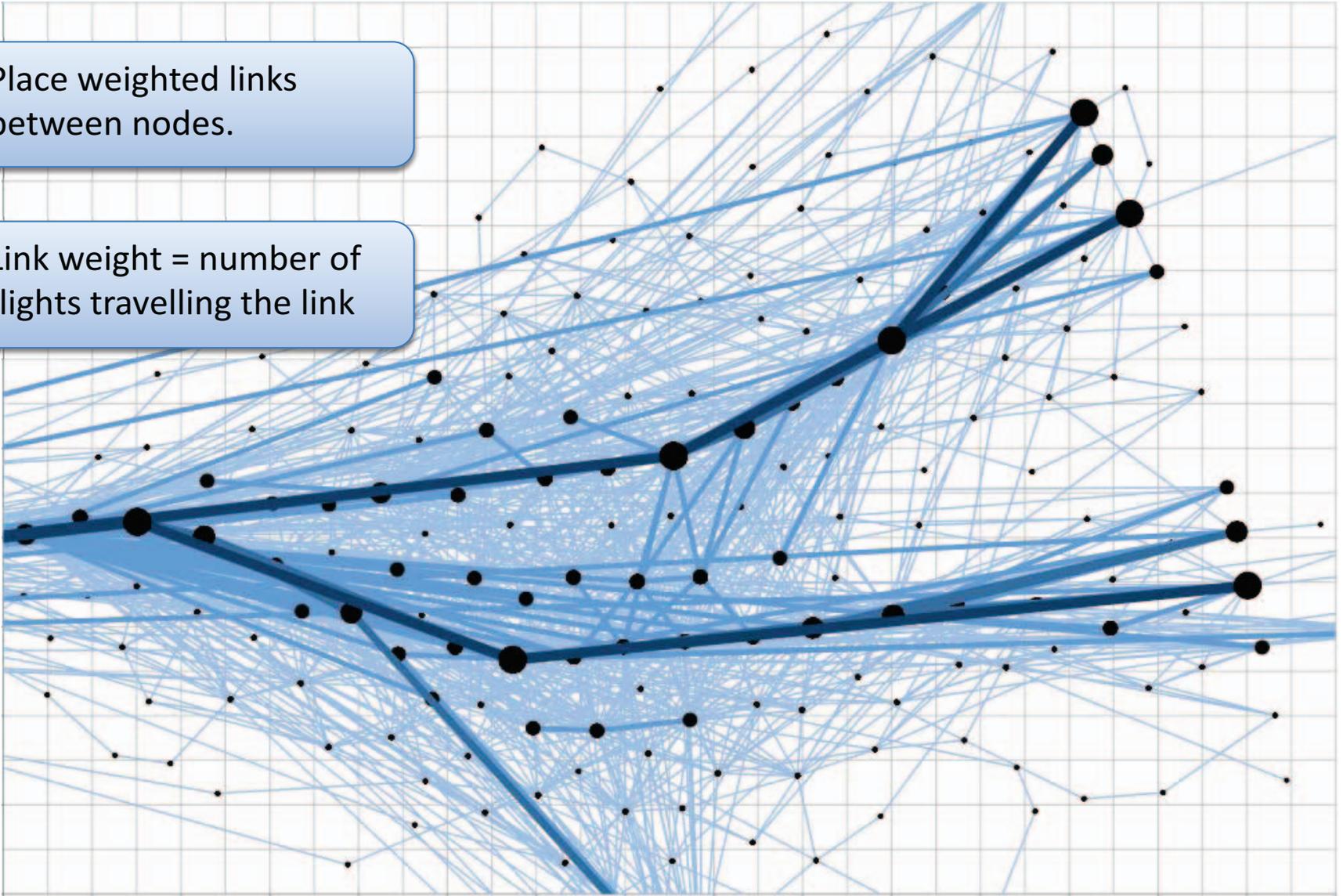
# Graph-Based Method
## Generate Shortest Path Graph



Find shortest path (Dijkstra) from each source to sink.

Link cost function = $\dfrac{\text{length}}{\text{weight}}$
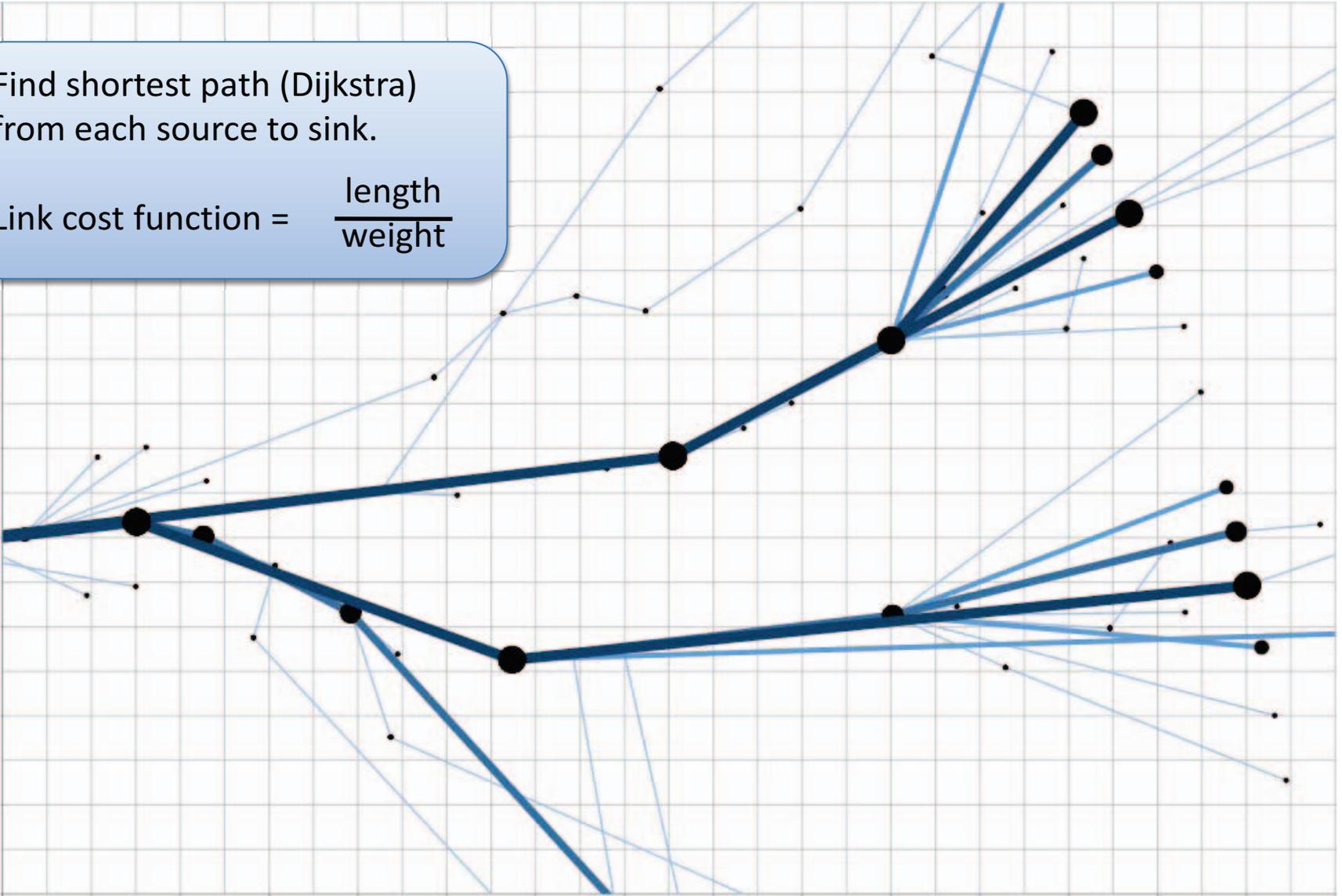
# Graph-Based Method
## Refine Shortest Path Graph



- Filter low weight links
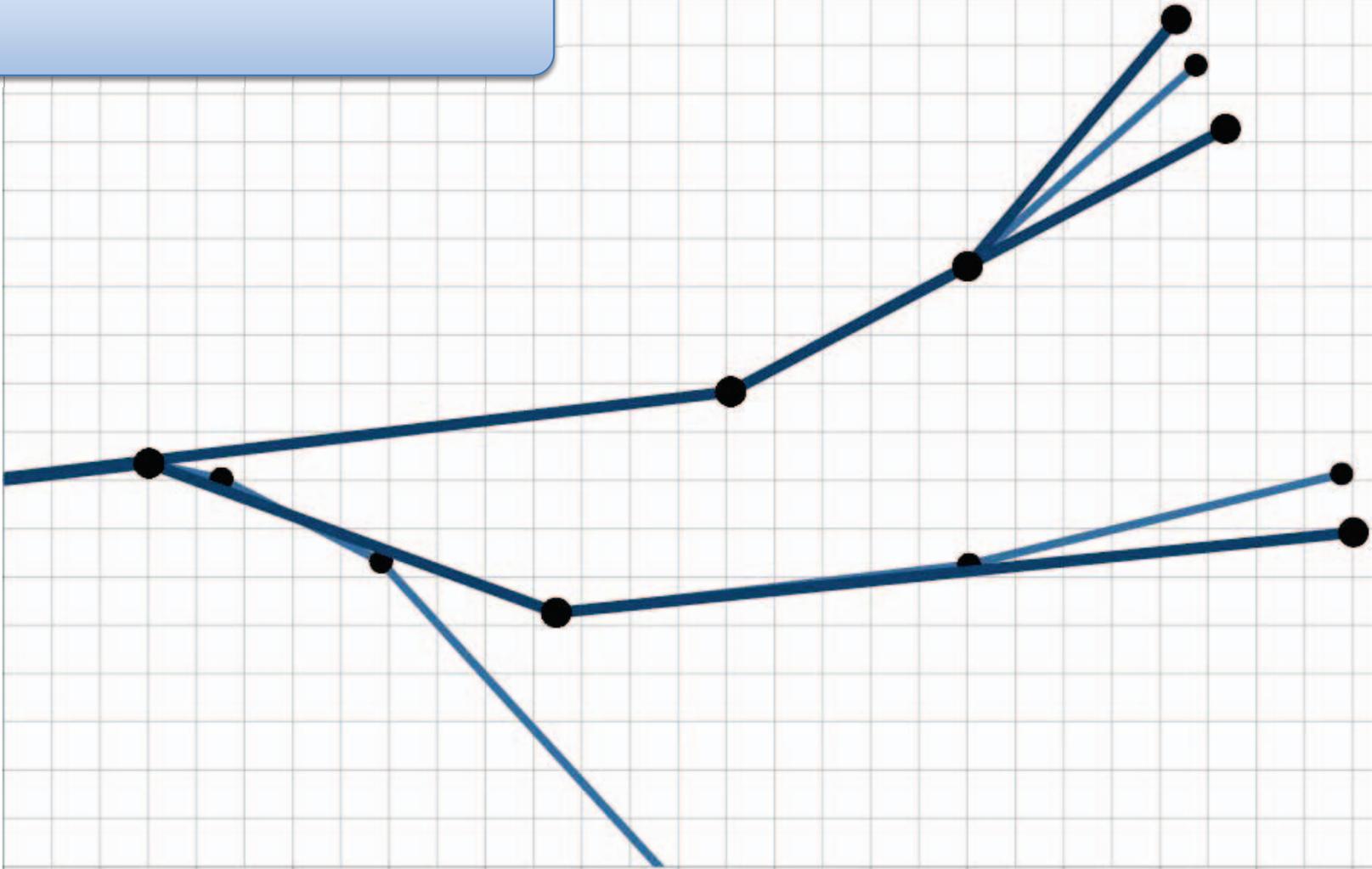
# Graph-Based Method
## Refine Shortest Path Graph

- Filter low weight links
- Refine further
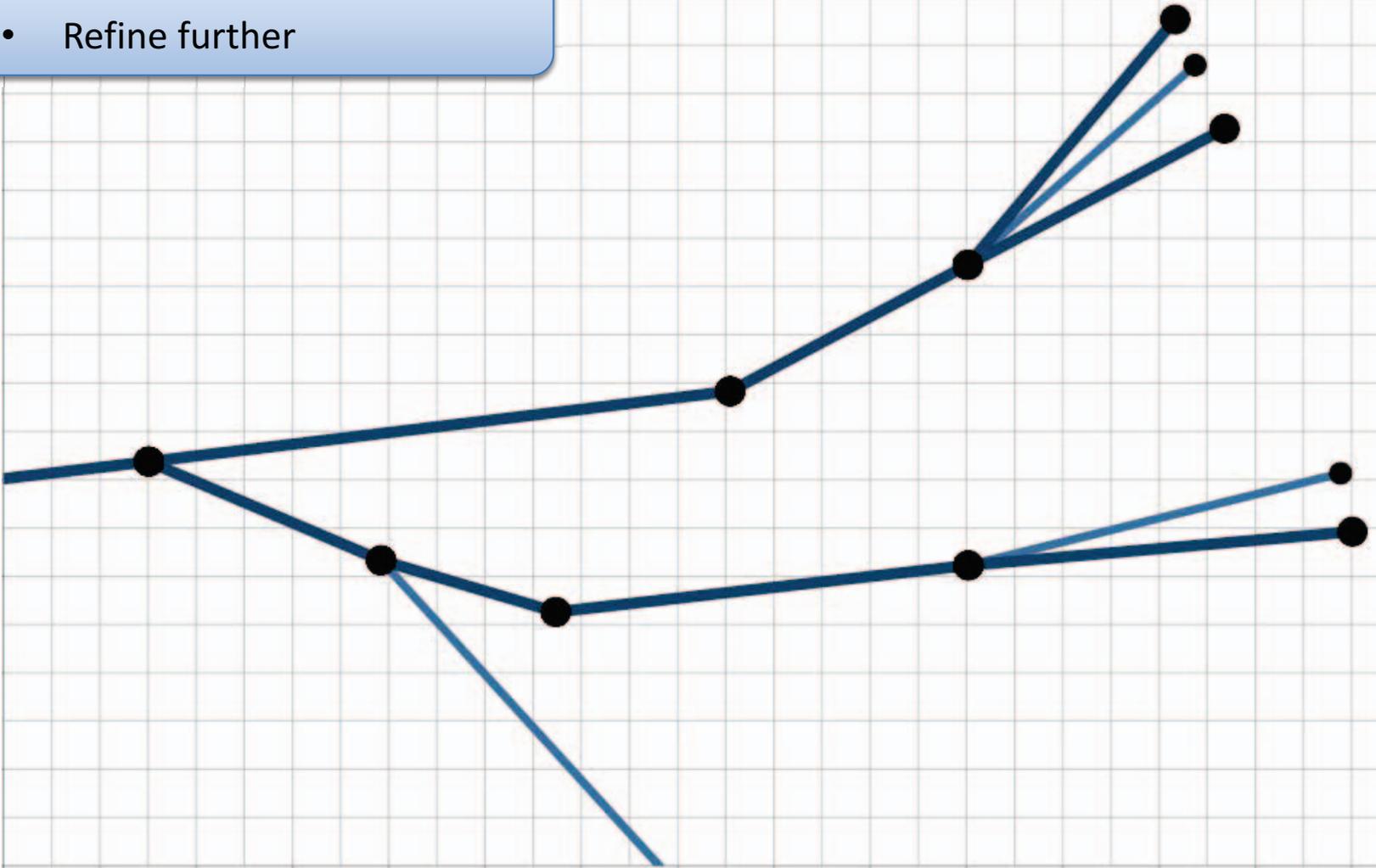
# Graph-Based Results
## Algorithm Input

52 days of Southern California TRACON track data

- Los Angeles International (LAX)

- Orange County (SNA)

# Graph-Based Results



LAX
24R ——————
25L – – – –

Jet

24R
25L

Turbo

Different routes for Jet and Turbo

# Graph-Based Results



24L

25R

LAX Departures
24L ———
25R – – – –

Turbo

Jet

Different routes for Jet and Turbo

# Graph-Based Results



SNA

Arrivals ———

Departures — — — —

Jet

Piston

Turbo

19R

Different routes for Piston than Jet and Turbo
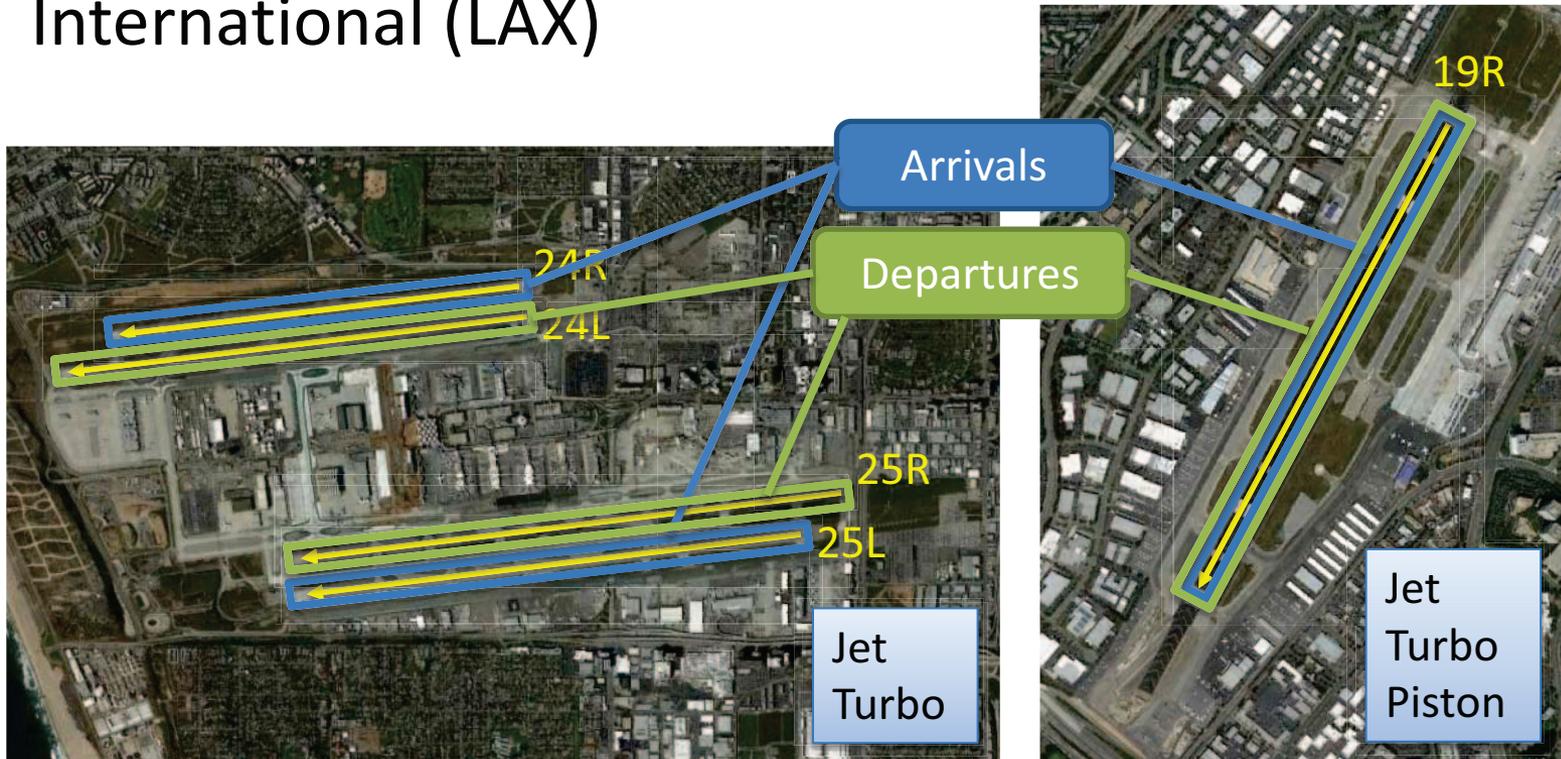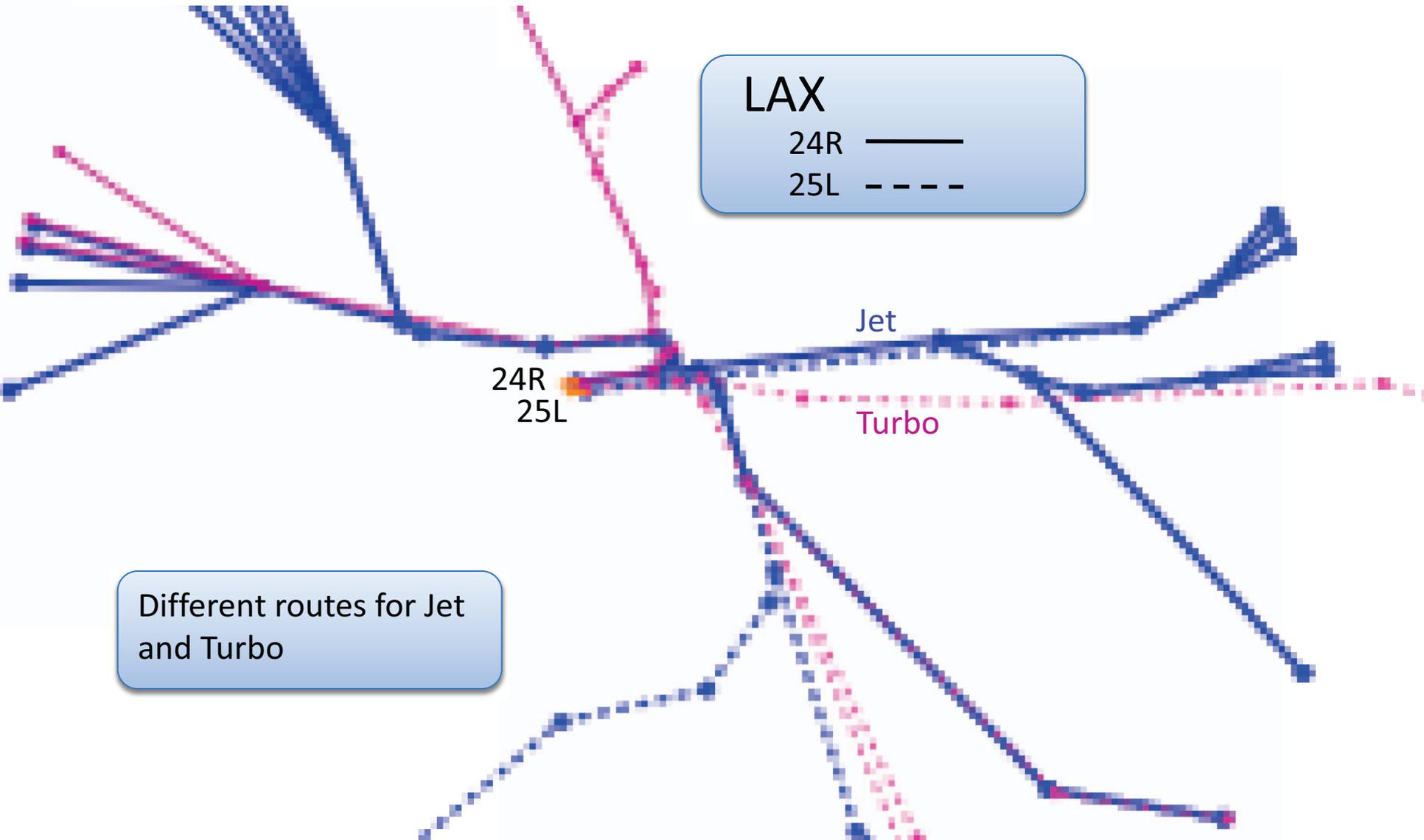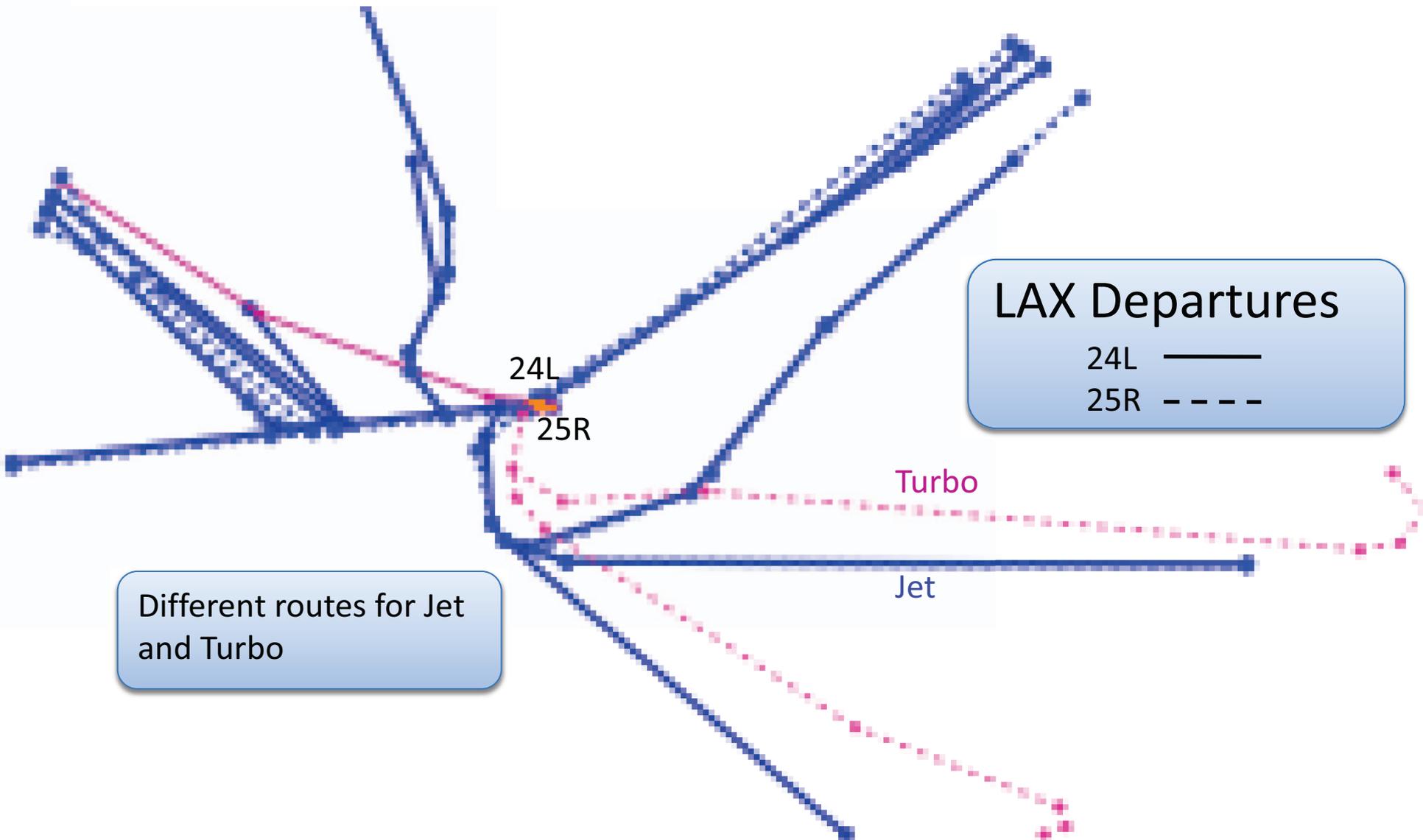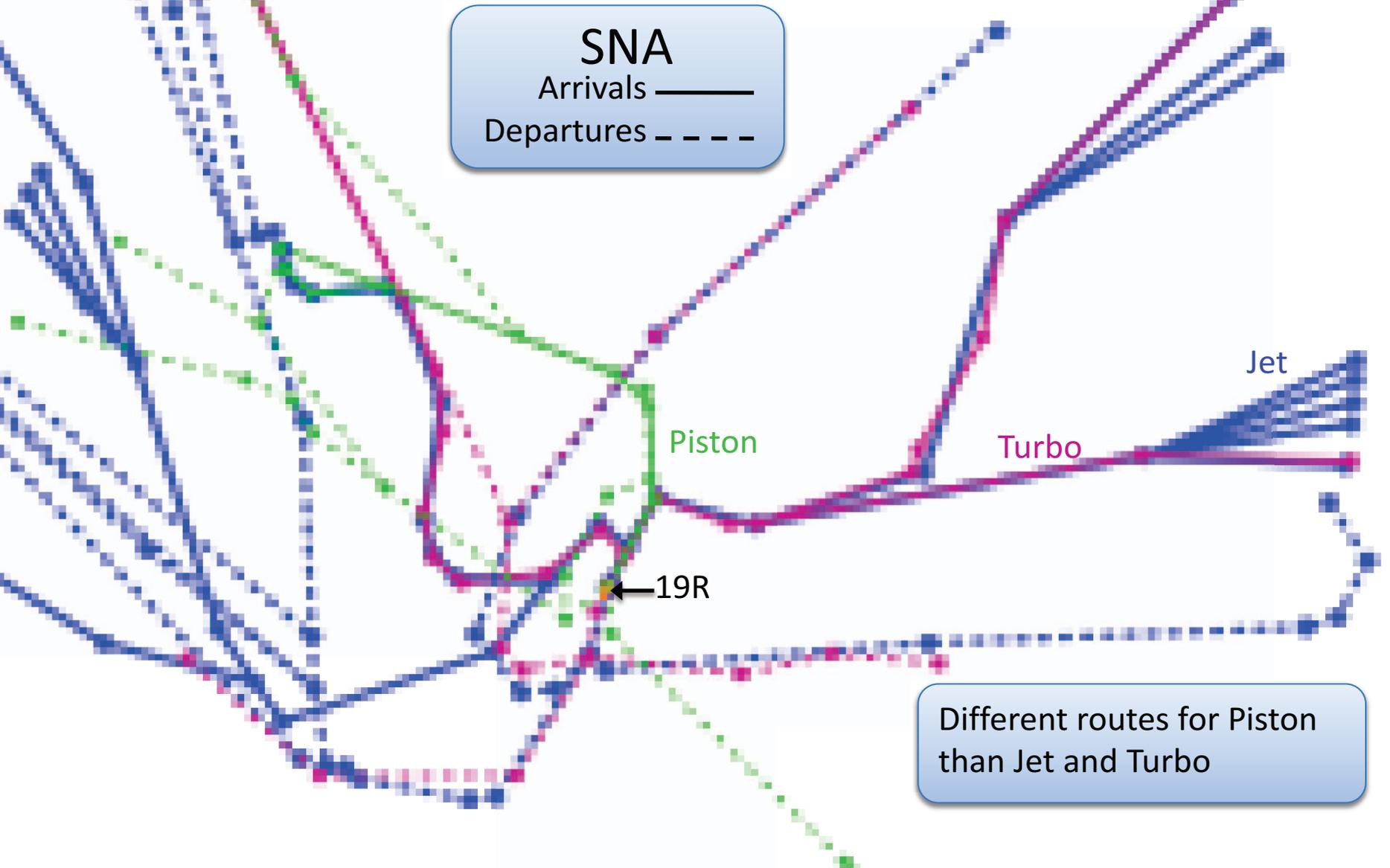
# Other Methods

- ## Manual method (Timar et. al., 2011)
  - Modified published routing based on detailed inspection of flight tracks
  - Detailed and subjective process

- ## K-means-based method (Leiden and Atkins, 2011)
  - Divide all flight trajectories into the same number of samples
  - K-means cluster trajectories based on average Euclidean distance between all $i^{th}$ samples along each trajectory

# Comparison Results



LAX Arrivals

Manual
K-means
Graph
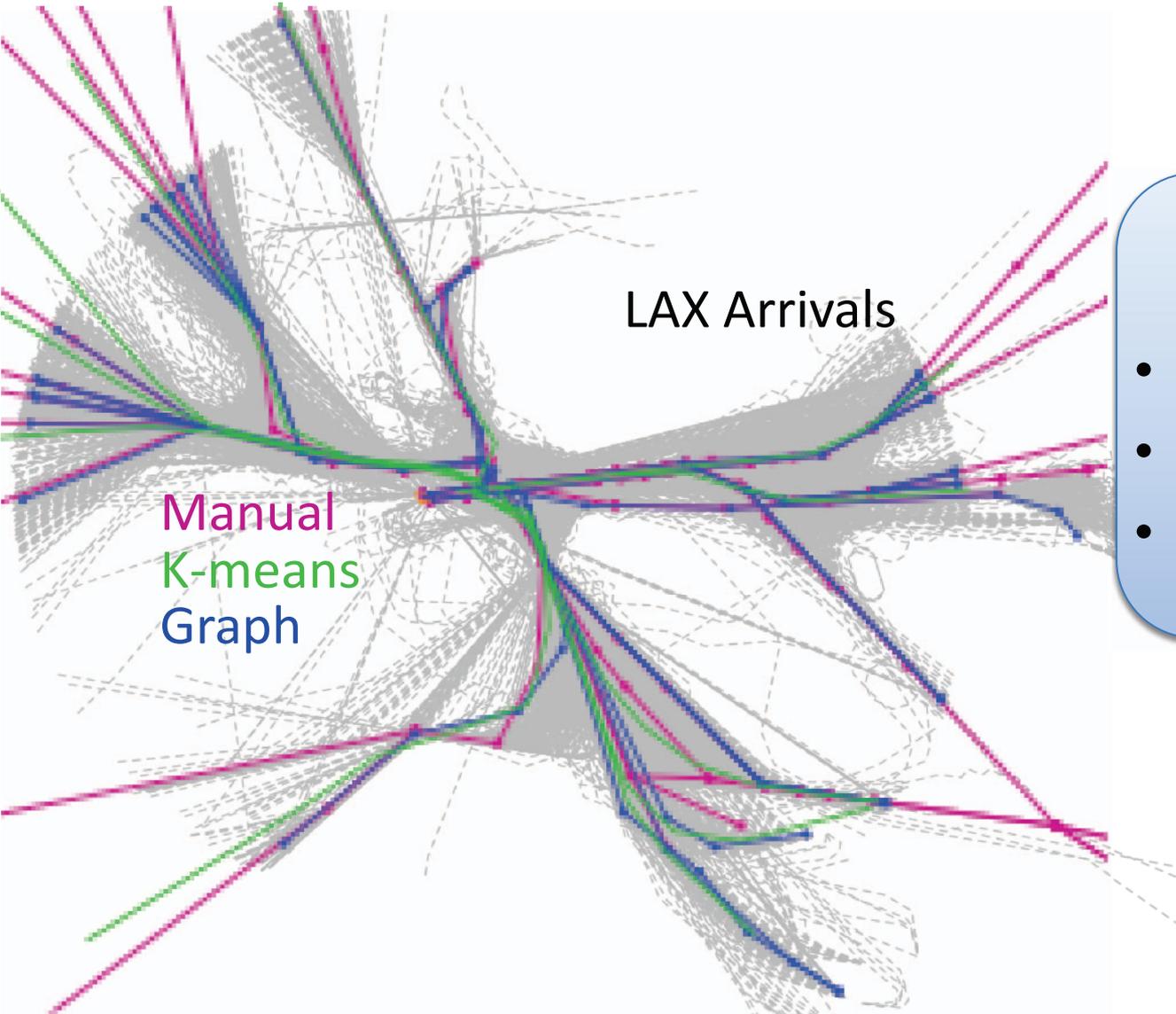
Track data

- Manual – 4 days
- K-means – 1 day
- Graph – 52 days

# Comparison Results



LAX Arrivals
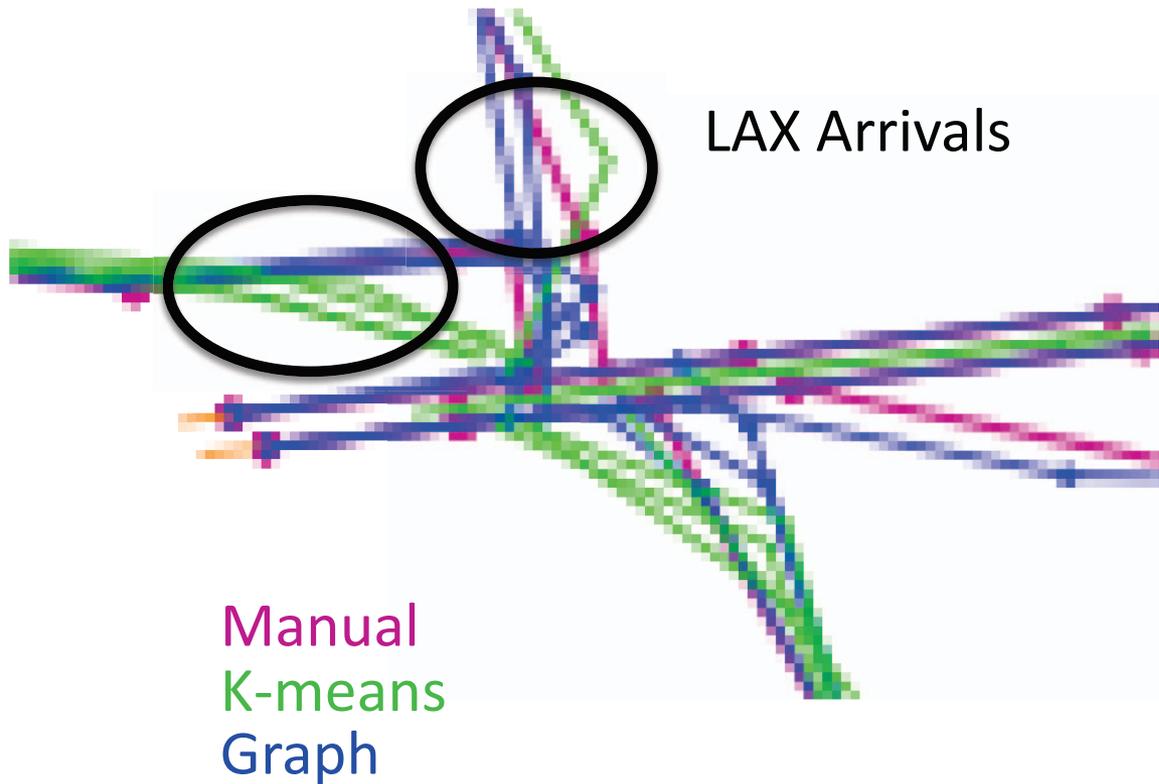
Implementation Choices

Algorithm resolution parameters tuned for different model use.

Manual
K-means
Graph

# Comparison Results



SNA Arrivals

Manual
K-means
Graph
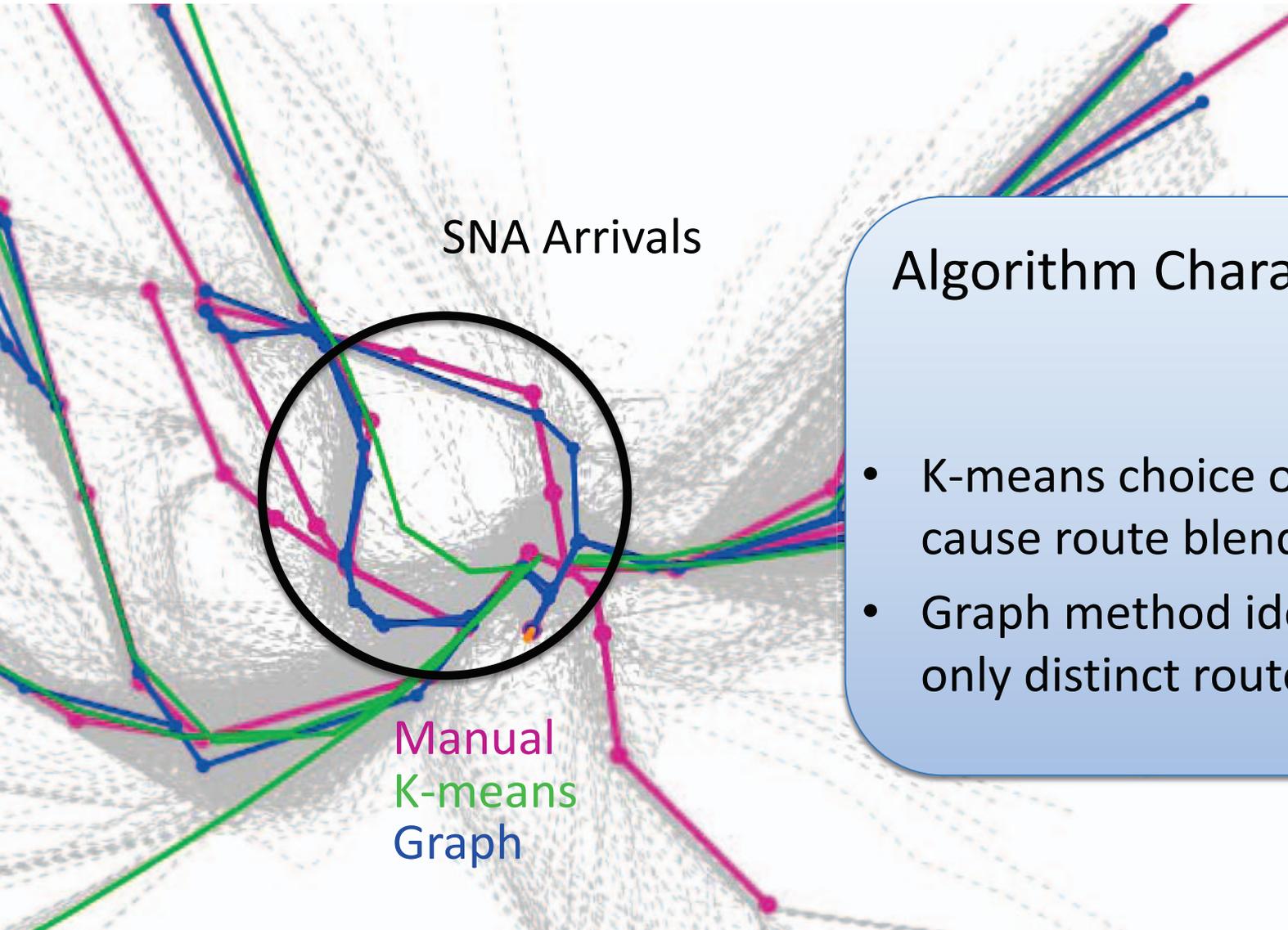
**Algorithm Characteristic**

- K-means choice of k can cause route blending.

- Graph method identifies only distinct routes.

# Comparison Results



LAX Departures

Manual
K-means
Graph
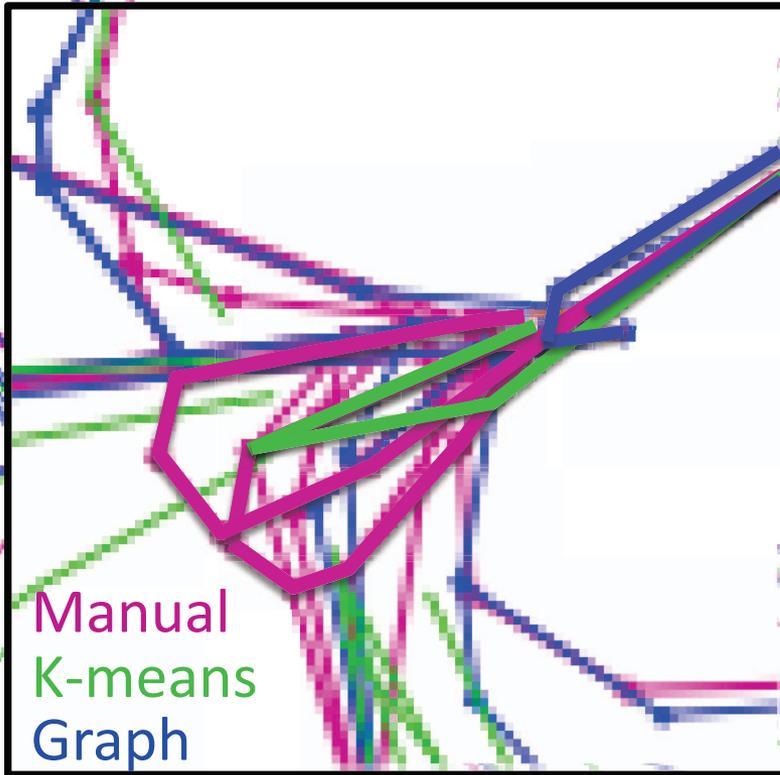
## Path Options

- Manual provides many departure options

- Graph and K-means provide single option

- Graph skips loop in favor of shorter 2D path

# Graph-Base Path Options
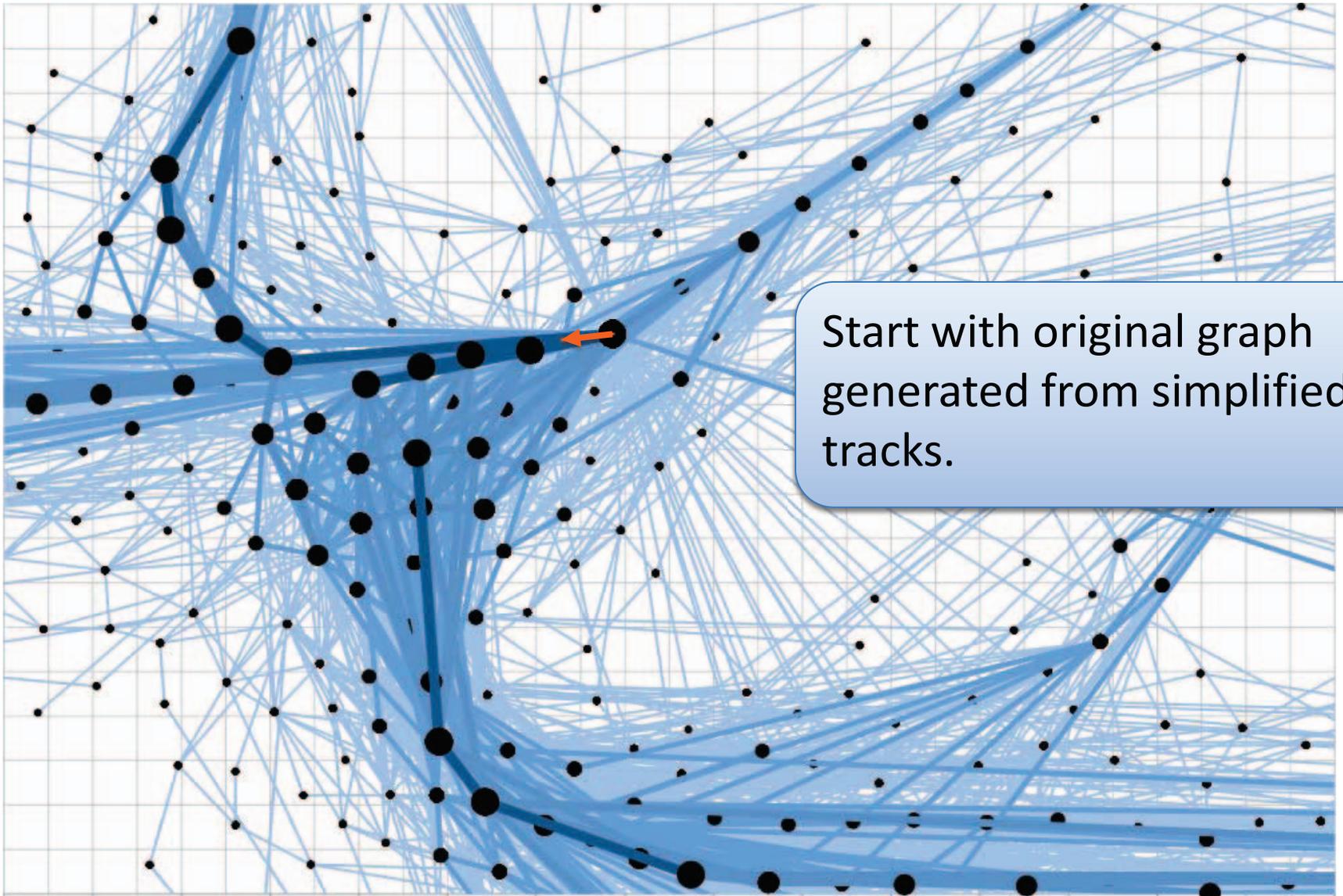


Start with original graph generated from simplified tracks.

# Graph-Base Path Options



Find shortest paths from all links of sufficient weight to sink.
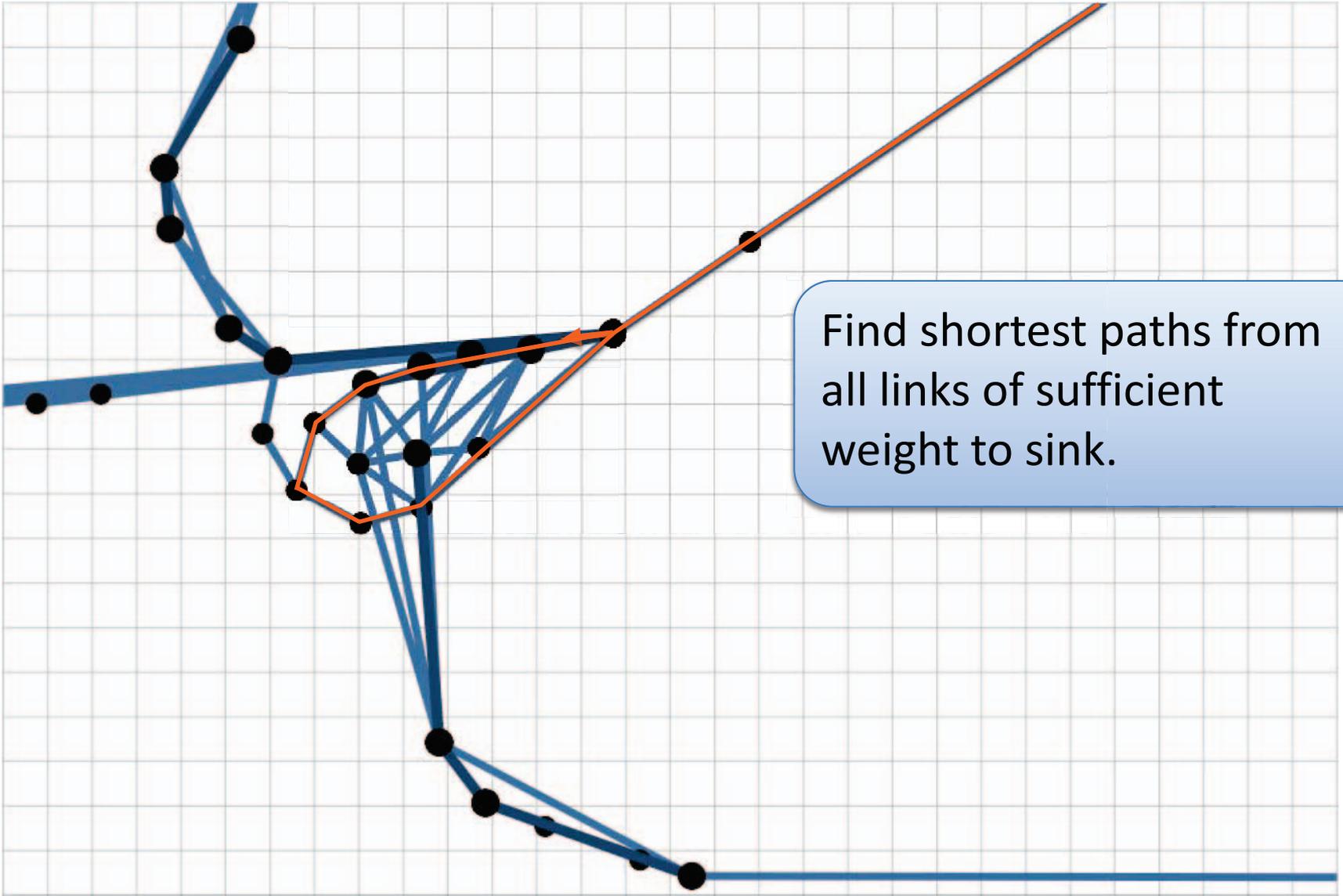
# Summary

Graph-based is:

- Efficient
  - Low cost
  - Fast

- Realistic
  - Objective
  - Distinct flows
  - Path options

✓ Graph-based algorithm processed ~50 days of track data objectively

✓ Graph limits routing to distinct flows so there is no blending effect

✓ Shortest paths from sufficient weight links identify additional path options

May use graph-based method to quickly develop routing models and expand the scope of terminal concept assessments.

# Next Steps

- Extend graph based method to 3D
- Perform input and parameter sensitivity analyses
- Perform more direct comparisons with other methods
- Investigate validation methods