AI4TFM: Advanced Traffic Flow Models for MPO Planning

S3, PAQ, and QVDF with automated plots and KPIs

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What is AI4TFM?

- A lightweight Python module to help MPOs analyze congestion with **observed speeds** and **derived flows**.
- Implements three complementary models:
    1. **S3**: S-shaped speed–density/flow model for deriving flow and density from speeds.
    2. **PAQ**: Polynomial Arrival Queue model to summarize congestion episodes (t0–t3, duration, discharge rate).
    3. **QVDF**: Queue-based Volume–Delay Function to synthesize time-varying delay, queue, and speed.
- Auto-exports figures and CSVs to an `output/` folder for quick review and reporting.

MPO Use Cases

- Identify **peak-period bottlenecks** and congestion windows.
- Compare **corridor performance** across TMCs and days.
- Compute **queued demand factors** and **discharge rates**.
- Visualize **speed heatmaps** (observed vs. modeled).
- Screen **project alternatives** with consistent KPIs.
- Support **CMP**, LRTP, TIP narratives with data-backed visuals.
- Provide **quick-look analytics** before microsimulation.

Data Inputs (typical)

- **TMC identification** (`TMC_identification.csv`): free-flow speed, capacity, length, lanes, FT/AT.
- **Speed readings** (`Reading.csv`): `tmc_code`, timestamp, speed (mph).
- Time step: e.g., 5 min. Periods: AM/MD/PM/NT (configurable).

Outputs are organized under `output/`: `s3_model/`, `paq_model/`, `qvdf_model/`.

Workflow Overview

1. **S3 model** $\Rightarrow$ derive *flow* and *density* from speed from TMC reading data; export enriched readings.
2. **PAQ analysis** $\Rightarrow$ detect t0, t1, t2, t3; computes congestion duration P, queued demand, factors, discharge rate.
3. **PAQ calibration** $\Rightarrow$ fit (f_d, n) and (f_p, s) across days; derive **QVDF** (α, β).
4. **QVDF synthesis** $\Rightarrow$ generate $w(t)$, $Q(t)$, and $v(t)$; draw time series and **speed heatmaps**.

S3 Model (sketch)

$$u = \frac{u_f}{\left(1 + \left(\frac{k}{k_c}\right)^m\right)^{2/m}}, \quad q = u\,k$$

$$\text{cap} = \frac{k_c u_f}{2^{2/m}}, \quad u_c = \frac{u_f}{2^{2/m}}$$

- From observed u and calibrated (u_f, k_c, m), derive q and k to build fundamental diagrams.
- Auto-saves per-TMC plots and an enriched CSV for downstream steps.

PAQ Model (t0–t3)

- Detect: t0 (start), t1 (max flow before t2), t2 (min speed), t3 (end).
- Duration: $P = \frac{t_3 - t_0}{60}$ (hours).
- Queue demand factor:

$$\theta = \frac{D}{V}$$

- V is assigned flow (total flow) across the period.
- Queue demand factor vs. Peak load factor

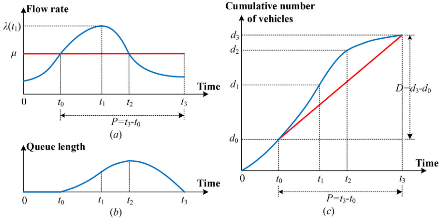

Figure: Graphical illustration of Newell's PAQ model for a single congested period

PAQ Model (t0–t3)

- Empirical relations:

$$P = f_d \left(\frac{D}{C}\right)^n, \qquad \mathrm{MSR}(u) = f_p\, P^s.$$

- KPIs: queued demand, factor, discharge, average speed during $[t_0, t_3]$.

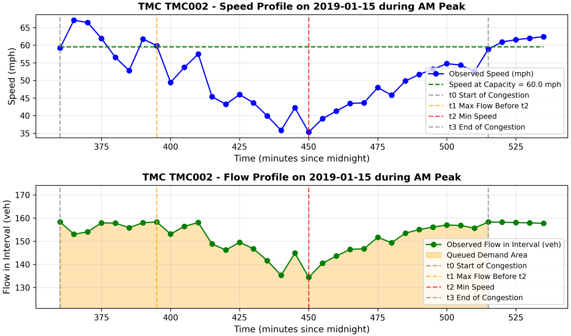

Figure: Speed and volume profile at TMC002

PAQ Calibration and QVDF Parameters

- Stage 1: fit (f_d, n) to $(\frac{D}{C}, P)$.
- Stage 2: fit (f_p, s) to $(P, \mathrm{Mag}(u))$ with reasonable s bounds.
- QVDF parameters (typical form): $\alpha = \frac{64}{120} f_p f_d^s, \quad \beta = n\,s$.

QVDF Time Series and Estimated Speed Heatmaps

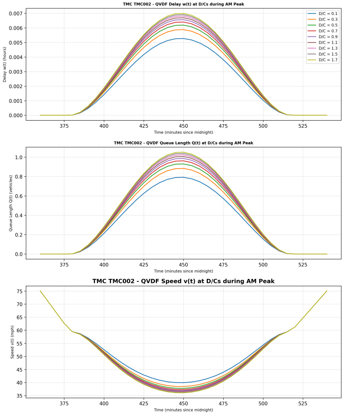

Figure: Derived queue, travel time, and speed

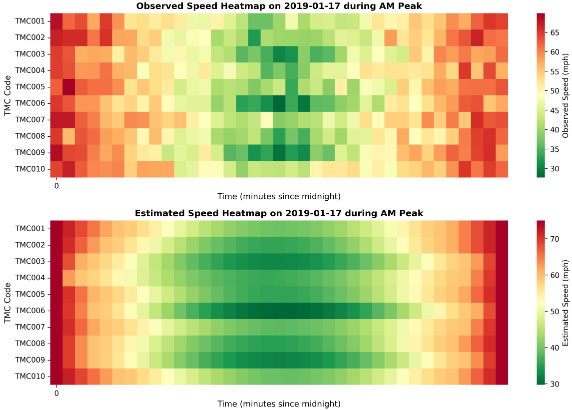

Figure: Estimated speed heatmap

Fundamental Diagrams (S3)

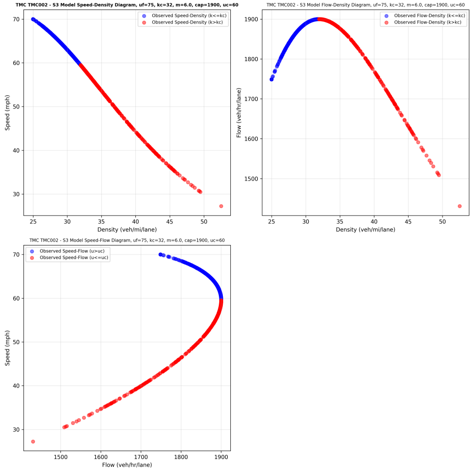

Figure: Fundamental diagram at TMC002

How to Run

1. Prepare input CSVs: `TMC_identification.csv`, `Reading.csv`.
2. Set peak windows and time step in `AI4TFM.py`.
3. Execute: `python AI4TFM.py` (or call `run_advanced_models()`).
4. Outputs appear under `output/` with per-model subfolders.

```
# Define peak period hours
am_peak_start = 6  # 6 AM
am_peak_end = 9  # 9 AM
pm_peak_start = 16  # 3 PM
pm_peak_end = 20  # 8 PM
current_period = 'AM'  # 'AM' or 'PM'
# Define time stamps
time_stamps = 5  # e.g., 5-minute intervals
```

Figure: Required inputs

Outputs and KPIs

- Daily PAQ parameters table (per TMC/day): $t_0, t_1, t_2, t_3, P, D, \frac{D}{C}$, discharge, avg speed.
- Calibrated PAQ and QVDF parameters (per TMC): $f_d, n, f_p, s, \alpha, \beta$.
- Figures: PAQ profiles, calibration plots, QVDF time series, heatmaps, S3 diagrams.

Takeaways for MPOs

- Fast, transparent congestion analytics using standard TMC inputs.
- Consistent KPIs for corridor screening and program narratives.
- Reproducible figures/tables ready for CMP and plan documentation.

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- Questions/collaboration ideas are welcome.