Coupling Computer Vision with the Cell Transmission Model to Assess Traffic Flow Prediction on I-94

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1 Introduction and Motivation

Traffic flow models play a pivotal role in analyzing and alleviating congestion on highways like I-94. Among these, the Cell Transmission Model (CTM) discretizes a roadway into cells to simulate traffic dynamics, such as flow and density, based on a fundamental diagram. A critical yet underexplored parameter in CTM is the cell length (Δx), which governs the spatial resolution of the model. The choice of Δx directly affects the accuracy of predicted traffic states—e.g., downstream flow and occupancy—as it influences the model's ability to capture phenomena like shockwaves and congestion propagation. However, determining an optimal Δx for a specific road link remains challenging, as it depends on local traffic characteristics and data availability, with no universal standard applicable across all scenarios.

Compounding this issue, traditional data sources like loop detectors, which measure vehicle presence and speed, are often noisy and unreliable due to sensor failures, environmental factors, and maintenance difficulties. These limitations can obscure the validation of CTM outputs and hinder the identification of an appropriate Δx. To overcome these challenges, this study leverages computer vision as a robust verification tool. Specifically, we employ the You Only Look Once (YOLO) algorithm to count vehicles at the upstream and downstream ends of an I-94 segment, providing accurate boundary flow data. While ground-truth data are available for I-94, such comprehensive measurements are rare in practice. Thus, we use YOLO-derived counts to both drive CTM simulations and validate their outputs, enabling us to assess which cell length best suits this link. Additionally, we introduce a fitness score to quantify CTM's suitability, offering a systematic approach to model evaluation.

2 Dataset and Computer Vision Approach

This study assumes camera feeds along I-94, akin to the I-24 MOTION testbed (`https://i24motion.org/how-it-works#infrastructure`), providing continuous traffic video. We process these feeds with YOLO to detect and count vehicles at the segment's upstream and downstream boundaries.

- **Vehicle Detection:** YOLO identifies vehicles via bounding boxes, counting those passing through each camera's view over 1-minute intervals.
- **Flow Rate:** Upstream and downstream flows, q_{up} and q_{down} (vehicles/hour), are derived, e.g., 20 vehicles/minute yields $q_{\text{up}} = 1200$ vehicles/hour.

These flows serve as CTM inputs and verification metrics, respectively. Figure 1 demonstrates YOLO's detection capability.

3 Methodology

3.1 Data Preprocessing

- **Vehicle Counts:** Apply YOLO to upstream and downstream feeds for time-series counts.
- **Flow Estimation:** Compute q_{up} and q_{down} over $\Delta t = 1\,\text{minute}$.

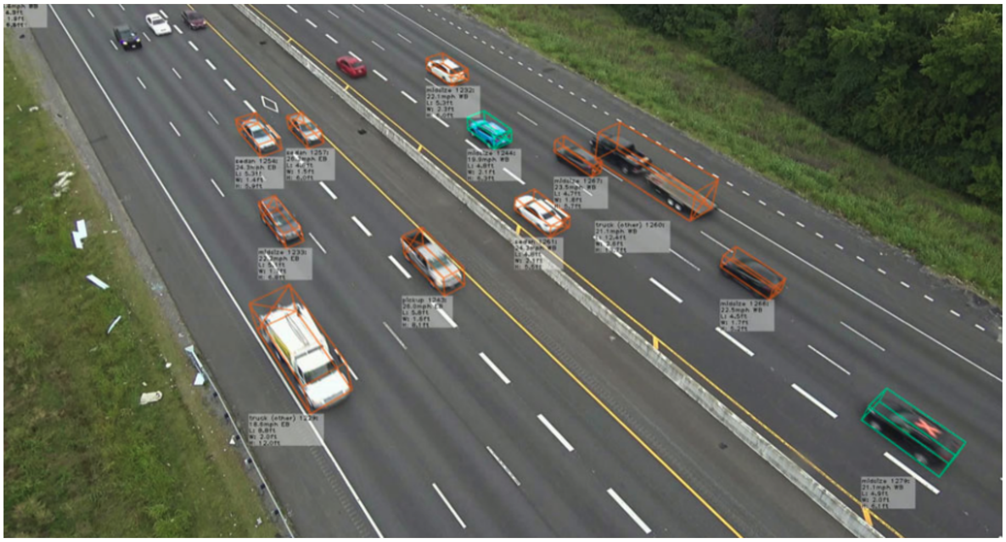

Figure 1: Vehicle detection on I-94 using computer vision, with bounding boxes around detected vehicles.

- **Ground-Truth Role:** Use I-94 ground-truth data for benchmarking, not as CTM input, reflecting real-world sparsity.

3.2 Cell Transmission Model Formulation

CTM divides the segment into cells of width Δx, with density k_i^t in cell i at time t, governed by a triangular fundamental diagram:

- Parameters: $v_f = 65\,\text{mph}$, $k_{\text{jam}} = 200\,\text{vehicles/mile}$, $q_{\max} = 2000\,\text{vehicles/hour}$, $w = \frac{q_{\max}}{k_{\text{jam}}}$.
- **Sending Flow:** $S_i^t = \min(v_f k_i^t, q_{\max})$.
- **Receiving Flow:** $R_{i+1}^t = \min(w(k_{\text{jam}} - k_{i+1}^t), q_{\max})$.
- **Inter-Cell Flow:** $y_{i,i+1}^t = \min(S_i^t, R_{i+1}^t)$.
- **Density Update:**

$$k_i^{t+1} = k_i^t + \frac{\Delta t}{\Delta x}(y_{i-1,i}^t - y_{i,i+1}^t),$$

  where $\Delta t \leq \frac{\Delta x}{v_f}$.

q_{up} drives the first cell; CTM predicts $\hat{q}_{\text{down}}$.

3.3 Experimental Design

- **Simulation:** Use q_{up} to simulate 1-hour traffic, predicting $\hat{q}_{\text{down}}$.
- **Error Analysis:** Compare $\hat{q}_{\text{down}}$ to q_{down}:
  - MAE: $\text{MAE} = \frac{1}{T}\sum_{t=1}^{T} |\hat{q}_{\text{down}}^t - q_{\text{down}}^t|$.
  - RMSE: $\text{RMSE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\hat{q}_{\text{down}}^t - q_{\text{down}}^t)^2}$.
- **Fitness Score:** $\text{FS} = \frac{1}{1+\text{MAE}} \in (0, 1]$; higher FS indicates suitability.
- **Cell Length Test:** Vary $\Delta x \in \{50, 100, 200, 500, 1000\}$ m to identify the optimal Δx via FS.
- **Benchmarking:** Compare against I-94 ground-truth flows for validation.